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HIGH INTENSITY PHENOMENA OBSERVED IN THE CPS

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Summary

A review of high intensity phenomena observed in the CPS is presented. At injection an attempt is made to describe the combined effect of space charge and resonances, which result in a loss of 70% of the injected beam intensity and a reduction by a factor of 3 of the central core brilliance. Results of measurements on the effect of a localised bad vacuum are given. The situation at transition is briefly described.

Seven different instabilities observed in the CPS in longitudinal or transverse phase plane are analysed. The compensation techniques are described in all cases. Whenever possible an attempt has been made to give some qualitative explanation of the mechanism.

Introduction

Last year a new customer, the ISR, was added to the list of the CPS users. In the years to come we will have to accept particles from the 800 MeV Booster and to inject our beam in the 300 GeV machine. As an injector both for the ISR and now the 300 GeV machine the CPS should not only be a high intensity accelerator but also should deliver a beam as dense as possible. Consequently a high priority is given in the CPS to the study of high intensity phenomena. This review being made while the work is still in progress, we have tried to list not only the effects we understand but also those for which both experiment and theory are uncomplete.

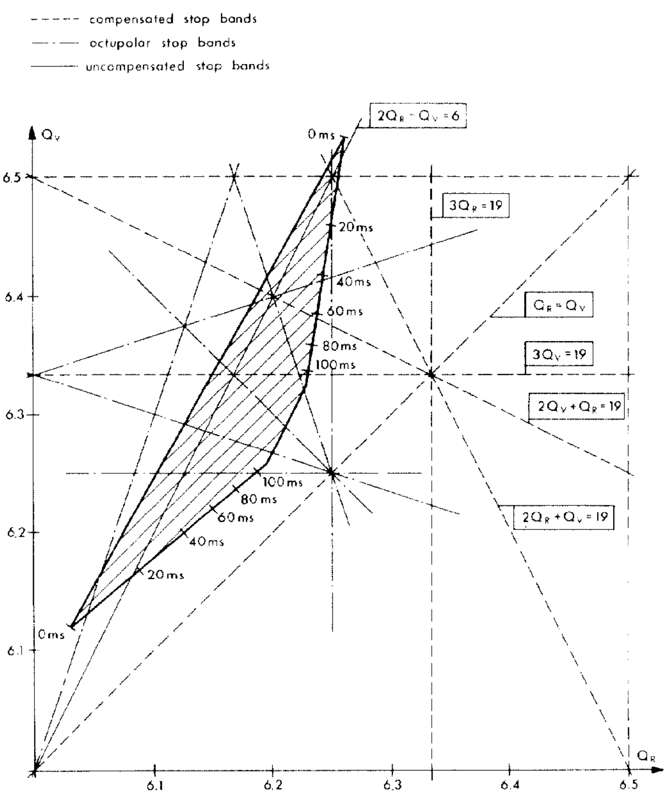
50 MeV Injection

About a year ago we modified our injection and trapping situation in the CPS in order to increase the final intensity of our machine. We were previously using the "high trapping" technique, described several years ago[1], combined with single turn injection, and a field rate of rise ($\dot{B}$) of about 1.3 tesla per second. This technique had the inconvenience of reducing the longitudinal acceptance. Also, during the process, one had a rather strongly bunched beam and therefore important space charge effects. On the other hand the large $\dot{B}$ provided a faster crossing of resonances, space charge effects could only develop for a short time.

We now use multiturn injection combined with RF adiabatic trapping[2,3]. A reduction of $\dot{B}$ is necessary in order to achieve a good longitudinal adiabatic trapping. The new value of $\dot{B}$ is 0.35 tesla s^{-1} for 80 ms then we increase it to about 1.9 tesla s^{-1} for the rest of the acceleration. The maximum longitudinal density of particles is reduced by a factor 2 to 3 but we stay longer on resonances at low energy. This last point turned out to be of some advantage because we could then separate the various resonances and therefore find a better compensation.

In order to achieve a high intensity we had to modify to a large extent the transverse focusing in the CPS. The injection quadrupoles, DC powered, bring the working point for small intensity above $Q_V = 6.5$, that is on the other side of the ½ integer stop-band that we have to cross when we accelerate a small beam. In fact, as shown in Fig. 1, we cross several stop-bands

The working point in the diamond time and space charge included



with the low intensity beam[4], our working conditions are clearly not adapted to such a beam.

At its best our linac produces[5] a beam of 110 mA, that is 1.4 10^{13} protons in the 20µs of our 3 turn-injection. About 50% of these are lost in those 3 first turns so that the maximum number of injected protons never reaches more than 7.10^{12}. The maximum number of protons we are able to accelerate to top energy being about 2.10^{12}, our trapping efficiency is only about 30%, the overall transfer efficiency being of the order of 15%. Most of these losses take place in the first 10 ms of the PS cycle.

If one assumes that the CPS beam after 10 ms is roughly gaussian and fills the vacuum chamber one finds that the corresponding brilliance if 20 times smaller than what it should be in an ideal transfer. This indicates that in addition to the 85% intensity loss we lose a factor of 3 in brilliance.

Thus, keeping the same assumptions one can calculate the maximum single particle Q shift inside the beam:

$$\Delta Q_V = 0.4$$

$$\Delta Q_R = 0.2$$

These Q shifts indicated in Fig. 1 seem the reasonable numbers to quote if one assumes that the distributions are stable.

Experimentally one can verify that the high intensity beam is not sensitive to the perturbations exciting the stop-bands $2Q_V = 13$ and $2Q_V + Q_R = 19$, but starts being sensitive to $3Q_V = 19$; this last stop-band is excited by sextupoles which are not symmetrical with respect to the horizontal plane. Also one should mention that most of our recent intensity increase resulted from sextupolar stop-band compensation.

After those very approximate estimations several questions remain

- Are the distributions stable ?
- Why cannot we move further the zero space charge working point ?
- Is the beam really filling the vacuum chamber after 10 ms ?

or to summarize : what happens during the first 10 ms ?

We believe that if we want to make further progress we have to study the dynamical properties of particle distributions. On the experimental side we are testing a computer acquisition of the Ionic Beam Scanner signals which we hope will help us to progress in that direction.

Vacuum Effect

About 2 years ago we decided to improve by an order of magnitude the vacuum in the CPS. An experiment was set up in order to prepare this decision. We installed nitrogen cooled baffles[6] around the vacuum chamber in most of the straight sections; this way we could reduce the pressure from $2.1\ 10^{-6}$ to $1.2\ 10^{-6}$ torr for a few hours. In this limited amount of time we were able to raise the maximum circulating beam intensity by about 10% which was already a favorable indication.

During the same experiment we had prepared a localised adjustable leak. The effects were much more evident even though the average pressure never reached the previous value of 2.10^{-6}.

The vertical "Head-Tail" instability appeared very quickly at high energy, we could stabilise it by increasing the energy spread in the beam.

Close to injection important beam losses appeared at the time we were crossing sextupolar stop-bands. We could eliminate most of these losses by installing a sextupolar compensation.

Finally we tried two gases Xe and Air. The effects were similar for two different pressures (localised on about 5 m)

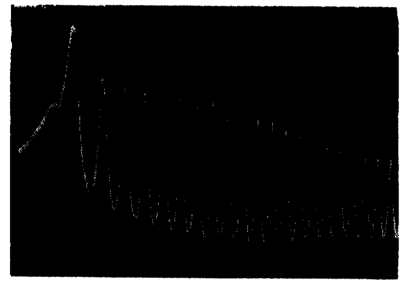
7.10^{-5} torr for Xe

2.10^{-4} torr for Air.

These correspond to the same reading of the ionisation gauge. These effects seem therefore to be related to the number of ionisable electrons. We have not yet found a satisfactory explanation.

Transition

For the same reasons that make it an interesting injector for ISR, namely a high longitudinal density, the CPS proved to be a difficult machine from transition point of view. It has strong longitudinal space charge effects. Picture 1 shows how the maximum longitudinal density (roughly the inverse of bunch length) varies when crossing transition in an uncompensated way. Linear theory of longitudinal space charge explains the oscillations but not the drop in average density.



Pict. 1 Transition without Q-Jump

Pict. 2 Transition with Q-Jump
- Longitudinal density
- Current in the quadrupoles

Transverse space charge and non-linear longitudinal space charge might explain this drop, calculations of these effects are underway but no result is yet available.

In 1969 the Q-jump technique was tried successfully on the CPS giving results shown on Picture 2. More recently a more powerful method called γ_{tr}-jump[8] was investigated but not tried experimentally. The idea of both these techniques is to achieve a long equilibrium bunch length by a large and fast decrease of γ_{tr} just after transition crossing; in the γ_{tr}-jump the change in γ_{tr} can be made significantly larger than the change of Q by exciting two sets of quadrupoles with opposite polarity. Various techniques are available to match the bunches to their lengthened equilibrium situations. We hope with this method to be able to cross transition with 10^{13} particles.

Instabilities

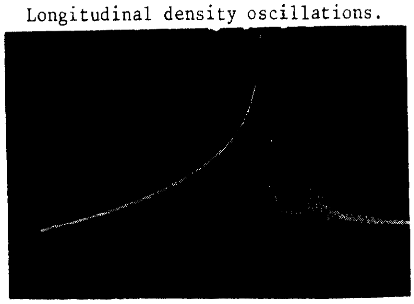
The number of collective phenomena observed[9] has steadily increased with the intensity of our machine. The easiest to recognize are the instabilities but various emittance blow-up[10], that we measure, could have their origin in similar effects.

Longitudinal Instabilities

Rebunching : for slow ejection or target operation we debunch the beam in order to deliver a structure-free spill to the physicists. After this debunching operation we noticed (with the help of the experimenters !) that the beam was rebunching on a 5th harmonic of revolution frequency. Hereward showed[11] that the impedance of the cavities, tuned at injection frequency during this operation was responsible for this effect. He also proposed various cures. The stagger tuning of the cavities was tried successfully. For the improved CPS beam we will have new RF cavities, a short circuit of the gap during debunching operation has been foreseen.

"Hereward Damping": that is the name we give to a damping system for coherent bunch shape oscillations of the type H.G.Hereward[12] and E.C.Raka[13] described a few years ago. The source of the oscillations we observe is not known but one supposes that they have their origin in imperfections of the beam control[14]. Picture 3 shows the envelope of the signal obtained from a sum pick-up electrode (roughly the inverse of bunch length). With the damping system Picture 4 the oscillations have disappeared. The oscillations induced at transition are damped.

Pict. 3 "Hereward Damping" off.
Longitudinal density oscillations.



Pict. 4 "Hereward Damping" on.
Longitudinal density oscillations.

Dipole Longitudinal Instabilities[15]: more recently an instability of the bunch position developped for the short bunches we have if we go through transition with Q-jump. A similar instability was observed and cured at the AGS[15]. Picture 5 shows a mountain range display of the position of one bunch with respect to the RF sinewave triggering the scope. The bunches oscillate with different phases with respect to the RF in a pattern of 5 wavelength around the machine. This corresponds to a $\pi/2$ phase shift from one bunch to the next which is the most unstable mode in our case. The beam control, seeing an average position of the bunches, is not effective.

In the CPS it is a parasitic resonance in the accelerating cavities which is responsible for the instability. Each bunch leaves in the cavity a wake that will excite the next bunch. If we do not use Q-jump at transition, the bunches are longer so that the instability is Landau damped by RF non-linearities.

We succeeded in damping this instability by powering at half RF frequency one of our cavities. This provides a bunch to bunch synchrotron frequency spread which decouples the bunches. We did this after discovering that we had to select a special pattern of synchrotron frequency modulation to be efficient. For example, a modulation at ¼ of the RF frequency would not be efficient. This effect was explained by including the beam control in our model. We can understand it by comparing the two types of modulation pattern. If we note + a bunch that has a higher synchrotron frequency and - the opposite one has the following patterns for the two modulations :

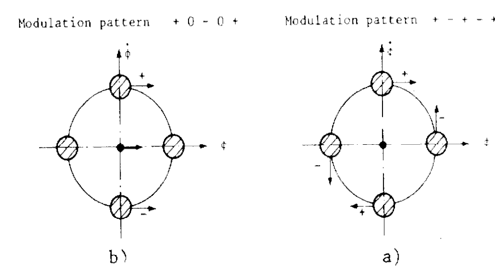
a) ½ RF frequency : + - + - + ...
b) ¼ RF frequency : + 0 - 0 + ...

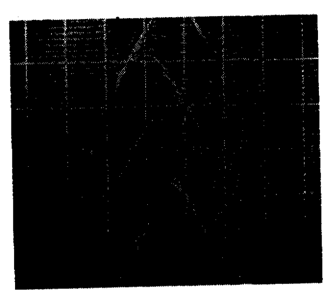
If we represent on one phase space diagram four consecutive bunches oscillating at $\pi/2$ phase shift one from the other we obtain Fig. 2 where the arrows indicate the phase drift corresponding to the frequency modulation. In case a) the center of gravity of the four bunches does not drift. In case b) the center of gravity does move. The beam control will counteract the motion, therefore diminishing the effect of the modulation.

It is by a similar interaction with the beam control that we could also explain the fact that the instability developped even in the case where several bunches were missing, for example, after fast extraction of a few bunches.

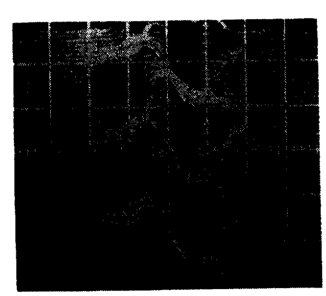
This stabilisation however is not powerful enough. When half of the available power at $\omega_{rf}/2$ is applied (Picture 5) the bunches still oscillate. At full power the stabilisation is barely sufficient. We cannot increase the number of cavities that we use for this purpose. For these reasons we are now looking into an active feed back, but with the large harmonic number of the CPS (h = 20) one has to be careful not to excite other modes.

Longitudinal Instability
Stabilisation by Synchrotronic Frequency Spread
from Bunch to Bunch





Pict. 5 5 ns/cm
Mountain range display of ½ stabilised bunch oscillations



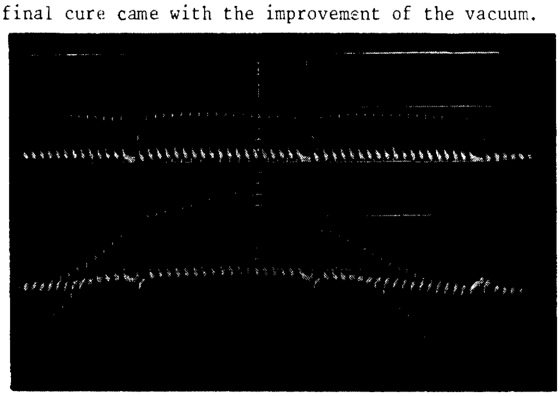
Pict. 6 5 ns/cm
Mountain range display of non stabilised bunch oscillations

Multipole Longitudinal Instability : Picture 6 corresponds to the same situation as Picture 5 but without the stabilisation. Clearly at large amplitudes the oscillations are not purely dipole. One could think that the filamentation explains the difference but the experimental evidence is that this is probably not the only effect. In fact, we were able to calculate[16] e-folding times of about 200 ms for a bunch shape oscillation with a similar mechanism. The frequency modulation seems rather efficient in stabilising these multipole instabilities. In case an active feed-back would work on the dipole instability we might still have to keep the modulation technique for the multipole effects.

With the high intensity beam (10^{13} p.p.p) the bunches will be longer, we will have new cavities. Predictions are therefore difficult to make.

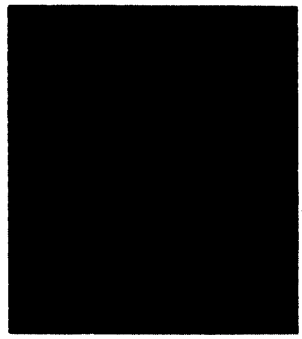
Transverse Instabilities

Ionic Oscillations : this was the first instability to be discovered, explained and suppressed in the CPS. It is a bunch to bunch coherent radial instability which starts at low energy. Picture 7 shows the voltage induced by the beam in the sum and radial electrodes, one sees the bunches oscillating with a well defined mode : with a pattern of 6 wavelength around the machine and a local frequency (Q-6) = 0.25 per turn visible on Picture 7.H.G.Hereward found[17] that the source of the instability is the ionic wake that protons leave behind them, the necessary phase shift between force and motion being introduced by the relative motion of the proton beam and the ion cloud. The final cure came with the improvement of the vacuum.



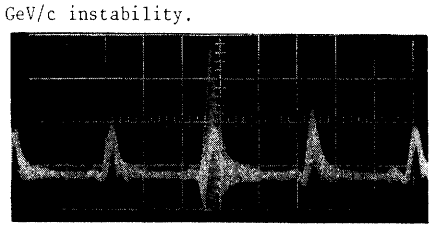
Pict. 7 Ionic Oscillations
- Sum signal from pick-up electrodes
- Radial signal from pick-up electrodes

6 GeV/c Vertical Instability : this rather long name implies already that we do not understand this instability. In fact we can hardly see it. Two effects are visible : - we lose beam if we do not stabilise it by octupoles - the Ionic Beam Scanner, Picture 8, shows that the beam vertical size is increasing with a growth rate of about 10 to 20 ms. We do not see anything on the vertical pick-up electrodes. We have only observed this instability from 6 to 9 GeV/c when we go through transition using the Q-jump technique that is when we have the shorter bunches. At first it would look like a quadrupole type motion of the bunch. However a normal head-tail motion with a high mode number would not be visible through our 35 MHz limited band-width pick-up stations. We can avoid the losses with relatively low current in our octupoles, but we have to feed them with all the power we have to reduce the beam size at top energy. In other words the octupoles stop the growth at a certain amplitude. This instability has been discovered fairly recently, a preliminary investigation[18] of wall effect does not give an explanation of such fast growth rates. We are improving the pick-up electrodes and should in principle get better observations soon.

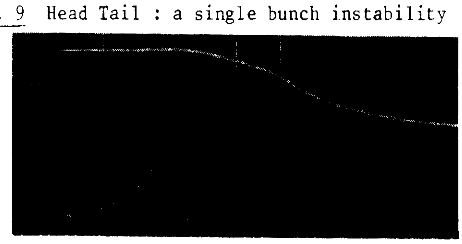


Pict. 8 Mountain range display (5 ms/cm) of the Ionic Beam Scanner signal during the 6 GeV/c vertical instability.

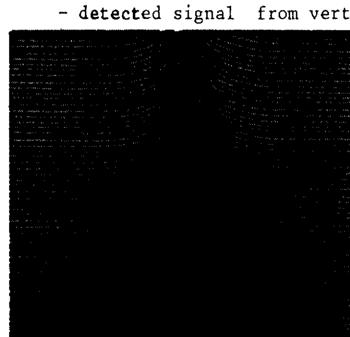
Vertical Head Tail : this instability we call head tail by analogy with the instability described for Adone[19]. It appears around 10 GeV/c and we usually stabilise it with octupoles. On Picture 9 the vertical pick-up electrode signals induced by 5 bunches during a few thousand turns are superimposed.Only one bunch oscillates : it is a single bunch instability. The signals from the oscillating bunch are only twice the signals from the non oscillating one, even though we were losing beam during this time. This comes from the fact that the frequency in the bunch is outside the bandwidth of the pick-up station (probably mode 2 in terms of head tail modes). Picture 10 shows the circulating beam intensity (we lose beam) and the detected signal from the vertical pick-up : the e-folding time is about 10 ms. Picture 11 is an Ionic Beam Scanner picture of the phenomenon, similar to the signal we obtained for the 6 GeV/c instability.



Pict. 9 Head Tail : a single bunch instability



Pict. 10 Head Tail Instability. 10 ms/cm
- circulating beam intensity
- detected signal from vertical pick-up electrode



Pict. 11
Mountain range display (5 ms/cm) of the IBS signal during head tail instability

Several difficulties appear if we want to compare our measurements with the available theory of head tail:

The betatron frequency spread in the beam is much stronger than in an electron machine. Even the calculation[20] that Zotter did for the ISR does not cover all the situations where we have observed instability (we can vary the dQ_V/dE in our machine by using sextupoles). In other words the betatron phase shift due to energy oscillation for a particle going from the head to the tail of the bunch is from 5 to 30 radians while in Sands model it is supposed to be of the order or less than a radian. Although Zotter extended this calculation to large phase shift one can doubt that the model of a hollow bunch remains valid.

We observe e-folding times as low as 2 or 3 synchrotronic periods. This implies rather power forces that we have not been able to find, if one still apply the theory as modified by Zotter the growth rates for wall effect are an order of magnitude too small.

We have not yet been able to find a mechanism which would explain the strong influence of a local bad vacuum as already mentioned.

Following a remark by F. Sacherer we calculated that the space charge detuning at 10 GeV/c is about as big as the Q shift due to energy oscillations. In fact below 10 GeV/c the space charge detuning is larger and above it is smaller.

Conclusion

At injection the situation is still unclear but the more intense 800 MeV beam that the new injector will deliver should be less uncomfortable in our machine from the point of view of space charge, than our present 50 MeV beam. At transition we need better understanding but the technique of γ_{tr}-jump should hopefully solve our problems. We have observed and more or less stabilised a total of seven different instabilities but we still have some dilution during the acceleration. The fact that in the near future the CPS will be at the centre of a complex of 4 machines makes it all the more important to solve our problems.

Acknowledgements

The collaboration of a variety of people is necessary to achieve any improvement in this field. It mixes theory, experimentation, new instrumentation and new hardware. We therefore acknowledge the work of many people in the MPS Division and the constant support of P.H. Standley. H.G. Hereward has been at the origin of most of the progresses which were made. We thank him for the long discussions we had concerning this review. We also profited from discussions with D. Boussard, M. Bouthéon, W. Hardt and A. Sørenssen.

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