Recent development in mitigation of long term beam loss

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Long term beam loss are due to the presence of several factors, but lattice nonlinearities and high intensity certainly rank among the main causes for long term beam loss. Experimental and numerical studies have shown that periodic resonance crossing induced by space charge in a bunched beam is a deleterious effect for beam survival [1, 2]. Given the complexity of the topic, the studies in the past have been focused to investigate one dimensional resonances, for example in Ref. [1] the resonance was $4Q_x = 25$, while in Ref. [2] the resonance was $3Q_x = 13$. The underlying mechanism leading to beam loss is explained, in this case, in terms of instantaneous stable islands in a two-dimensional phase space and their crossing the particles orbits. This mechanism was studied in details in Ref. [3].

Studies for SIS100 have shown, however, that in the injection scenario of the uranium ions, random components of magnets nonlinearities excite a significant web of resonances including coupled resonances [4]. One of the simpler of the nonlinear coupled resonances is the $Q_x + 2Q_y = N$. Although the mechanism of the beam loss remains the same (the periodic resonance crossing induced by space charge), the details of the mechanism have never been, in this case, studied. The reason for that is in the complexity of the 4-dimensional coupled motion, which poses an extraordinary challenge to disentangle the dynamics. While for 1-dimensional resonances the mechanism is relatively well understood, for 2-dimensional resonances it remains still unraveled.

In this context, within the collaboration between CERN and GSI, in 2012 a new experimental campaign in the CERN-PS for investigating the resonance $Q_x + 2Q_y = 19$ has been undertaken. The results of measurements collected in a scan of beam intensity/profiles versus tunes have shown puzzling features: when the space charge tunespread overlaps the third order resonance an asymmetric beam response is found: in one plane we find halo, whereas in the other plane a core growth takes place. In Fig. 1 we show a plot with the beam profiles resulting from the space charge tune spread overlapping with the third order resonance, the tunes of the measurement are reported on the picture, the tune-shift is $\Delta Q_x \simeq -0.046, \Delta Q_y \simeq -0.068$. The asymmetry of the profile is quite evident and shows that a new and more complex dynamics is driving the beam halo formation. The details of these measurements will be part of a dedicated article.

The explanation of this beam profile shape have to be searched into the effects created by the 4D coupled dynamics. In this scenario the analogous of the fix points become the fix-lines [5]. These extended closed lines play a similar role as the fix points for the crossing of the 1D resonances. The description of this dynamics is beyond the purpose of this proceeding, a full study for the case of single particle is part of a future work [6].
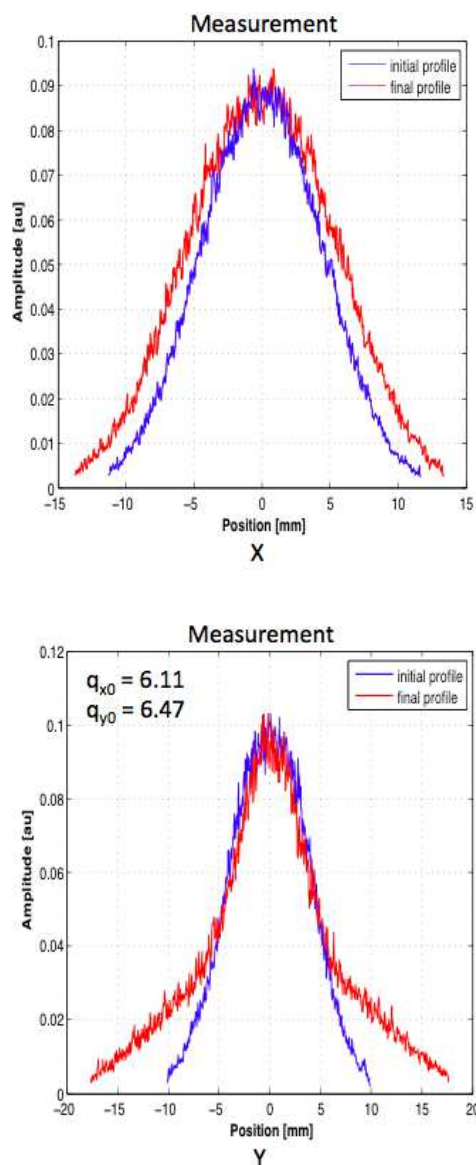

Figure 1: Beam profiles after 1 second storage of the beam in the CERN-PS. The asymmetry of the beam response is evident.

If the halo edge is exceeding the beam pipe, long term beam loss is unavoidable. While the issue of the self-consistency during a substantial change of the space charge intensity is of relevance, practically this scenario is not really foreseen in practical operation in order to avoid significant machine or collimators damage.

The relevant issue is therefore if a strategy that allows to mitigate beam loss in a conventional operational scenario can really be effective over long term storage of a high intensity bunched beam. Past numerical studies have shown that resonance compensation is certainly a way to attack the problem, and simulations using a *frozen space charge* model has shown a beneficial effect of the resonance compensation [7, 8, 4]. From the fundamental point of view, however, it remains to be established if this procedure can be operated in a real high intensity bunched beam.

In the common practice, resonance compensation is understood as the creation of an artificial driving term that counteract the driving term created by the machine nonlinearities. The effectiveness of the procedure relies on the assumption that a resonance is excited mainly by a single harmonics. While this assumption may prove to work decently in standard operational regimes, it is not obvious what are the consequences of a periodic resonance crossing induced by space charge.

For these reasons in parallel with the CERN experimental effort, at GSI a campaign for testing the effectiveness of a resonance compensation in presence of space charge has been undertaken.

We have proceeded as follows. First we have measured the resonance chart of the SIS18, and afterwards we implemented a compensation of a third order resonance. On the best compensation we could achieve we explored the robustness of the mitigation scheme for moderately intense bunched beams.

ASSESSMENT OF RESONANCES IN SIS18

The campaign started with an assessment of the resonance chart of SIS18 after its return to operation from the shutdown. In Fig. 2 it is shown the resonance chart of SIS18 after the re-alignment of the SIS18 magnets operated during the May/June shutdown. The apparent mismatch of some of the resonance lines with the theoretical solid lines is due to small systematic tune-shifts present in the machine model used by the control system. Most of the resonances in the picture are weaker than they were before the re-alignment, which speaks for a beneficial effect of the machine re-alignment. The linear coupling resonances are significantly mitigated, in particular the line $Q_x - Q_y = 1$ is weakened. However, the benefit of the magnets re-alignment is not completely obvious: the machine has now a new third order resonance before not present, which is the line $3Q_y = 10$. The third order resonance $Q_x + 2Q_y = 11$ appears stronger, as well as the half integer $2Q_y = 7$.
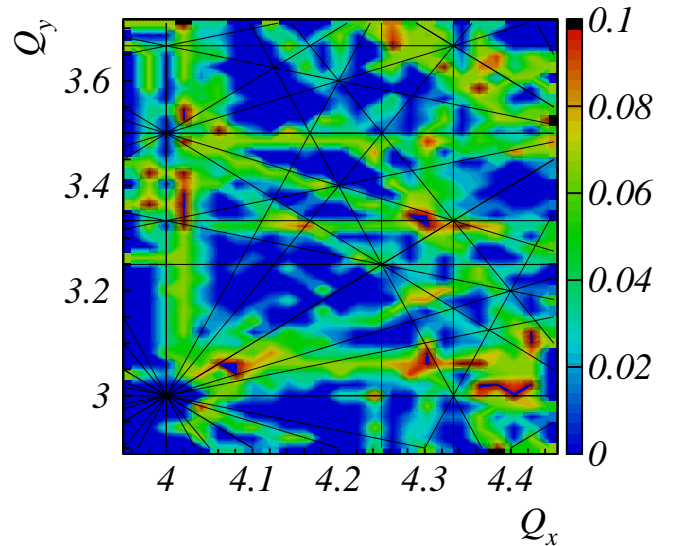

Figure 2: Resonances of SIS18 measured on the 16/7/2014 after the magnets re-alignment. This picture have been obtained by using SISMODI control system.

THIRD ORDER RESONANCE MITIGATION

The third order resonance $Q_x + 2Q_y = 11$ is of particular interest because a similar resonance will affect the SIS100 for the preliminary working point for ions (example for the uranium beam scenario at the working point $Q_x = 18.84, Q_y = 18.73$) and fast extraction. The same type of resonance was investigated in the CERN-PS campaign.

The major effort of the experimental campaign was to compensate this resonance line and verify the robustness of the compensation for a bunched beam in a SIS100 "type" scenario, i.e. a bunched beam stored for 1 second at injection energy.

First, the resonance strength was assessed by measuring the beam loss while the resonance is crossed in 1 second from $Q_y = 3.45$ to $Q_y = 3.35$. The horizontal tune was kept fix to $Q_x = 4.2$. We used a coasting beam with an intensity low enough to prevent space charge effects; in fact, for 2×10^8 ions of U^{73+}, the tune-shift is $\Delta Q_x \simeq -2.5 \times 10^{-3}, \Delta Q_y \simeq -5 \times 10^{-3}$. The injected beam is chosen to completely fill the transverse acceptances of SIS18, thus emphasizing the beam loss due to resonances. Throughout the resonance crossing the beam was always kept coasting. Fig. 3 top shows the beam survival during the crossing of $Q_x + 2Q_y = 11$ in 1 second for the un-compensated machine: only $\sim 35\%$ of the beam survives. The stop-band is found in the range $450 \div 750$ ms, which corresponds to $Q_y = 3.375 \div 3.405$ because of the linear tune ramp.

The effort for compensating this resonance is based on creating a controlled driving term by using the normal sex-

tupoles of SIS18. They are set to act against the driving term created by the "natural machine errors". The driving term is identified by its strength Λ and by an angle α. The pair (α, Λ) allows the complete determination of the strengths of two arbitrary sextupoles through the machine optics, which is supposed to be completely known. For the experiment we used the sextupoles GS05KS3C, GS07KS3C. Figure 3 center shows the effect of the two sextupoles in terms of beam survival as function of α for the strength of the driving term of $\Lambda = 0.002$. (the units of Λ are of integrated sextupole strength, as used in the LSA setting generation system, which we used in replacement of the SISMODI). This picture shows a peculiar feature of the power supply of the SIS18 sextupoles. In fact, the attempt of correcting the resonance by using a too small Λ, has set small currents to the two correcting sextupoles. In this situation the power supply system is not able to resolve these small currents, and set therefore some threshold current. The resulting effect appears as a discontinuous beam survival at $\alpha \simeq 20, 170$ degree. This feature certainly becomes a limitation for compensating a resonance at low machine rigidity.

Fortunately the rigidity of the U^{73+} at 11.4 MeV injection energy is high enough to prevent this situation. The third order coupled resonance is in fact better compensated for a different strength of the correcting driving term, namely for $\Lambda = 0.025$. For this strength the angle of $\alpha \sim 270$ degree yields the best performance, improving the beam survival from $\sim 35\%$ to $\sim 85\%$. This result is shown in Fig. 4 bottom. A better optimization of the compensation was not reached, and the reasons for this were beyond the beam time available: this would require an ORM analysis and verification of the SIS18 optics, with especial attention to the sextupole correctors used.

EFFECT OF HIGH INTENSITY BUNCH DYNAMICS

The effectiveness of the best resonance compensation achieved was tested with a bunched beam with a moderate intensity. The beam was injected, bunched, and stored for 1 second keeping the machine tunes fixed (standard operation mode). We explored the bunched beam survival for several working points Q_y, keeping $Q_x = 4.2$ at each measurement. The beam intensity allowed a moderate space charge tunes-shift of $\Delta Q_y \simeq 0.05$ corresponding to 6.5×10^8 ions of U^{73+} present in the machine before bunching. This tune-spread is not significantly affected by the chromaticity because the momentum spread of the beam at injection is $(\delta p/p)_{rms} \simeq 7.5 \times 10^{-4}$, which for the natural chromaticity yields a maximum tune spread of $(\delta Q_y)_{max} \simeq \pm 0.0072$. Hence the space charge remains the dominant effect. The same argument shows that the effect of the dispersion enlarges/reduces particles amplitudes of ~ 6 mm, which compared with full machine acceptance, becomes of minor relevance.
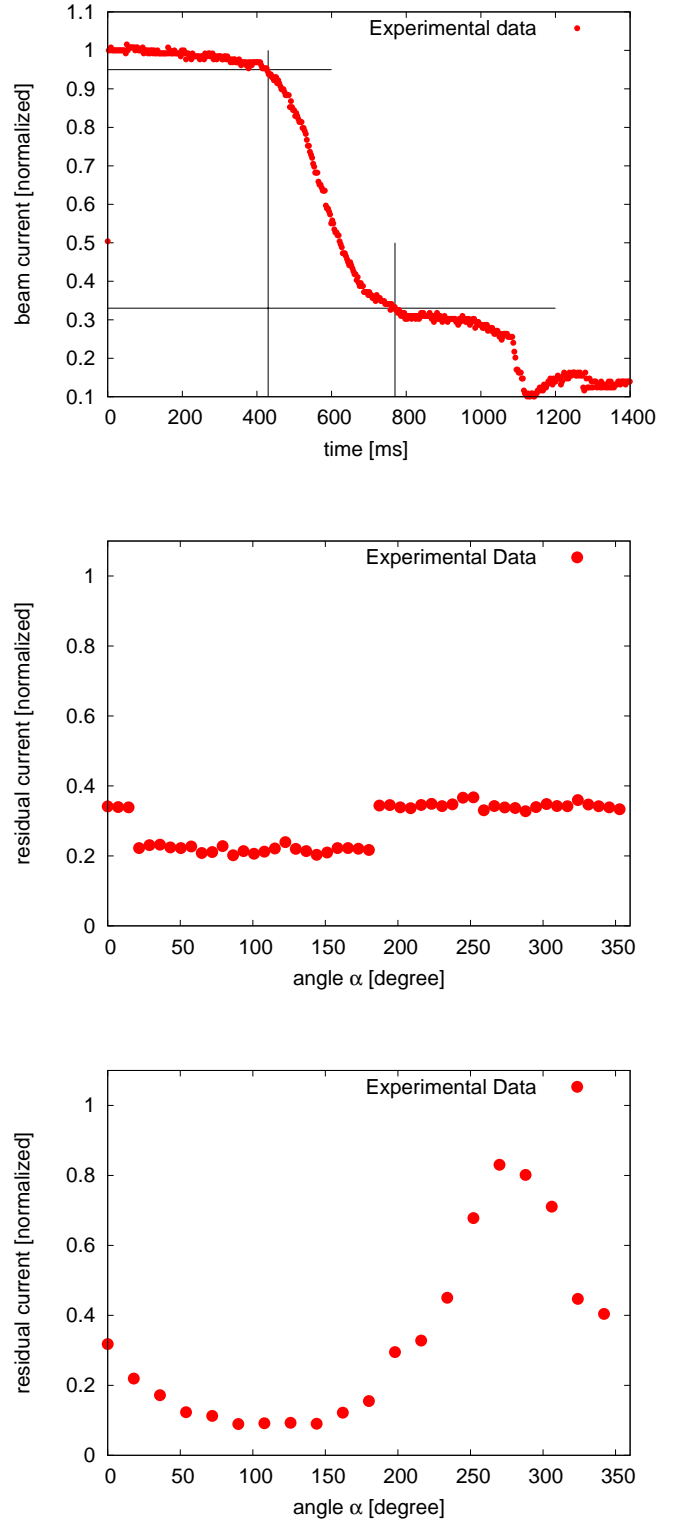

Figure 3: Top: beam survival by crossing the resonance $Q_x + 2Q_y = 11$ in 1 second. The survival is $\sim 35\%$. Center: effect of the power supply, note the discontinuity of beam survival at $\alpha = 20, 170$ degree for a small driving term. Bottom: best compensation for $\Lambda = 0.025$ at $\alpha = 270$ degree.

The results of this scan are shown in Figure 4. The red markers show the beam survival without correction. We identify three "valleys" corresponding to the effect of three resonances: the half integer $2Q_y = 7$, the third order coupled resonance $Q_x + 2Q_y = 11$, and the third order one dimensional resonance $3Q_y = 10$. If we set the tune at the edge of the resonance stop-band at $Q_x = 3.405$, the impact on beam survival is dramatic: in 1 second only $\sim 10\%$ of the beam survives, whereas in absence of periodic resonance crossing due to space charge, the survival on this working point is of 100%.

The blue markers in Fig. 4 show the very same measurements with the two correcting sextupoles activated for the best correction of $Q_x + 2Q_y = 11$ at $\alpha = 270$ degree (Fig. 3 bottom). The result is that the partial resonance compensation still yields an advantage to mitigate the beam loss induced by the periodic resonance crossing over 1 second storage. The blue markers yield a beam survival of $\sim 70\%$ in the range $3.415 < Q_y < 3.46$ except for the new valley appearing at $Q_y = 3.43$. The advantage is evident for $Q_y = 3.42$ where beam survival goes from $\sim 30\%$ to $\sim 75\%$.

At the tune $Q_y \simeq 3.43$ there is a slight discontinuity in the red curve. This indicate the presence of a higher order resonance. This resonance appear clear in the measurement with the resonance compensation activated (a new valley in the beam survival appears). We have no information on the nature of this resonance, except of its weak strength.

Interestingly we also observe that the compensation here implemented does not affect the other two resonances shown in Fig. 4. In fact in $3.35 < Q_y < 3.37$ and in $3.45 < Q_y < 3.48$ green and red markers fully overlap, showing that the compensating method really affects only this specific resonance. Other resonances far away from the investigated area might be excited by this compensation scheme, but this is not part of this study.

CONCLUSION

The measurements and the results obtained in this campaign allow to conclude that

1. The technique used to compensate the resonance seems a promising tool for a first order compensation. The implementation of this "fast" technique completely relies on the feature of the new settings generation system (LSA) for automatizing the data acquisition process.

2. The experimental evidence shows that the resonance compensation for a third order resonance allows to mitigate the beam loss due to the effect of moderate space charge in bunched beams stored for 1 second.

The physics case, and further details on these measurements will appear in dedicated studies.
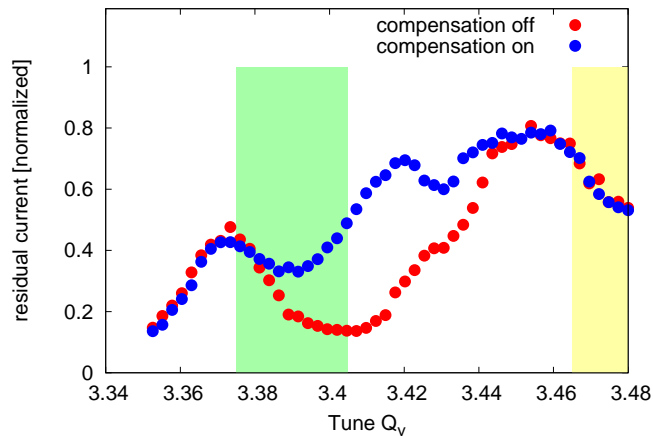

Figure 4: Beam survival for a bunched beam stored for 1 second. The green curve is obtained for a partially compensated third order resonance, whereas the red curve is measured for the naked machine.

OUTLOOK

Although the results are encouraging, the following issues remain to be investigated:

1. We have no clear evidence of why we cannot compensate completely the resonance. This may lay in the imperfect knowledge of the optics at the location of the sextupole correctors, or due to other unknown details of the machine. In addition we have got evidences that different pairs of sextupoles excited to create the same driving term do not produce the same beam survival. All these discrepancies require further investigations to consolidate the method and/or to improve it.

2. The verification with the bunched beams was made with a relatively low intensity $\Delta Q_y \simeq 0.05$. The space charge tune-shift here obtained do not compare with that foreseen in the SIS100 scenario, which is expected to be a factor 4 larger. Further measurements on a single third order resonance with more intense beam have to be foreseen to consolidate this first findings.

3. Further experimental studies on half integer, and linear coupling, as well as on the 4th order 1 and 2 dimensional resonances will be carried out as well.

ACKNOWLEDGMENT

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