DETAILED STUDY OF THE BEAM-BEAM INTERACTION AT THE ORSAY STORAGE RING (ACO)

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1. Abstract and Introduction

In the normal operating conditions of ACO the two beam behaviour is dominated by the beam-beam interaction. Single beam behaviour in the range of energy and current described below ($250 \leqslant E \leqslant 510$ MeV, $I \leqslant 35$ mA) exhibits no effect such as resonances, beam losses, etc..., in comparison with the ones observed with two beams. In this clear situation a detailed study of the beam-beam interaction has been performed on ACO in 1973.

The normal operating conditions are : one bunch per beam, two crossing points and head-on collisions. Radial and vertical wave numbers per turn are set just below an integer, near the coupling resonance $\nu_x - \nu_z = 2$ (usually $\nu_z \sim .835$, $\nu_x \sim 2.845$). Table 1 shows some relevant ring parameters at the crossing points.

The main result obtained is the important part played by high order non-linear resonances in the beam loss induced by the beam-beam interaction. This appears in the study of the beam-beam limit as a function of the operating point in the wave number diagram.

Other results are reported on :

- The tune shift parameter ξ at the beam-beam limit.
- The influence of the number of bunches.
- The absence of any difference between the interaction of two strong beams versus the strong beam-weak beam interaction.
- Coherent motion induced by small vertical separations at the crossing points.

More details can be found in recent ACO reports[1].

Betatron amplitude function β^*	radial		$\sim$ 2 m
	vertical		$\sim$ 4 m
Off-momentum function η^*			$\sim$ 2 mm
Transverse beam dimensions	radial	σ_x^*	$\sim$ .5 mm
	vertical	σ_z^*	$\sim$ .5 mm
Longitudinal beam dimension		σ_ℓ	$\sim$ 15 cm
Single beam lifetime at 30 mA		τ	$\sim$ 35 h

Table 1 : Ring parameters at E = 510 MeV and V_{RF} = 17.5 kV.

†The values ν_x,ν_z are determined by the quadrupole settings, calibrated with a single beam stored in the ring. This calibration does not take into account the small perturbation of wave numbers on the coupling resonance.

2. Operating points and non-linear resonances

It has been studied how the operating point can be moved in the ν_x,ν_z plane as a function of the intensity for two equal beams at 510 MeV.

The ν_x,ν_z diagram has been explored in the region†

$$.67 < \nu_z < .90 \qquad 2.67 < \nu_x < 2.90$$

According to the intensity, three cases can be distinguished :

2.1 Low current : $I^+ \sim I^- < 5$ mA

Whatever the tune, the beam-beam interaction does not affect the beam lifetime. Away from the coupling resonance $\nu_x - \nu_z = 2$, many beam transverse enlargements are observed, indicating the excitation of non-linear resonances. No enlargement is observed with only one single beam stored in the ring. Hence we may infer that these resonances are excited by the beam-beam interaction. Between two well separated non-linear resonances, the beams are flat, but the beam-beam limit (very short lifetime) is already reached at $I \sim 5$ mA.

2.2 High current : $I^+ \sim I^- > 10$ mA

Using a lifetime criterion ($\tau > 1$ h), the possible tunes are found to be restricted to small areas along the coupling resonance $\nu_x - \nu_z = 2$. Figure 1 shows 4 different areas which were specially investigated. They are separated by stopbands near rational numbers p/q. Other areas between rationals may exist, but were not searched for.

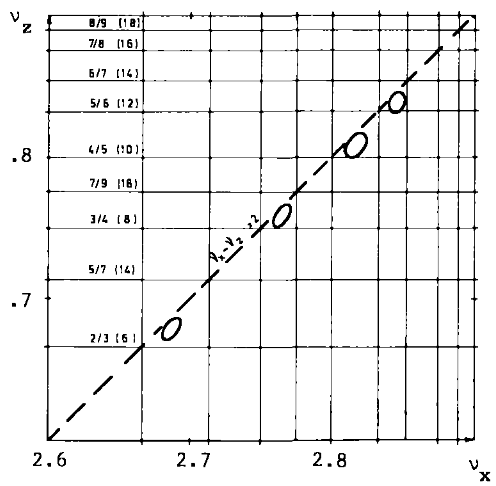

Fig. 1 : ν_x, ν_z diagram

Studied operating points are indicated by small circles.

Rational values of ν_x and ν_z are indicated by vertical and horizontal lines.

The number between parenthesis gives the order 2n of the non-linear resonances associated to the rational number m/n.

The existence of such stopbands can be attributed to the influence of non-linear resonances in the beam loss mechanism induced by the beam-beam interaction.

High order resonances seem to be involved. For instance the stopband near 5/6 is related to 12^{th} order resonances in the case of two crossing points per turn*. Many 12^{th} order resonances cross at $\nu_x = 2+5/6$, $\nu_z = 5/6$. The stopband may be due to a single or a cluster of such resonances. There is no experimental answer to this question.

2.3 Medium current : 5 mA < $I^+ \sim I^-$ < 10 mA

The size of the area is larger than for higher currents, but still restricted to the neighbourhood of the coupling resonance (Figure 2). Beam enlargements appear when ν_z is approaching a rational value. Sometimes these resonances can be crossed, by varying ν_z, without beam loss.

For instance, at $I^+ \sim I^- \sim 7$ mA, three groups of resonances have been observed (Figure 2), corresponding to $\nu_z = 6/7$, 5/6 and 4/5. One may guess that the strength of these resonances is too low to reduce the lifetime. For higher current (I > 10 mA), their strength increases and the lifetime is reduced before a beam enlargement appears.

At high current, the boundary of the area available for an operating point is characterized by a sharp decrease of the beam lifetime (from a few hours to much less than one hour). For a fixed value of ν_x, the beam lifetime remains almost constant as ν_z is varied, and a sharp decrease is observed when the boundary is reached.

The size of the ν_x, ν_z area decreases when the current is increased (Figure 3). At the same time, its center shifts below the coupling resonance.

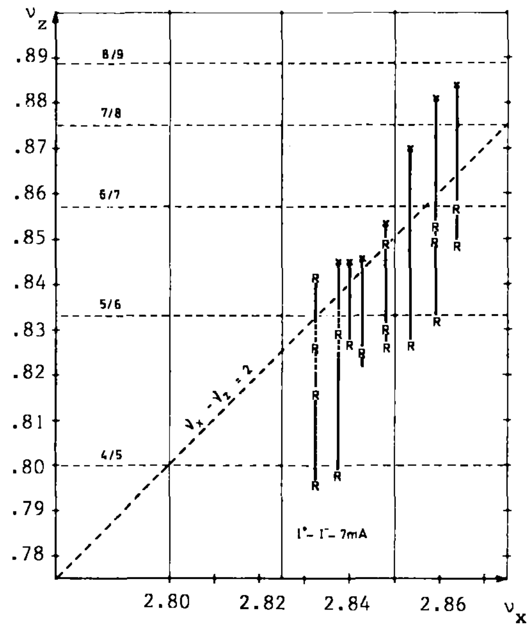

Fig. 2 : Range of ν_z versus the radial wave number ν_x.

Enlargement of one beam near a resonance is indicated by R or **R**.

Low order rational values $\nu_z = m/n$ are indicated by horizontal dotted lines.

(× : limit of the ν_z range when the lifetime drops)

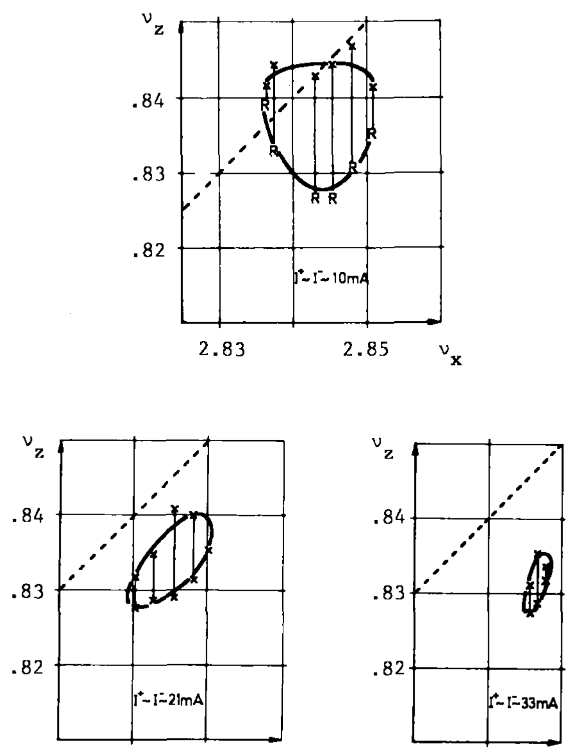

Fig. 3 : Range of ν_z versus the radial wave number ν_x for different intensities.

The coupling resonance $\nu_x - \nu_z = 2$ is indicated by a dotted line.

Enlargement of one beam at an end point of the ν_z range is indicated by R.

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*Here the order of a resonance is defined as the smallest degree of the terms which excite this resonance in the Taylor expansion of the space charge potential. The wave number $\nu = k \times p/q$ (k : the number of crossing points, p and q : relatively prime integers) corresponds to a resonance of the order either q (q even) or 2q (q odd), since the potential parity is even. For k = 2, and writing $\nu = m/n$, the resonance order is 2n.

Figure 4 shows how the limits of the ν_z range vary with the intensity I for three different operating points. The lower bound $\nu_{z\ min}$ is almost independent of I, but the upper bound $\nu_{z\ max}$ decreases as I increases.

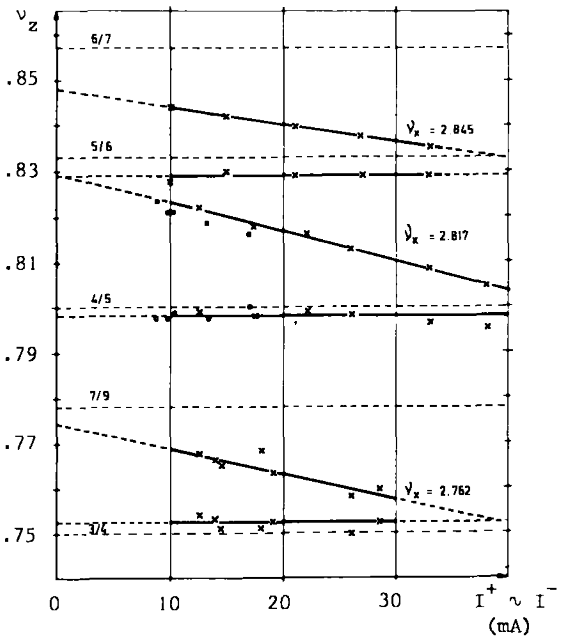

Fig. 4 : Limits of ν_z range versus the intensity of each beam and for 3 values of ν_x.

Low order rational values ν_z = m/n are indicated by horizontal dotted lines.

x : one bunch per beam.
o : two bunches per beam.

The $\nu_{z\ min}$, $\nu_{z\ max}$ bounds, extrapolated to zero current, are quite close to rationals, as shown in table 2. The same behaviour has been found for the ν_x bounds.

ν_x	$\nu_{z\ min}$	$\nu_{z\ max}$
2.762	.752 ∿ 3/4	.774 ∿ 7/9
2.817	.798 ∿ 4/5	.830 ∿ 5/6
2.845	.829 ∿ 5/6	.848 ∿ 6/7

Table 2 : Upper and lower bounds $\nu_{z\ max}$, $\nu_{z\ min}$ extrapolated to I = 0, for three different radial wave numbers ν_x.

All these experimental results can be summarized as follows :

a) At high intensity, operating points are separated by stopbands near rational numbers.

b) Beam enlargements appear at low and medium current near such values.

c) The I = 0 extrapolated values of the ν_x, ν_z bounds are also close to rational numbers.

The excitation of high order non-linear resonances by the beam-beam interaction may explain such a behaviour.

The beam-beam limit is said to be reached at an intensity for which the beam lifetime is less than one hour, inside the available area of the operating point. At this limit, the ν_x or ν_z range is about 3.10^{-3}.

Since the operating point is set below an odd integer, and the beam-beam interaction shifts the tune upwards, it is currently believed that the half integer resonance is responsible of the beam-beam limit observed on ACO[2,3]. The experimental result reported here is not inconsistent with this idea, but it shows that the limit is also due to the excitation of non-linear resonances.

At 510 MeV the intensity limit, and the maximum luminosity, are about the same for the three operating points studied : ν_x = 2.845, 2.817 and 2.762.

$$I_{max} \sim 35 - 40 \text{ mA}$$

$$L_{max} \sim 10^{29} \text{ cm}^{-2} \text{ s}^{-1}.$$

These maximum values scale with the energy like :

$$I_{max} \sim E^{3.5 \pm .2} \qquad L_{max} \sim E^{5.4 \pm .6}$$

in the ACO energy range : 250-540 MeV. The I_{max} scaling law appears to be inconsistent in the cubic law ($I_{max} \sim E^3$) predicted by a simple model[4]. It is worth point out that the measured beam cross section varies as $E^{2. \pm .2}$

3. Tune shift parameter

The tune shift parameter :

$$\xi_{x,z} = \frac{N r_e}{2\pi\gamma\ (\sigma_x^* + \sigma_z^*)} \times \left(\frac{\beta}{\sigma}\right)^*_{x,z}$$

(N is the number of particles per bunch, and γ the ratio of the particle energy to their rest mass energy)

has been derived from the luminosity measurements with a double Bremsstrahlung monitor.

At 510 MeV, and at the two operating points ν_x = 2.817 and 2.845, the maximum ξ values are :

$$\xi_{x\ max} = .021 \qquad \xi_{z\ max} = .030$$

Systematic errors on these values, due to biases on the intensity and luminosity measurements, are less than 30 %.

These values disagree with former values derived from transverse beam dimensions measured inside a bending magnet : $\xi_{x\ max} \simeq .03$, $\xi_z \simeq .055$.

It is believed that the new measurments, using a luminosity monitor, are more reliable. A bias on the former values could arise from the correcting factor relating the measured dimensions to the actual beam dimensions at the crossing point. The factor used does not account for optical perturbations due to the beam-beam interaction.

From the energy law of the maximum intensity and luminosity, a slight dependance of ξ_{max} is deduced :

$$\xi_{max} \sim E^{1/2}.$$

The exponent is smaller than the one observed at ADONE.

4. Beam-beam interaction with two bunches per beam

Assuming a constant ξ_{max}, the maximum luminosity should be proportional to the number of bunches. Already at the first stages of ACO[5], it has been observed that the maximum luminosity is the same with two bunches per beam, at the usual operating point $\nu_x = 2.845$.

This result has been confirmed at the other operating point $\nu_x = 2.817$. More precisely the ν_z range as a function of the intensity is about the same with one or two bunches per beam (Figure 4).

5. Strong beam-weak beam interaction

Simple models for the beam-beam interaction study the motion of one particle crossing an opposite beam. Such models are only relevant for strong beam-weak beam interaction.

Since storage rings operate with two equal beams, it is important to check if there is any qualitative difference.

The strong beam-weak beam interaction has been studied at the usual operating point $\nu_x = 2.845$, and at 510 MeV. The weak electron beam intensity was about 1/20 of the strong positron beam intensity. No qualitative difference has been observed.

The ν_x, ν_z range, and its variation with the strong beam intensity, are about the same than those obtained with two equal beams. In particular the conclusion about the excitation of non-linear resonances is the same.

6. Coherent motion induced by the beam-beam interaction

In the head-on collision mode, only a very small coherent motion of the beams can be observed (about 3 % of $\sigma_{x,z}$) whatever the operating conditions[6]. The coherent frequency is approaching the revolution frequency at the beam-beam limit, but with no amplitude increase. Therefore it is difficult to imagine how such a small amplitude motion can participate to the beam loss mechanism.

When the two beams are slightly separated in the vertical direction at the crossing points, the situation is quite different.

A large amplitude (about $\sigma_{x,z}$) coherent motion appears in a small range of ν_z, when the beam separation reaches a threshold around $\frac{\sigma}{20}$. At high intensity (above 20 mA) this coherent motion leads to a poor lifetime*.

It is worth to try to relate the observation of the difficulties encountered in various rings with beams crossing at angle[8]. Obviously a longitudinal displacement of the crossing point leads to a small separation, which in itself has already a bad effect, as observed on ACO.

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*Preliminary results, published at the San Francisco Conference[7] must be corrected on this point.

DISCUSSION

Sergio Tazzari (Frascati): What parameters did you measure with the strong beam-weak beam?

J. Buon (Orsay): We have measured the ν_x, ν_z areas.

Alberto Renieri (Frascati): What is the threshold for radial coherent motion of separated beams?

Buon: There is a sharp threshold, true, but the result at the moment is not very reliable. But it's quite small, something like the transverse dimension divided by 10.

Gerhard Fischer (SLAC): Is the value of ξ that you quote per interaction region or total?

Buon: It's per interaction region.