Summary for the Session of "Ion and Dust Effects"

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In the session of "Ion and Dust Effects", we have five presentations, which show us the ion-related studies in several labs or machines, and the possible ways to cure the ion-induced instabilities.

(1) Dr. Nakamura from Spring-8, Japan, reported the fast ion instability in the Spring-8 storage ring. After the installation of the new beam chambers of four 30-meter long straight sections, the vertical multi-bunch instability of low frequency modes is observed.

During the observations after the replacement of the chambers, many strong vertical betatorn lower sideband peaks were found on BPM signal, even with chromaticities as high as 6 or 7. The highest peak was located at 2~3 MHz, while the lowest betatron sideband was not observed. Meanwhile, the beam size monitor got an increased beam size as much as 150 μm in horizontal. The filling pattern is a full-bucket filling, with a total beam current of ~100 mA. The height of the peaks of the instability becomes higher as the length of bunch train increases. Since they are not the frequencies of the cavity HOMs, the instability is not the HOM effect.

The position dependence of betatron oscillation amplitude is measured with a special apparatus setup, which contains a gate generator, a linear gate, an oscilloscope, a spectrum analyzer and a button-type pickup. The antennas are fed to 180 deg, hybrid junction to cancel their carrier of RF acceleration frequency. The component of the amplitude modulation by the beam's betatron motion can be extracted with such instrumentation. From the spectrum analyzer, it is found that higher peaks are harmonics of revolution frequency and lower peaks vertical betatron sideband.

Big gaps between bunch trains reduce the height of the peaks of the instability. The instability limits the length of bunch train. The gaps of the length more than 100 ns can suppress the instability. Several filling patterns, such as 1/2 filling, 1/3 filling, 1/6 filling, etc., are tested. For user operation, the filling pattern is 12×(152 bunches + 51 empty buckets). 51 empty buckets ~ 100 ns. The beam size increasing is also observed at ~2000th bucket.

Beam is stored in one third of the ring, 812 buckets in the first train, and then 20 ~ 120 ns gap, followed by the 2nd train with the length of 300 ns. The measurement shows the amplitude of betatron oscillation for the first bunch train starts to increase from the ~560th bucket and for second train, the amplitude drops from ~860th bucket to the noise floor. No betatron sideband is observed in the 2nd train with 120 ns gap.

The vacuum pressure dependence is also measured. Vacuum pressure is changed by switching on/off the DIP and LP. Under the different vacuum pressure, the amplitude of betatron oscillation of the bunch trains is also measured at the normal sections and long straight sections.

This vertical multi-bunch instability limits the filling pattern of the stored beam. The strength of this instability depends on the length of bunch train and vacuum pressure. Dividing the long bunch train into short bunch trains with more than 100ns gap between them can suppress the instability.

(2) Dr. Mochihashi from KEK gave the talk on modulation of trapped ion density due to passage of bunch train in the KEK-PF electron storage ring. Residual gas ions (mainly CO^+) are influenced due to the periodic force from the passage of beam. Ion trapping is observed in the multi-bunch case in the KEK-PF storage ring.

A kind of "Ion Twiss Parameters" is applied with the method of matrix to deal with the ion trapping. The so-called $\beta_i(\tau)$ for ions has the similar meaning as the beam twiss parameter. The size of an ion cloud is proportional to the square root of β_i, and the oscillation amplitude of ion also proportional to the square root of β_i. Large β_i means low ion density, while small β_i means high density. The ion cloud size changes along the bunch train. Modulation of the ion density occurs along the train.

The tune shift due to the trapped ions can be got with the following equation:

$$\Delta \nu_y(\tau) \approx \frac{\Delta \nu_y^0}{\varepsilon_y(\tau)}, \tag{1}$$

where $\varepsilon_{x,y}(\tau) = \Sigma_{x,y}(\tau)/\sigma_{x,y}$ are the modulation factor, and

$$\Delta \nu_y^0 = \frac{r_e E_0}{2\pi E} \lambda_e \eta \int_C \frac{\beta_y(s)}{\sigma_y(\sigma_x + \sigma_y)} ds \ . \tag{2}$$

The tunes change along the bunch train, arising in the head and falling in the tail.

Bunch-by-bunch tune measurement can give the experimental results to compare with the calculated value got from the previous theoretical predictions. Table 1 lists the comparisons between measured and calculated values.

Table 1. Comparison between calculated and measured tune shifts along bunch train.

Ave. tune shift along 20 bunches	In the head	In the tail
Theoretical prediction	$\Delta\nu = 5.1\times10^{-6}$ /bunch	$\Delta\nu = -6.4\times10^{-6}$ /bunch
Experimental result	$\Delta\nu = 4.0\times10^{-6}$ /bunch	$\Delta\nu = -2.1\times10^{-6}$ /bunch

The experimental results are consistent with the theoretical calculations.

(3) Dr. Qin from IHEP, Beijing, discussed a kind of ionized-particle interaction happened in the synchrotron radiation operation of the Beijing Electron-Positron Collider (BEPC).

The BEPC runs as not only a collider at the energy of tau-charm region, but a synchrotron radiation facility with the energy of 2.2 GeV. During the SR operation, running with electron beam, a kind of beam lifetime reduction may happen no matter how many bunch numbers are and how much the beam current is. The beam lifetime can be reduced from the normal value of 8~10 hours to 2 hours or less in the single bunch case, and from 15~20 hours to 5~6 hours in the multi-bunch case. When the beam lifetime reduction happens, sometimes it can resume automatically without any change on beam parameters. If beam is dumped when lifetime is low, and refill the beam, the beam will be stable. But at any time, any beam current, the lifetime reduction may happen again. In the operation of electron-positron collision, no such a phenomenon was observed.

This kind of phenomenon is ascribed to the beam-dust interaction, or dust effect. Different species of metallic oxide may be produced from some hardware around the storage ring, such as vacuum pumps, valves, scrapers, profiles, etc. The dust particles or metallic oxide molecules can be positively ionized and thus be trapped by the electron beam.

The SiO_2 ionized particle is applied to analyze in the dust effect. Those charged particles lie on the bottom of the chamber will not be attracted by the beam, according to the analyses of forces acting on the macro-particles. The dust source is considered to be the distributed ion pumps (DIPs) installed in bends around the ring, which can spray out the positively charged ions into the chamber, or the macro-particles drop from the top of the chamber wall.

The lifetime due to two kinds of bremsstrahlung can give the possible region of A/Q_d (ratio of dust particle's mass and charge) for trapped ions. The critical beam current for the dust effect can also be got from the linear treatment with transfer matrix method. The frequency of ion oscillation can be found as well.

Some experiments on DIPs and lumped pumps (LPs) were carried out. Switching on/off the DIPs influences the beam lifetime, similar with the phenomenon observed in the routine operation, while LPs didn't show any effects on beam except for the normal lifetime down due to worse vacuum pressure. Some transverse external kicks can have the dust ions resonated and make the beam stable. Periodic change of RF voltage with a small fraction also stabilizes the beam sometimes, which is still beyond our knowledge.

Cures of the dust effect could be switching off all or part of the DIPs, using transverse kick, such as strip-line shaker for the betatron tune measurement or injection kicker, and changing the RF voltage. The thorough measure to solve the problem is to use the positron beam, which is convinced no beam lifetime reduction with the same optics and beam parameters, as the observations show. The problem for positron beam is the low injection rate.

(4) Dr. Tawada from KEK did some simulations on ion instability at the Super KEKB, which will have beam current about 10 times higher than the current value. Due to such a high beam current and a big bunch number in the Super KEKB, the ion-beam instability could be problematic, preventing it from achieving the expected luminosity. The low neutralization factor makes it possible to cause the instability by ions produced and trapped in only one revolution. Gaps can be used to abort the beam, and also the produced ions can be cleaned during the gap passage.

Linear theory (Keil-Zotter) is adopted in the estimation and Ohmi-model is used in the simulation. It is a weak-strong model, with a rigid Gaussian distribution for electron beam, macro-particle for ions, but bunch length and synchrotron radiation damping are not considered.

Simulations on fast-ion instability gives the growth time of 0.3 ms for 30 turns and 0.05 ms for 5 turns, in the case of 4800 bunches and the CO^+ pressure of 1 nTorr and 5 nTorr, respectively. The damping rate of the feedback will be 0.5 ms, so the vacuum pressure for Super KEKB should be better than 0.5 nTorr for residual CO^+.

(5) Dr. Ng from Fermilab analyzed the beam-ion instability in the Fermilab Linac. In the Fermilab Linac, H^- beam is accelerated. The residual gas is mostly proton. A peak current of 49 mA can be got in the Linac and 65 mA in the transport line.

Some kinds of gas are filled to observe the instability formation and frequency change with the vacuum pressure.

- Argon at 6×10^{-5} Torr, two resonant frequencies are clearly visible. Resonant frequency does increase with the pressure.
- Helium, resonant frequency does not vary with pressure.
- Nitrogen, resonant frequency does not vary with pressure.
- Krypton, resonant frequency changes with pressure.
- Hydrogen, instability takes place at $p = 4.8\times10^{-5}$ Torr, while no any instability happens at $p = 6.2\times10^{-6}$ Torr.

Some disagreements with the fast ion instability:

- Resonant frequency does not drop with mass number A
- Resonant frequency increases with pressure for Ar and Kr.
- There are difference between electron storage ring and linac.

The beam-ion instability is observed in the Fermilab Linac. It partly agrees with the fast ion instability in fast growth and fast saturation, and roughly the right resonant frequency and ion-in-beam bounce frequency. Resonant frequency increases with gas pressure.

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References:

[1] T. Nakamura, et al, Fast-Ion Instability in the Spring-8 Storage Ring, presentation at this workshop.
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[4] M. Tawada, Simulation of Ion Instability at Super KEKB, presentation at this workshop.
[5] K. Ng, Beam-ion Instability in the Fermilab Linac, presentation at this workshop.