SUMMARY OF WORKING GROUP A AND A+B+D JOINT SESSION

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Abstract

We summarize the presentations and discussions of the HB2006 Working Group A, devoted to beam instabilities, and of the joint session of Working Groups A, B (on space charge), and D (beam cooling and experiments). First we review the progress on conventional instabilities and impedances, and then the advances on electron cloud.

INTRODUCTION

Working Group A on "Beam Instabilities and Their Cures," was convened by A. Burov and F. Zimmermann on Tuesday 30 May 2005. The joint session of Working Groups A, B and D, was assembled by A. Burov, S. Cousineau, A. Fedotov, I. Hofmann, I. Meshkov, J. Wei and F. Zimmermann on Thursday 01 June 2006. Working Group B was devoted to "Space Charge Theory, Simulations, and Experiments," and Working Group D to "Beam Cooling and Experiments". The joint session included, in the afternoon, a "General Parallel Session with Focus on Code Benchmarking", organized by I. Hofmann, E. Shaposhnikova, J. Wei, and F. Zimmermann, which is summarized in a separate presentation [1].

CONVENTIONAL INSTABILITIES

In total 7 talks in Working Group A addressed conventional instabilities and impedances [2, 3, 4, 8, 9, 10, 11].

SNS Instabilities

Viatcheslav Danilov and Sarah Cousineau reviewed measurements and interpretation of instabilities in the SNS Accumulator Ring [2]. Up to 10^{14} protons per bunch were accumulated in a coasting beam mode. No instabilities were observed with the natural chromaticity of about -7 to -8 units. After reducing the chromaticities about 100 times, the coasting beam got unstable at 2×10^{13} protons per bunch. Three distinct sources of impedance were detected in beam measurements and their sources identified: injection kicker, chamber resistive wall, and electron cloud. The impedance estimated from the measured growth rates shows that, at high beam intensity (10^{14} protons per bunch), the electron-proton interaction gives rise to the largest effective impedance, followed by the resistive wall, and finally by the extraction kicker. The electron-cloud impedance exhibits a strong dependence on the beam current (possibly as the 4th power). Conventional instability frequencies and impedances are in good agreement with predictions from simulations, laboratory measurements, and calculations.

FNAL Booster Instabilities

Valeri Lebedev described the present understanding of instabilities in the FNAL booster [3]. Here, at a reduced chromaticity the beam gets transversely unstable. Beam measurements show how the instability develops. This data is then analysed in detail: the tunes, chromaticities and growth rates are extracted. The growth rates are compared with expectations from an impedance model. A first analysis shows that the model underestimates the impedance several times. Electron cloud could be a reason. Longitudinal emittance growth at transition was suppressed by means of the RF jump technique.

Damping by Internal and External Nonlinearities

Vladimir Kornilov discussed Landau damping in the presence of internal and external nonlinearities [4]. There are two controversial dispersion equations for the description of transverse modes with space-charge nonlinearities taken into account, due to Laclare-Hereward and Mohl-Schonauer [7], respectively. Since the first one does not obey momentum preservation, it cannot be correct. Simulations with the PATRIC code were run, and the results were compared with the two equations. The Mohl-Schonauer equation is supported by simulations where space charge only is taken into account. Some quantitative disagreement between the Mohl-Schonauer equation and simulation was, however, found for a case of combined action of octupoles and space charge.

CERN SPS Instabilities

Elena Shaposhnikova reported on longitudinal beam instabilities in the CERN SPS [8]. Longitudinal coupled bunch instabilities of the LHC beam with very low threshold have been cured in the SPS up to nominal intensities by active damping, use of a higher-harmonic 800 MHz RF system and controlled emittance blow up. The main limitations of using the 800-MHz RF system in bunch lengthening mode for Landau damping have been studied and are now understood. Studies of limitations in the bunch shortening mode will continue (beam transfer functions, instability threshold). Problems with beam quality at extraction to LHC can be explained by the effect of residual beam loading affecting the controlled emittance blow-up in a double RF system. It is planned to test possible solutions in 2006.

Impedance and Radiation Generated by a Ceramic Chamber with RF Shields and TiN Coating

Yong Ho Chin discussed the impedance and radiation generated by ceramic chambers for the J-PARC RCS [9]. The longitudinal and transverse impedances of a copper shielded ceramic chamber with TiN coating were calculated. The longitudinal impedance was also measured with wires; a good agreement with the calculated value for the relativistic case is found. The impedance budget for the RCS was presented.

Coupling Impedance for J-PARC Kicker Magnets

Takeshi Toyama addressed the impedance of the J-PARC kickers [10]. The longitudinal and transverse impedances of the RCS and MR FX kickers were measured with wires. The results were compared with the available theoretical model. Agreement requires elimination of the delta-function term in the transverse impedance formula.

Tune Shift Induced by Nonlinear R.-W. Wake

Frank Zimmermann discussed the effect of the nonlinear wake field components on the coherent tune shift for a flat resistive collimator [11]. The nonlinear resistive-wall (r.-w.) terms become important if the aperture is comparable to the rms beam size. A generalized formula combining the Burov-Lebedev formula, with detuning wake and “inductive bypass” taken into account, and a geometrical factor derived from Piwinski’s r.-w. theory is in good agreement with SPS measurements on a prototype LHC collimator. The geometrical factor represents the effect of the nonlinear dependence of the wake field on the transverse coordinates of both test and drive particles.

ELECTRON CLOUD

A total of 11 presentations were fully devoted to electron cloud [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22], and 5 further talks partially [2, 3, 23, 24, 25]. The accelerators concerned were the following: SNS (2), J-PARC (1), LANL PSR (2), HCX (2), FNAL MI (2), FNAL Booster (1), FNAL Recycler (1), RHIC (1), CERN SPS (2), LHC (2), and KEKB (2), where in parentheses the number of talks has been indicated. A large variety of themes were addressed: electron-generation mechanisms (3); observations of beam instabilities, emittance growth and/or other electron-cloud effects (7); simulations of electron build up for existing or future machines (3); simulations and understanding of electron effects on the beam (5); self-consistent simulations and code benchmarking (3); and cures (4).

Electron Cloud at SNS

The SNS design includes numerous measures of electron-cloud mitigation, such as electron collection near the stripper foil, TiN coating of all vacuum-chamber pieces, solenoids near regions with high beam loss, clearing electrode near the stripper foil, electron detectors for studying electron accumulation, high-energy spread for enhanced Landau damping, and provision of broadband feedback, as describd by Viatcheslav Danilov and Sarah Cousineau [2]. As a result of some of these precautions, no instability is observed in normal operation. A special mode is required to trigger e-p instabilities, namely a coasting beam with low chromaticity. In this mode the instability is observed over a large range of intensities, at charges between 4 and 16 μC. The instability is fast with a rise time of 20 of 200 turns, and it occurs in both transverse planes. The vertical instabilty is stronger. The instability gets faster at higher intensity. Also, at higher beam current the frequency spectrum is more sharply peaked and the peak frequency itself tends to increase. At the highest intensity, the frequency is 79 MHz. The frequency decreases as the instability develops, presumably due to beam loss and emittance growth, which both lower the electron oscillation frequency. A peculiar coupling between the horizontal and vertical plane is noticed in the instability behavior: in the limited regions of the beam with large horizontal instability, the vertical one is suppressed, and both fractional tunes are observed in the horizontal betatron spectrum. The real part of the effective impedance characterizing the e-p instability was deduced from the experimental instability rise time τ using the relation $\mathrm{Re}(Z) = 2\gamma\beta^2 E_0/(\tau\beta_{\mathrm{twiss}} I_{\mathrm{ave}})$, with E_0 the beam energy, β_{twiss} the beta function at the location of the impedance source, γ the Lorentz factor, and $\beta = v/c$. Table 1 shows that the e-p instability occurs at a frequency much higher than the conventional instabilities driven by the impedance of the extraction kicker and the resistive wall, and that, in particular, the associated impedance is almost two orders of magnitude larger. This supports the prediction, by one of the authors (F.Z.), that the electrons may represent the largest effective impedance in the LHC.

Table 1: Characterization of SNS instabilities [2].

type	frequency	impedance measured	impedance predicted
extr. kicker	6 MHz	$\sim$ 28 kΩ/m	$\sim$ 25 kΩ/m
res. wall	191 kHz	$\sim$ 34 kΩ/m	$\sim$ 40 kΩ/m
e-p (at 16 μC)	78 MHz	$\sim$ 1.9 MΩ/m	N/A

Transverse Instablity in FNAL Booster

Valeri Lebedev described that the measured real part of the impedance in the FNAL booster is 5–10 times higher than expected [3]. A possible explanation, put forward by V. Dudnikov, is the accumulation of electrons. The electron plasma frequency is of order 100 MHz. The effective impedance value is set by the beam radius and not by the beam pipe. The explanation is quite probable. More experimental observations are needed for confirmation.

Incoherent Emittance Growth

There exists a threshold in the electron-cloud density, above which a strong head-tail or TMCI-like instability occurs [26, 12]. Even below this threshold density simulations indicate a residual, slower and more gradual emittance growth. For a long time is has been an open question whether this growth represents a physical effect or is an artifact of PIC simulations.

Two mechanisms by which the electron cloud causes incoherent emittance growth have now been identified by Elena Benedetto and coworkers: (1) periodic crossing of resonances, and (2) periodic crossing of a region with linear instability [12]. The `HEADTAIL` PIC code was successfully benchmarked against G. Franchetti’s code `MICROMAP` using an analytical field description. `MICROMAP` simulations were then performed for a realistic model of the SPS. The electron cloud induces a z-dependent tune shift proportional to the local electron density, which increases during the bunch passage. For certain tunes and large enough tune shifts, in some longitudinal regions of the bunch the linear optics can become unstable. Synchrotron motion leads to a periodic sampling of these unstable regions as well as of higher-order resonances. If unstable regions are encountered, the core of the beam blows ups. If a resonance is crossed, particles can either be trapped on the resonance or, if the crossing happens too fast, they may scatter of a chaotic region, leading to halo generation and beam losses.

In SPS studies with LHC beam a short lifetime is observed, which is tentatively attributed to the mechanisms described above. Both in the SPS experiment [27] and in the MICROMAP simulations by G. Franchetti the working point (0.15,0.18) shows much less losses than (0.18,0.15) lending some credibility to the proposed explanation in terms of an incoherent electron-cloud effect. The losses are accompanied by a shrinking bunch length, i.e., primarily particles with large synchrotron amplitude are affected.

The simulated LHC emittance as a function of electron density suggests that the emittance growth remains significant even at moderate electron density. If this is verified for more accurate models of the LHC lattice and electron distributions, the incoherent emittance growth may well set the ultimate tolerance on the acceptable electron density, rather than the heat load. It was pointed out by V. Lebedev that the effect of noise in the seed electrons could lead to additional emittance growth. A first look at this question had been taken by G. Stupakov in 1997 [28].

Chaos and Emittance Growth

Kazuhito Ohmi discussed the dependence of diffusion and emittance growth on the number of degrees of freedom and symmetry [25]. The simulated diffusion of particles in a round charge potential with equal transverse tunes and no synchrotron motion is extremely weak. Breaking the symmetry induces strong diffusion, which does not seem to be related to resonances. Linear coupling worsens the diffusion. The emittance growth observed is attributed to Arnold diffusion. It will be interesting in the future to reconcile K. Ohmi's and E. Benedetto's results.

PSR Instability

Robert Macek presented news on the e-p instability at the LANL PSR [13, 18]. This instability is characterized by wideband transverse motion in the frequency range 50–300 MHz. The spectrum varies with the square root of the proton-beam density. The instability has a fast amplitude growth rate of 50–150μs, or of the order of 200 turns. The threshold proton intensity varies linearly with the ring rf buncher voltage, and it showed signs of conditioning over a period of 4 years.

In recent years an analog damping system was developed in order to suppress this instability. Its component are a stripline BPM, a variable attentuator for changing the feedback gain, a 250-MHz low-pass filter, a fast RF switch, an adjustable fiber-optic delay line, an optional comb filter, two 100-W power amplifiers (one per kicker plate), a stripline kicker, and a 4-turn delay applied at the kicker [29]. The bandwidth of the feedback system is 50–250 MHz, and, therefore, it nearly matches the frequency range of the instability. Turning the feedback off and on allows measuring the instability rise time and the feedback time, and allows for mode decomposition. The measured damping rate is 1.75×10^4 s^{-1}. In some cases, while the instability could be suppressed initially, a second phase of instability developed after an intermittent quiet period, though the feedback was still active. For an example, the instability rise time in the second phase was estimated as 3×10^4 s^{-1} or 3 times faster than that in the 1st instability phase. The reason for the faster 2nd phase of instability is not understood. Highest amplitude growth rates to be damped at PSR (up to 10^5/s) are a challenge, requiring 10–20 times more power than presently available or multiple kickers. Nevertheless, the damping of the vertical e-p instability by transverse feedback was successfully demonstrated. The ep threshold was increased by 30%, limited by a horizontal ep instability, which implies the need for a feedback in both planes. Beam leakage into the gap also appears to limit the improvement from the feedback. In addition, there is a large variability in the instability growth rate from cycle to cycle, the causes of which are not understood.

Another open question at the PSR is the so-called 1st pulse instability. Namely, the first pulse re-injected after a period of several minutes or longer without beam shows an e-p instability with a threshold that is considerably lower than for the subsequent pulses. Since a large increase in the foil current is observed for this first pulse, a possible explanation is changes on the surface of the stripping foil, e.g., hydrogenation, which may lead to a temporary dramatic increase in the secondary emission yield of the foil. This hypothesis could be tested by biasing the foil at 10–20 kV, which however requires a rebuilding of the stripper foil mechanism. Until then a 1st pulse increase of the electron cloud in other regions of the ring cannot be ruled out.

Electron-Cloud Build-Up Simulations

Miguel Furman reviewed the state of the art in electron-cloud build-up simulations, taking as examples an LHC dipole and the FNAL Main Injector [14].

For the LHC, the heat load on the beam screen inside the dipole was simulated using the code POSINST [30]. The key parameters are the bunch charge, the bunch spacing, and the maximum secondary emission yield $\delta_{\max}$. For the nominal charge and spacing, the POSINST simulations suggest that $\delta_{\max} < 1.2$ is required to stay within the available cooling capacity. This is more pessimistic than the CERN simulations with ECLOUD, which yield the requirement $\delta_{\max} < 1.3$ [31]. The two codes give consistent results if in POSINST the so-called 'rediffused' electrons are suppressed. The secondary energy spectrum is important in addition to the yield per se. If rediffused electrons are present to the extent assumed the simulated heat load increases by about 100%, for the same value of $\delta_{\max}$. With a bunch spacing of 75 ns instead of 25 ns, the heat load remains inside the cooling capacity even for $\delta_{\max} \approx 2.0$, which is consistent with the CERN simulations.

New results were also presented for the FNAL Main Injector and its upgrade [32]. At the present bunch intensity of 6×10^{10} protons, the simulation shows little electron build up. However, above an intensity threshold of about 1.2×10^{11} at $\delta_{\max} = 1.3$ the simulated electron density increases by 5 orders of magnitude. The upgrade intensity is 3×10^{11} and, hence, far above this threshold.

Electron-Cloud Evidence at FNAL MI

Some evidence of electron cloud in the Main Injector has already been seen, as discussed by Robert Zwaska [19]. This evidence consists in a sharp pressure rise by more than two orders of magnitude, up to a few hundred nTorr, over the course of a cycle (1s), detected at several locations, including one near a ceramic beam pipe. New instrumentation, such as electron detectors, ion gauges, and bunch-by-bunch beam position measurements, is being installed. The beam consists of two portions, a first high intensity segment, followed by a long lower-density batch. It is surmised that the electron cloud is produced in the first segment, and that the electrons bombard the wall during the passage of the second part. The intensity of either beam portion can be varied and the response of the pressure is studied. Higher resolution pump readings at 50 Hz reveal the detailed pressure evolution over the cycle.

Electron Cloud in RHIC

Jie Wei reviewed the electron-cloud situation in RHIC [15]. Electron-cloud effects are here seen since 2001. They strongly depend on the bunch spacing. The evidence includes pressure increases by a factor 1000 in both warm and cold regions of the machine, degradation of background and of the signal from the ionization profile monitor, electron flux measured at the wall, beam losses and emittance growth. Countermeasures include NEG coating in singular short sections, rf manipulations, and octupoles. Electron cloud is a serious obstacle for the RHIC upgrade. Mitigation is not trivial, e.g., induction rf across transition or wide-band damper are considered.

If the electron-cloud instability occurs, usually at transition due to lack of Landau damping, between 10 and 70% of the beam is lost. The instability is transverse, and lasts for about 100 ms starting 10 ms after transition. Transverse emittance growth, longitudinal profile variation within a bunch, and a tune shift along the train are observed concurrently. The severity of instability depends on the bunch position in the train. An open question is why the beam loss of the first bunch in the train is much higher for 108 ns bunch spacing than for the nominal 216 ns bunch spacing. This could be attributed to a memory effect from the previous turn (surviving electrons and/or ions). The effect resembles observations at the CERN SPS, where with 25-ns bunch spacing the first bunch in an LHC-beam train also has a worse lifetime than a single stored bunch, though the lifetime is still much better than for later bunches.

WARP-POSINST Code Suite

The `WARP-POSINST` code suite developed by the Heavy Ion Fusion Science Virtual National Laboratory is unique in many different ways, as explained by Jean-Luc Vay [16]: it is a merger of codes developed in different communities; it includes new modules for electron-generation, residual gas and ions; it features an adaptive mesh refinement increasing the speed by a factor 10–10^4; and it includes a novel electron mover allowing time steps much larger than a cyclotron period with smooth transitions between magnetized and non-magnetized regions, gaining another factor 10–100 in speed. The `WARP-POSINST` code was benchmarked against experimental results at HCX, using a 5-μs, 180-mA, 1-MeV coasting K+ beam (potential on axis 2 kV, tune depression 0.1) propagating in a four-quadrupole magnetic lattice intentionally flooded with electrons, by intercepting the potassium ions on a conducting plate at the exit of the lattice. Nearly perfect agreement of the simulations with the experimental data is achieved by initializing the K+ beam distribution in `WARP-POSIINST` such that it exactly corresponds to the phase-space measurement upstream of the magnets. The detailed dynamics of the electrons in a quadrupole was studied in simulations and experiments, again showing a good agreement, e.g., the same 6-MHz signal, time evolution, and increase in rms power as a function of distance from the quadrupole center. The importance of secondary emission was demonstrated as well.

In the future, the `WARP-POSINST` will be applied also outside the HIFS programme. As part of LARP, self-consistent simulations have started of the electron-cloud build up for an entire LHC FODO cell.

Surface Properties

Art Molvik discussed how measurements of gas desorption and electron emission have led to an improved understanding and to the development of mitigation measures [17]. Ion induced electron emission scales with $1/\cos\theta$ [33]. Roughening the target surface reduces the emission. An improved model was developed using the `TRIM` code of the scaling of the electron yield with beam energy and angle of incidence θ [34]. The theoretical predictions from `TRIM` and experimental results are in reasonable agreement. Ion-induced gas desorption is large and shows a weaker dependence on the angle of incidence. Still a rougher surface reduces the desorption except for higher-energy ions, whose range is larger than the scale of roughness [35].

The HCX experiment succeeded in a measurement of the absolute electron-cloud density [34]. A retarding-field analyzer (RFA) for gas ions determines the potential on axis, which arises from the combination of beam and electron density. In parallel the electron current is detected at the clearing electrodes. The absolute electron fraction can be inferred either from the RFA or from the clearing electrodes. The results agree, and indicate a neutralization level of 80–90% without clearing, and 0–7% when the clearing electrodes are active. This also confirms that clearing electrodes are a highly efficient cure against electron cloud.

Electron Cloud with Barrier Cavities

For the SNS upgrade, ORBIT simulations were run comparing dual harmonic RF systems and barrier buckets [23]. Jeffrey Holmes showed that barrier buckets reduce the electron build up by an order of magnitude, and also decrease the number of electrons surviving the beam gap.

Electron Cloud in J-PARC

Kazuhito Ohmi reviewed the predictions of electron-cloud effects in J-PARC [20]. He studied the RCS and the Main Ring during injection and extraction, considering various potential sources of electrons, such as stripper foil, second stripper foil, halo collimator, and uncontrolled losses, plus the associated estimated primary electron rates. Several mitigation measures are implemented, such as an electron catcher near the stripper foil, and 30-G solenoids around the collimators. Although the expected beam losses at the collimators are 50 times higher than for the rest of the ring, the electron density is sufficiently suppressed by the solenoids, so that these regions do not dominate the total integrated electron density. The beam stability for the simulated electron-cloud densities is estimated using theoretical formulae for Landau damping and a resonator model for the electron-cloud impedance. Simulations confirm the theoretical prediction that the J-PARC beam is always stabilized by Landau damping. They also reveal the essential role of synchrotron motion for this stabilization. Electron cloud in quadrupole magnets will be studied in the future.

Two-Beam Instability in Electron Cooling

Alexey Burov pointed out that the drift response of electrons inside a solenoid is orthogonal to the direction of beam displacement ($\vec{E} \times \vec{B}$ term) [24]. As a consequence, coupling and tune split are important for the development or suppression of two-stream instability. The instability can be either a dipole instability or a quadrupole one. The theory presented explains observations the FNAL recycler electron cooler, and it was successfully applied to cure an instability in this machine. Various different theories proposed in the past could be reconciled.

Single-Bunch Instability at KEKB

Above the threshold of the single-bunch electron-cloud instablity at KEKB, a single upper synchrotron sideband of the vertical betatron tune is observed. The distance between sideband and tune increases along the train. This single sideband was now reproduced in electron-cloud simulations by two different codes, HEADTAIL, and PEHTS. The simulated sideband position and current dependence are in good agreement with KEKB measurements. In addition, the KEKB bunch-by-bunch feedback can suppress the betatron tune line, but not its synchrotron sideband. The same effect of feedback is seen in PEHTS simulations, as shown by Kazuhito Ohmi [25].

CONCLUSIONS

Since HB2004, our understanding of instabilities and space-charge effects has considerably improved and many previous challenges have been overcome. There is unabated, even growing, interest in electron cloud. In this field too, a lot of progress has been made in the past two years. This includes the PSR ep feedback, WARP/POSINST self-consistent simulations, the HCX experiments, understanding of incoherent electron-cloud effects by trapping or scattering off resonances and linear instability, explanation of KEKB single sideband, and predictions for various future machines. Nevertheless the uncertainty on important surface parameters is still high. The electron cloud has proven no limitation for the SNS, whose careful design has paid off; neither are e-p instabilities expected to occur in J-PARC. However, at SNS the electron cloud represents the largest measured source of impedance, and it appears to be a potential obstacle for the FNAL Main Injector upgrade, the RHIC upgrade, the LHC and its upgrade. The main limitation for the LHC could be the effect the electron cloud has on beam lifetime and emittance rather than the heat load.

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