SUMMARY OF IMPEDANCE ISSUES AND BEAM INSTABILITIES*

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Abstract

This paper summarizes the session on impedance issues and beam instabilities at the ICFA workshop on future circular electron-positron factories "eeFACT2016" [1] held at the Cockcroft Institute, Daresbury, from 24 to 27 October 2016. This session also covered active beam stabilization by feedback systems. Beam-beam effects and coherent beam-beam instabilities were addressed separately and, therefore, are not included here.

OVERVIEW

The eeFACT2016 [1] session on impedance issues and beam instabilities featured the following ten presentations:

1. Low SEY Engineered Surface for Electron Cloud Eradication [2], by Reza Valizadeh, STFC;
2. Collective Effects Issues for FCC-ee [3], by Mauro Migliorati, University of Rome La Sapienza;
3. Impedance Measurement Techniques and Lessons from Light Sources [4], by Victor Smalyuk, Brookhaven National Laboratory;
4. Coherent Wave Excitation in a High Current Storage Ring [5], by Alexander Novokhatski, SLAC National Accelerator Laboratory;
5. Electron Cloud and Fast-Ion Instability plus Mitigation Methods for Future Factories [6], by Kazuhito Ohmi, KEK;
6. Electron Cloud at SuperKEKB [7], by Hitoshi Fukuma, KEK;
7. Electron Cloud and Collective Effects in the Interaction Region [8], by Eleonora Belli, CERN and La Sapienza;
8. An Overview of Active Coupled-Bunch Instability Control [9], by Dmitry Teytelman, Dimtel, Inc.;
9. Feedback Experience at DAFNE [10], by Alessandro Drago, INFN/LNF;
10. Instability Issues in CEPC [11], by Na Wang, Institute of High Energy Physics, Chinese Academy of Sciences.

The topics and presentations can be classified according to three grand themes: (1) classical wake fields and instabilities, (2) electron cloud, and (3) ion instability. The focus was on forecasts for the proposed future large circular colliders, CEPC [12] and FCC-ee [13, 14], recent experience during the commissioning of SuperKEKB [15], and lessons from DAFNE [16] and PEP-II [17].

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Concerning classical wake fields and instabilities, in the transverse plane the resistive-wall driven coupled-bunch instability is of greatest concern [3, 11]. Assuming a fractional betatron tune above an integer, for FCC-ee the expected growth time of the fastest growing mode is about 7 turns, but there are many modes with a growth rate of order 10 turns. Fortunately, advanced transverse feedbacks could control instabilities with a damping time of about 1–2 turns. Such feedbacks can be realized either by using multiple BPMs ("folding the ring") [9], by doubling or quadrupling the feedback system [10], by multiple feedforward systems, or by a combination thereof.

Longitudinally, the potential single-bunch microwave instability driven by the broadband impedance appears to be the most dangerous effect [3, 11]. In addition to the resistive wall, the broadband impedance contains noticeable contributions from the RF cavities, photon stops, etc.

Indeed, many elements are contributing to the total impedance, both transversely and longitudinally. First models of total wake fields are available for FCC-ee and CEPC [3, 11]. Experience from the light sources suggests, however, that reality often differs from expectation [4].

When operating with high beam current and/or with short bunches higher-order mode (HOM) heating and HOM driven instabilities need to be controlled [5]. HOM heating destroyed numerous beam-pipe components at PEP-II and at many other storage rings. A particular topic of ongoing research is HOM excitation around the interaction point [8], where — depending on the various beam-pipe dimensions — a cavity-like object may be formed.

Nowadays powerful codes are available for solving Maxwell's equations inside the beam pipe. Such codes can compute the combined effects of sychrotron radiation, space charge, and wake fields [5].

The electron cloud is a potential threat to positron beams, especially for the Z-pole operation of FCC-ee [6, 8], where even the photoelectrons created by a single bunch passage yield an average electron density above the single-bunch instability threshold. Electron cloud is still an issue for SuperKEKB despite numerous countermeasures incorporated in the design [7], and even after installing additional permanent magnets in the short uncoated aluminium bellows chambers. One reason is that the TiN coating applied for most the vacuum chambers has proven insufficient to reduce the secondary emission yield to the required low level. A potential, highly efficient cure for future and present machines is the laser surface treatment LASE developed in the UK [2], which can dramatically reduce the secondary emission yield.

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Ion-driven multi-bunch instabilities are being experienced by the SuperKEKB electron beam [7]. First predictions of ion instabilities are available for the FCC-ee [6].

RESISTIVE-WALL INSTABILITY

Due to the large circumferences, one of the most important transverse instabilities for FCC-ee and CEPC is the coupled-bunch instability driven by the resistive wall of the beam pipe. The transverse resistive-wall impedance scales linearly with the circumference, and also with the inverse cubic power of the beam-pipe radius. A small beam pipe is preferred, however, so as to limit the electrical power consumption of the arc magnets. Figure 1 shows the fast rise time for FCC-ee when running on the Z pole, and its dependence on the fractional tune. The right picture reveals that not only a few, but many of the multi-bunch modes exhibit significant growth rates.

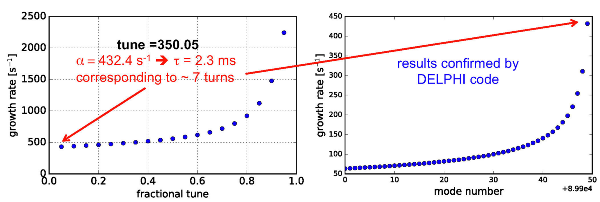

Figure 1: Growth rate of fastest rising mode in FCC-ee, at the Z pole, as a function of fractional tune (left) and growth rate versus coupled-bunch mode number for a betatron tune just above the integer (right) [3] (M. Migliorati). Only the effect of the resistive wall is considered.

ACTIVE INSTABILITY CONTROL

The coupled-bunch instabilities driven by resistive wall, electron-cloud and residual-gas ions can be controlled by active damper systems. Expressed in number of turns the fastest rise times seem short, e.g. less than ten turns, even if in terms of actual time the instabilities are not faster than those in existing machines. Advanced configurations, shown in Fig. 2, can achieve the desired damping times, e.g. multiple BPMs (folding the ring) [9], multiple feedback systems [10], or feedforward systems, based on fast data transfer across the ring [10].

LONGITUDINAL SHORT-RANGE WAKE

The longitudinal short range wake field drives the microwave instability. It has been computed for CEPC and FCC-ee taking into account various contributions. Impedance ingredients for CEPC are illustrated in Fig. 3. The wake fields expected for CEPC and FCC-ee are of similar order of magnitude; see Fig. 4.

MICROWAVE INSTABILITY

The microwave imstability is a threat in the longitudinal plane. The longitudinal resistive wall impedance alone already has a large effect on the beam dynamics.

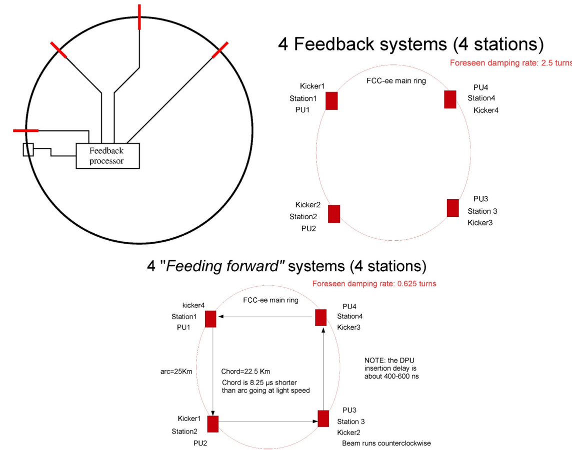

Figure 2: Various damper systems controlling fast coupled-bunch instabilities with a damping time of either a few turns or even less than a turn: (top left) feedback based on multiple BPMs [9] (D. Teytelman), (top right) multiple feedback systems [10] (A. Drago), and (bottom) multiple feed-forward systems [10] (A. Drago). .

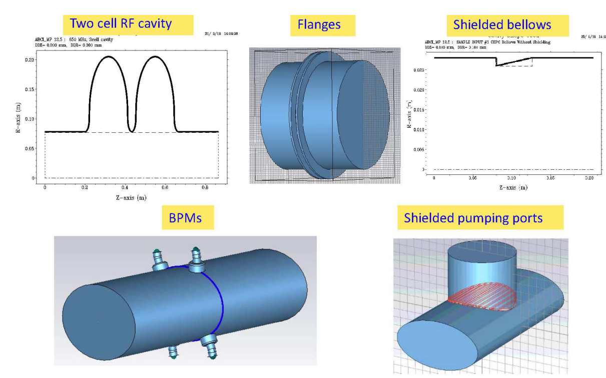

Figure 3: Beam-pipe elements included on the geometric impedance model for CEPC [11] (N. Wang).

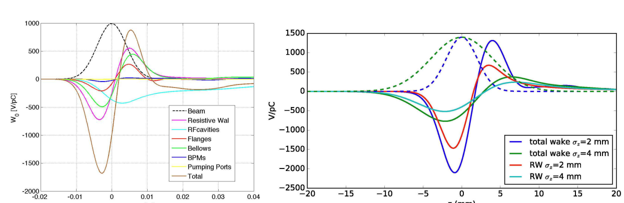

Figure 4: Short-range wake field for CEPC [11] (left) and FCC-ee [3] (right). The CEPC wake field considers contributions from resistive wall, 384 RF cavities, 10,000 flanges, 2300 BPMs, 10,0000 bellows, and 10,000 pumping ports [11] (N. Wang). The FCC-ee wake field comprises effects of resistive wall, 10,000 optimized photon stops, 400-MHz RF cavities, and 4,000 double tapers for quadrupoles and BPMs [3] (M. Migliorati).

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Figure 5 shows bunch lengthening and energy spread as a function of bunch population for the FCC-ee. The sudden increase in energy spread is the hallmark of the microwave instability. The threshold from a Vlasov-Fokker-Planck solver [18] is slightly above the threshold obtained from the criterion of Ref. [19].

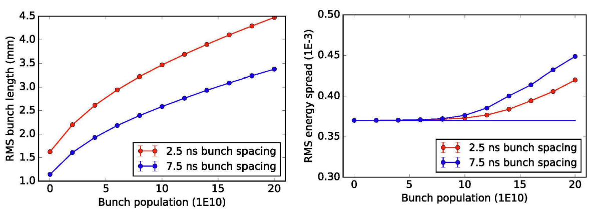

Figure 5: Bunch length (left) and energy spread (right) for two running modes of FCC-ee on the Z pole, as computed by a Vlasov-Fokker-Planck solver [3] (M. Migliorati).

For CEPC Higgs running the Boussard-Keil-Schnell threshold prediction is slightly below the design current, while for operation on the Z pole it is almost 3 times below the design [11]. The potential difficulty is further supported by numerical solutions of the Haissinski equation, which no longer seem to converge at bunch currents close to the Boussard-Keil-Schnell threshold, which is taken as an indication of microwave instability; see Fig. 6.

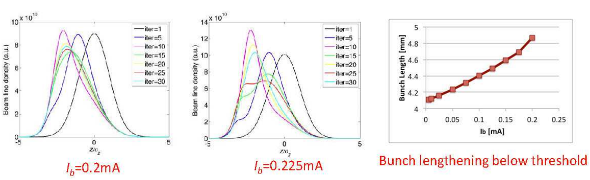

Figure 6: Numerical solution of Haissinski equation for different iterations below (left) and above the microwave threshold (right) [11] (N. Wang).

The onset of the microwave instability appears as an increase in the energy spread. The corresponding change of bunch length often is not easily visible and superimposed on the inductive bunch lengthening. The instability might have complicated character with several thresholds corresponding to different modes of instability. These features are illustrated in Fig. 7.

IMPEDANCE MEASUREMENTS

Impedances can be measured in a variety of ways, as is indicated in Table 1.

A comparison of calculated and measured impedances for various storage-ring light sources is presented in Fig. 8. This comparison suggests that the longitudinal impedance often is smaller than expected, while the measured transverse impedance frequently is larger than computed.

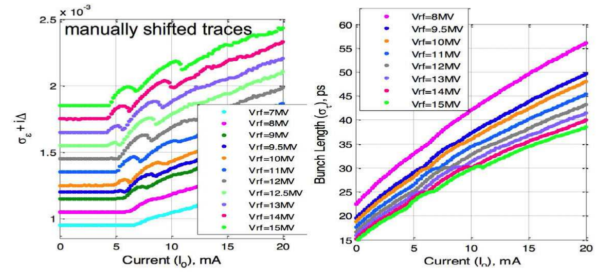

Figure 7: Energy spread and bunch length at NSLS-II, obtained from a Vlasov-Fokker-Planck solver (SPACE code), versus bunch current revealing multiple thresholds of microwave instability [4, 20] (V. Smalyuk).

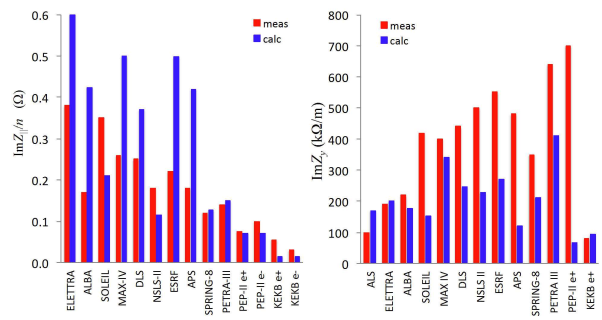

Figure 8: Longitudinal (left) and transverse impedance (right) measured at varius light sources compared with the calculated values [4] (V. Smalyuk).

HIGHER-ORDER MODES

Many storage rings operating at high beam current and/or with short bunches have suffered from heating of beam-line components due to higher-order mode (HOM) excitation.

A simple estimate of the loss factor for an obstacle of transverse size Δr in a pipe of radius $r = a$ is [5]

$$k \sim \frac{Z_0 c}{2\pi^{3/2}\sigma_z}\frac{\Delta r}{a}, \tag{1}$$

with σ_x denoting the rms bunch length and Z_0 the vacuum impedance. or a bunch length of 1 mm, radius 10 mm, and obstacle size 1 mm, the loss factor is about 0.1 V/pC.

The higher-order mode power itself can be estimated as [5]

$$P_{\rm HO} \approx \tau_b k I_b^2, \tag{2}$$

where τ_b denotes the bunch spacing, and I_b the total beam current. At a bunch spacing of 2.5 ns, and a current of 2 A the above small loss factor would already result in an HOM power of 1 kW [5].

Example images of the resulting damage at PEP-II are shown in Fig. 9.

If the vertex-detector chamber at the interaction point has a larger size than the incoming and outgoing beam pipes a cavity-like geometry is formed, in which trapped higher-order modes can exist, potentially leading to unwanted, and possibly dangerous heating. Figure 10 presents a calculation of the real part of the impedance for this beam-pipe region,

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Table 1: Impedance measurement techniques at light sources [4] (V. Smalyuk).

impedance	measurable effects	instrumentation
longitudinal broadband impedance	bunch lengthening, synchronous phase shift, dispersive orbit distortion, energy spread increase	streak camera, dissector tube, beam-position monitors, RF system diagnostics, pin-hole X-ray camera, synchrotron light monitor
transverse broadband impedance	coherent betatron tune shift, chromatic head-tail damping, orbit distortion (bump method)	beam-position monitors, pinger
transverse narrowband impedance	mode growth / damping of transverse coupled-bunch instabilities	bunch-by-bunch feedback system

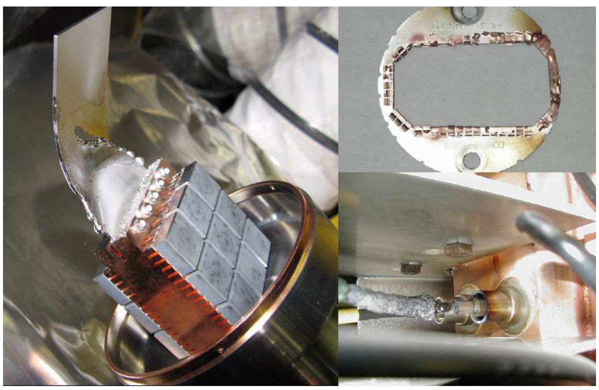

Figure 9: Images of PEP-II spoiler, RF shield and beam-position monitor damaged by higher-order mode heating [5] (A. Novokhatski).

revealing a large number of TM modes in the critical frequency range between 5.74 GHz (cutoff for 20 mm radius) and 9.57 GHz (cutoff for 12 mm radius).

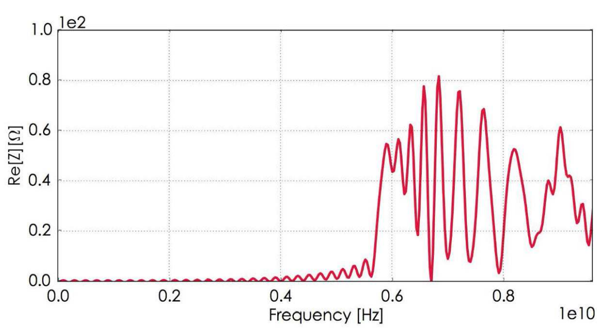

Figure 10: Real part of the longitudinal impedance for the FCC-ee interaction-region chamber as a function of frequency [8] (E. Belli).

ELECTRON-CLOUD EFFECTS

Serious electron cloud effects have been seen in the commissioning phase 1 of SuperKEKB despite a variety of countermeasures incorporated in the design (ante-chambers, TiN coating, grooved chambers, clearing electrodes). As in KEKB a vertical blow up is observed above a certain threshold of bunch current normalized to bunch spacing.

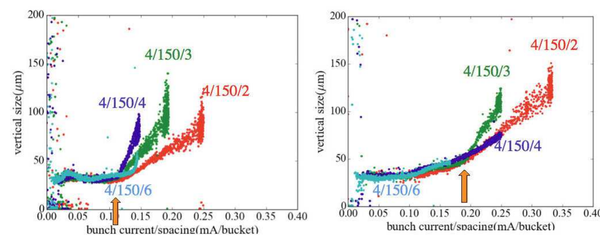

Figure 11: Vertical beam size as a function of bunch current over spacing before (left) and after the installation of permanent magnets around the uncoated bellows chambers (right) [7] (H. Fukuma).

During the phase 1 of SuperKEKB beam commissioning, the installation of permanent magnets (such as to produce a longitudinal "solenoid-like" magnetic field) in the 5% of the ring without TiN coating increased the threshold current of the vertical beam-size blow up by about a factor of two, as is shown in Fig. 11.

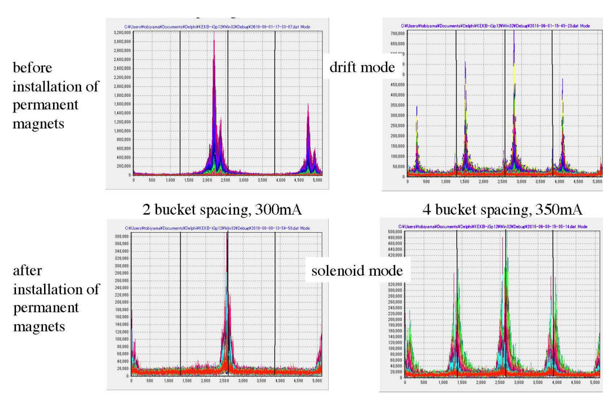

Figure 12: Vertical sideband spectra before (top) and and after the installation of permanent magnets in the uncoated bellows chambers (bottom), with two (left) and four bucket bunch spacing (right) [7] (H. Fukuma).

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Also the vertical sideband spectrum changed after the installation of the permanent magnets, hinting at a different dynamics of the residual electron cloud (Fig. 12). Significant electron cloud remains in the TiN coated aluminium beam pipe with ante-chamber, which is held responsible for the observed beam-size blow up, based on observations and coincidences like those in Fig. 13.

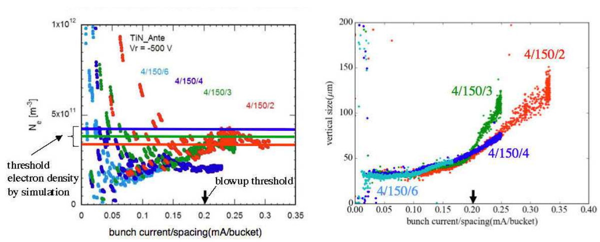

Figure 13: Electron density measured in a TiN coated chamber (left) and vertical beam size (right) as a function of bunch current per bunch spacing, recorded after the installation of permanent magnets in the uncoated bellows chambers [7] (H. Fukuma).

The numbers in Fig. 14 indicate that electron-cloud effects can be a severe issue for the future large circular colliders, especially for the Z-pole running with 2.5-ns bunch spacing at FCC-ee, where the photoelectrons created during the passage of a single bunch may exceed the threshold value for the electron-driven single-bunch instability (value in red).

		CEPC	TLEP-Z	TLEP-W	TLEP-H	TLEP-t
Circumf	C (km)	54	100	100	100	100
Energy	E (GeV)	120	45.5	80	120	175
No. bunches	N_b	49	90300	5162	770	78
Bunch pop	N_p (10^{11})	3.8	0.33	0.6	0.8	1.7
Beam l-density	λ (10^{10}m^{-1})	0.74	3.0	0.3	0.06	0.0013
Beam size (av.)	σ_x/σ_y (μm)	583/32	95/10	164/10	247/11	360/16
Bunch length	$\sigma_{z,tot}$(mm)	2.6	5.0	3.0	2.4	2.5
Synch. tune	ν_s	0.18	0.015	0.037	0.056	0.075
γ prod. rate	N_γ (/m/e$^+$)	0.28	0.059	0.10	0.16	0.23
e$^-$ prod. rate	$n_{e,prod}$ (10^{10}m^{-1})	1.1	0.020	0.062	0.12	0.39
Electron freq.	$\omega_e/2\pi$ (GHz)	137	127	171	174	171
Electron osci.	$\omega_e\sigma_{z,tot}/c$	7.5	13	11	8.7	9.0
Thr. density	$\rho_{e,th}$ (10^{10}m^{-3})	104	0.78	3.4	7.7	15
Tune shift	$\Delta\nu$ at $\rho_{e,th}$	0.034	0.0025	0.0061	0.0092	0.012

Figure 14: Parameters related to electron-cloud instability [6] (K. Ohmi).

Laser Ablation Surface Engineering (LASE) on a metal surface is a viable solution for reducing the maximum secondary emission yield δ_{max} to values well below 1.0 [2]. Even the initial (unconditioned) δ_{max} = 0.93 for LASE-treated stainless steel is low enough to suppress the electron-cloud build up in machines like the SPS, HL-LHC, or FCC, etc. LASE reduces the secondary emission yield through a combination of two geometrical effects, which can be varied by modifying relevant LASE parameters. Surface resistance measurements indicate that the LASE-produced so-called "shallow groove type with superimposed nano-sphere" is the preferred solution.

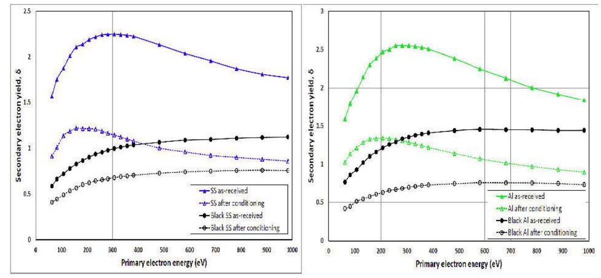

Figure 15: Measured secondary emission yield with and without LASE treatment before and after conditioning: stainless steel (left) and copper (right) [2] (R. Valizadeh).

Another possible mitigation of electron-cloud build up is adding gaps in the bunch train. The resulting reduction of electron-cloud heat load is illustrated in Fig. 16.

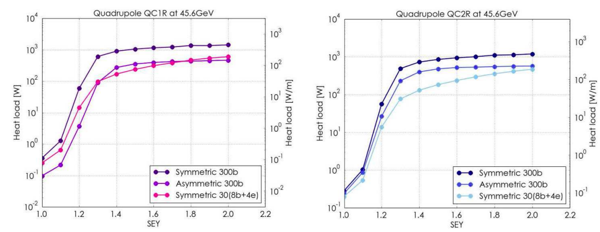

Figure 16: Simulated electron-cloud heat load in the final quadrupoles of FCC-ee, under various conditions, showing the beneficial effect of adding gaps in the bunch train (E. Belli).

ION INSTABILITY

Trapped or transient ions generated by residual gas ionization can drive electron beams unstable. In order to avoid performance degradation due to such instabilities the vacuum pressure should be below 10^{-8} Pa [6], and, in addition, for FCC-ee a bunch-by-bunch feedback with a damping time of about 10 turns will be required. Ion instabilities have already been observed at SuperKEKB during its commissioning phase 1. The present modelling of ion instability appears quite insufficient: for example, the mode spectrum observed at SuperKEKB would be consistent with expectations for a rigidly moving ion cloud much larger than the electron beam, i.e. $\sigma_{i,y} \approx 40 \times \sigma_{y,e}$. A related outstanding question is how ions are (partially) cleared in the abort gap with a duration of a few microseconds. Despite the remaining puzzles, K. Ohmi concluded that the âĂIJion instability does not seem to be serious (for present and future colliders) if a good vacuum pressure is realizedâĂİ [6].

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