TECHNOLOGICAL ASPECTS OF CRAB CAVITIES*

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Abstract

Some technical aspects of a crab cavity system with respect to an application in LHC are described.

INTRODUCTION

For the use of crab cavities see [1][2] as well as the previous talks. For technical developments concerning crab cavities see e.g. [3]-[9].

FREQUENCY AND CAVITY SIZE

As discovered by Panofsky andWenzel [10] long ago (see also e.g. [11]), a TE (transverse electric) mode does not kick particles transversely since the effects of the electric and magnetic forces perfectly integrate to zero along the particle path for any particle speed v. Only the magnetic field of TM (transverse magnetic) modes produces such a deflection at locations where the field pattern has a transverse gradient of the longitudinal accelerating voltage (Fig. 1), precisely

(1) $\Delta p_x = -ie/\omega \;\; dV_z/dx \; \exp(-i\omega \cdot z/v)$

z is here the longitudinal deviation from the synchronous particle in the centre of the bunch. Since sin(ωz/c)=-Im(exp(-i·ωz/c)), particles at z=0 encounter no deflection as should be the case for the bunch centre. Then the longitudinal voltage V_z and bunch current are in phase, i.e. have maximum interaction if the beam does not pass exactly at a spatial zero crossing. Therefore the field pattern is chosen such that the (beam passes at a zero crossing of the longitudinal E-field (Fig. 1).

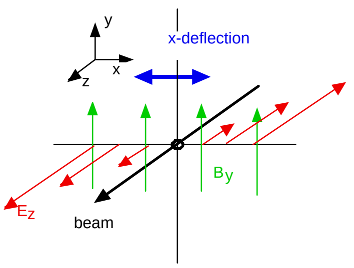

Fig.1: RF field with horizontal (x) kick

Due to the longitudinal kick strength modulation being as sin(ωz/c) only particles with z<<c/ω have a deflection proportional to z, the desired situation for straight head-on bunch collision (Fig. 2). In the nominal LHC the 4σ bunch length is 30 cm, excluding a crab frequency of 800 MHz as too high. For 25 ns bunch spacing (or any multiple) any multiple of 40 MHz could be envisaged as a crab frequency but certain upgrade options might be excluded. Therefore the next lowest 'reasonable' frequency appears to be 400 MHz, identical to the main RF frequency and hence adding no bunch pattern restriction at all. Even for 400 MHz the above length condition is not ideally fulfilled but a lower frequency e.g. 200 MHz would require a cavity size incompatible with feasible beam separation.

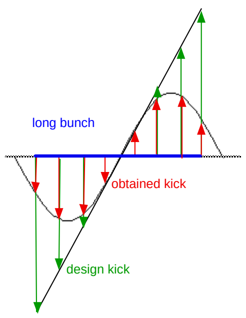

Fig.2: Desired and obtained kick for long bunches.

For a cavity frequency-size estimation one can approximate a typical crab cavity by a rectangular box of dimensions L_x, L_y and L_z (Fig. 3), keeping in mind that a real superconducting (sc) cavity needs rounded edges and hence some more space in all directions.

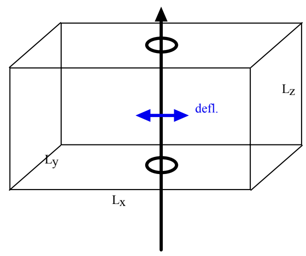

Fig.3: Box cavity approximating squashed crab cavity.

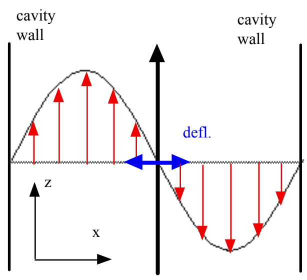

Fig. 4: Field pattern in beam plane for x-deflection

The field pattern with the lowest frequency has then no electric field in (transverse) x and y direction. E_z has one full 'oscillation' when walking along the deflecting direction (chosen as x here, Fig. 4) from wall to wall with a zero on the nominal beam axis and half an 'oscillation' in the perpendicular y-direction. The frequency *f* of such a field pattern is given by

$$f^2 \;=\; c^2 \;\; (1/L_x^2 \;+\; 1/(2L_y)^2)$$

On the other hand for the nominal LHC the maximum separation between the two beams (in IP4) is 42 cm. Of this distance one beam tube radius and some 'technical space' for a He-tank, super-insulation, vacuum tank and flanges have to be reserved such that any sc cavity can have a maximum horizontal radius of about 35 cm.(For the cavities of the LHC main RF system the second beam passes through a special tube *inside* the cryostat). This excludes a 'classical' squashed crab cavity, such as the KEK/Cornell design [3][4], at 400 MHz with a horizontal kick, with the present beam separation (for an optics giving more beam separation see [12], this WS). Any completely different 'adventurous' cavity shape may carry the risk of multipactor (MP), generally deadly for sc cavities. But there might be a possibility of 'adiabatically' deforming a squashed cavity by bending the longer ends 'downwards' and slightly displacing the beam tube 'upwards'. This method does not significantly change the surface fields, essentially responsible for MP, while allowing the second beam tube to be closer as in the classical design. Evidently this design has the drawbacks that the efficiency (i.e. R/Q) is lower and the kick depends already to first order on the perpendicular transverse (y) co-ordinate; but the beam passes on a zero crossing of E_z as it should be. Another aspect is the increased difficulty for 'H'OM distinction ('H'OM: here read 'H' = any mode except the working crab mode), the symmetries exploited in the squashed cavities being partly broken here. Further investigations would be necessary to follow up this path. The efforts in R&D and probably increased production cost for this design have to be balanced against a beam optics concept with larger beam spacing.

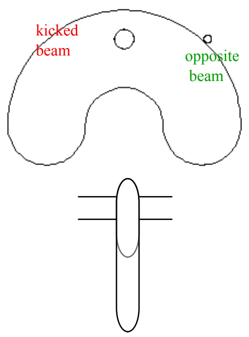

Fig. 5: 'Adiabatically deformed' version of a 'squashed cavity' to approach the two beam lines while keeping the resonant RF frequency low.

CAVITY FABRICATION

One may follow the path of bulk Nb cavities as established in the framework of TESLA [13] and now ILC [14]. An increased wall-thickness could help since crab cavities are not round, i.e. mechanically less stable, and should be very stiff to keep frequency stability. This might be realized in Nb/Cu technology, the LEP2 cavities being one example. There are two points of concern requiring R&D [15]:

•in contrast to accelerating cavities crab cavities have their magnetic field maximum on the iris where the mechanical deformation of the Cu substrate cavity is the worst

•squashed cavities have steeper walls so that the impact direction of Nb atoms (coming from a cathode in the region of the beam axis) during sputtering is less perpendicular, sometimes leading to columnar Nb films.

LEP2 Nb/Cu cavities had a larger Q at low field but also a steeper Q-drop, so that the performance at the operating field has to be compared with bulk Nb cavities.

N-CELL CAVITIES

Multicell cavities offer higher real estate gradient (voltage per total length) with N times less couplers, tuners, control units, … The price to pay is that each single-cell mode appears in N instances with only slightly different frequency and each such 'higher' order mode couples less well to the single coupling device at the end(s) of the cavity due to the larger stored energy and (for several modes) lower end-cell field, i.e. the coupling has to be reinforced correspondingly to preserve mode damping. Also trapped modes (different end cell shape) can be a nuisance, having only weak field at the end-cell with the coupling device close to it; this effect can even be reinforced if field flatness is badly preserved due to fabrication tolerances, especially critical for designs with low cell-to-cell coupling.

Another problem is the N-fold multiplicity of the crab mode itself, all modes in this pass-band having similar frequency and local cell field pattern. If vector-feedback is necessary to prevent coupled bunch instabilities and undesired beam loading effects – in any case a judicious choice in such a sensitive hadron machine as LHC – a filter-box is necessary to prevent auto-oscillation of the (N-1) other modes. Such a device may increase RF noise, a critical point for crab cavities.

It is also necessary that the RF high power system covers the whole range of the crab mode pass-band and has sufficient power to keep all beam loading under control.

M CAVITIES WITH ONE TRANSMITTER

Installation cost and energy consumption wise it is more economic to use a large power transmitter, splitting the power to feed several (M) cavities. The drawback is that there are M degrees of freedom – each cavity may have its own field while the total vector sum is still as desired – but only one control variable, the transmitter RF voltage. This can lead to instabilities, e.g. ponderomotive oscillations as observed in LEP2 where 8 cavities were driven by one klystron. To safely prevent this, each[†] cavity has to be foreseen with an additional *high power* control unit compensating (small) individual deviations. A prototype of such a device [16] has been built in the framework of SPL [17] at 352 MHz at CERN, an 'amplitude and phase modulator' using hybrids and controllable high power ferrite phase shifters. This device

[†] theoretically M-1 can be sufficient, but very complex in control

allows the outgoing phase of the wave coming from the power splitter to be changed and/or part of the wave to be deviated into a RF load, hence compensating individual cavity deviation from the average. However, these devices are much too slow (some 100 Hz, maybe kHz) to handle e.g. coupled bunch mode instabilities, this has to be dealt with the (fast) transmitter over the vector sum.

The combination of N-cell cavities and M cavities per transmitter also brings with it the necessary combination of the required hardware, a filter-box and a high-power controller per cavity with a vector-sum 'driving' the transmitter, thus increasing the complexity of the system.

'H'OM DAMPING

To avoid excitation of beam instabilities, all modes except the working mode should be damped sufficiently. The essential problem is to distinguish between the working mode, to be left undamped, and all the others, to be damped as strongly as possible. There are two ways of mode distinction: •field pattern and •frequency. In the KEK/Cornell design the first is chosen to couple the monopole modes using a centred (hollow) coaxial line that does not couple (in theory) to multipoles – including the working crab mode – due to symmetry. *All* other multipoles, are selected by frequency. Each has a higher frequency (hence the squashed shape to increase the frequency of the complementary crab mode) above the cut-off of the second beam tube and flows along this tube to a (separately cooled) internal RF load 'far' away from the cold cavity itself.

One modification of this scheme might be the use of 'resonant' couplers (with incorporated sc stop filter) – as in the LHC main RF system – increasing coupling on a dedicated (group of) mode(s) and/or couplers located azimuthally such that they do 'not' interact with the working crab mode. The power then might be transported out of the cryostat and dumped in an external (warm) load. But extensive R&D has to be performed to validate such an option and compare it with the existing design.

TRANSIENT BEAM LOADING

It was already stated above that beam current and longitudinal crab voltage V_z are in phase. Therefore any voltage induced by a beam transversely not exactly passing on the V_z zero crossing creates an in-phase (i.e. amplitude) change and – for an ideally phased system – no quadrature voltage (i.e. no phase change).

For the 'global' crab option [18] with only a single (uncompensated) system the induced voltage has to be compensated to a high degree. For the 'local' option with two theoretically compensating systems left and right of the IP and beam-optical distance π, the induced voltage difference is the important parameter, provided the absolute value remains in a range still preserving a tilt for a reasonable head-on collision. If the first crab system makes e.g. the bunch head rise (Fig. 6a), the latter has its maximum excursion at the IP during collision and then starts to drop again, crossing the axis at the second crab system. To stop this movement, again a kick that would raise the bunch head is necessary, i.e. both crab systems must have equal polarity when the beam passes.

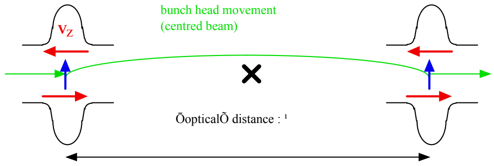

Fig. 6a: Movement of crabbed bunch head

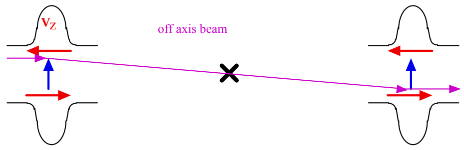

Fig. 6b: Movement of displaced beam

If a beam slightly off-axis (Fig. 6b) induces e.g. a negative voltage in the first system, it induces then a positive voltage in the second system since the beam changes its off-axis side due to the optical transfer by π. Therefore an amplitude *difference* between the two systems is induced, not an identical change. Therefore a vector feedback system working on the difference between the two cavity voltages is recommended to avoid an unstable situation.

POWER CONSIDERATIONS

As long as the beam passes on its nominal transverse position, the V_z zero crossing, there is no energy transfer between beam and crab field. Each cryostat (or better even, each cavity) has to be transversely adjustable (remote control) to minimize the residual voltage. Even then the beam might be slightly displaced with respect to the ideal position, e.g. when trimming the orbit or by limited setting precision.

To cover these excursions, the crab RF system has to be able to deliver *or absorb* the corresponding power, depending on the direction of the excursion. But for a *sizable* crab system for large crossing angle ('local' option [18]) the power bottleneck might not be the crab RF system itself, but the main RF system: even for the worst case it has to absorb or deliver the complementary power since in coast, averaged over one turn, bunches will not take or give energy. There is one positive point in the mutual polarity found previously: the crab system on one side will deliver, the other absorb power so that in this case the main RF has not to cope with a huge power unbalance for larger excursions with well defined polarity.

Defining the transverse voltage $V_\perp$ as the transverse momentum kick Δp_x per charge multiplied by c and exploiting the Panofsky-Wenzel theorem [10] for the absolute peak values one gets

(2) $$V_\perp = \frac{c \cdot \Delta p_x}{e} = \frac{c}{\omega}\frac{dV_z}{dx} = \frac{1}{k}\frac{dV_z}{dx}$$

V_z is (to very good approximation in the considered range) proportional to Δx, hence longitudinal and transverse quantities are related as

(3) $$V_z = V_{\perp} \frac{\omega}{c} \Delta x = V_{\perp} \cdot k \cdot \Delta x$$

and (circuit Ω definition)

(4) $$(R/Q)_{\perp} = \frac{1}{2} \frac{V_{\perp}^2}{\omega U} = \frac{1}{2} \frac{V_z^2}{(k \cdot \Delta x)^2 \omega U} = \frac{(R/Q)}{(k \cdot \Delta x)^2}.$$

where *U* is the cavity stored energy.

The generator (g) and reflected (r) model currents for a well-tuned cavity (no reactive beam loading here) are

(5) $$I_{g,r} = \frac{V_z}{2(R/Q) \cdot Q_{ext}} \pm I_b = \frac{V_{\perp}}{2(R/Q)_{\perp} k\Delta x \cdot Q_{ext}} \pm I_b$$

where I_b is the *DC* beam current (adjusted by the *relative* bunch form factor, about 0.9 for 4σ=30 cm bunches at 400 MHz) and '+' for the transmitter current, '–' for the reflected one. The corresponding RF power is

(6) $$P_{g,r} = \tfrac{1}{2}(R/Q)_{\perp}(k \cdot \Delta x)^2 \cdot Q_{ext} \cdot \left|I_{g,r}\right|^2$$

i.e. the power for arbitrary Q_{ext} and Δx is

(7) $$P_{g,r} = \tfrac{1}{2}(R/Q)_{\perp} \cdot Q_{ext} \cdot \left(\frac{V_{\perp}}{2(R/Q)_{\perp} Q_{ext}} \pm k\Delta x \cdot I_b \right)^2$$

To minimise power consumption the optimum choice of Q_{ext} corresponds to a zero *reflected* power for the maximum allowed excursion Δx_{max}

(8) $$Q_{ext,opt} = \frac{V_{\perp}}{2(R/Q)_{\perp} k\Delta x_{\max} \cdot I_b}$$

For this $Q_{ext,opt}$ the peak generator current and the corresponding power as function of Δx becomes

(9) $$I_{g,opt,\max} = 2 \cdot I_b$$

(10) $$P_{g,opt,\max} = \Delta x_{\max} \cdot k \cdot V_{\perp} \cdot I_b$$

Assuming [18] a kick voltage of 5 MV with an (R/Q)=47.5 Ω (circuit Ω, in [18] *linac* Ω are quoted which is equivalent[‡]), a DC beam current of 1 A (about the ultimate current with f_b=0.9), a solid state amplifier of 500 W can tolerate an excursion of about 12 µm, provided $Q_{ext,opt}=5 \cdot 10^8$ is set. This maximum excursion is already marginal for mechanical setting precision, but, even worse, at this Q_{ext} the system bandwidth is about 1 Hz, preventing any usual tuning method for sc cavities. ny small frequency shift (vibration, LHe pressure) will induce large phase excursions, a very critical parameter for crab cavities.

To have a bandwidth of at least 400 Hz (the main RF will work with about 4000 Hz in coast), $Q_{ext} \leq 10^6$ is required. Under these conditions to keep up the field even for Δx=0 already 65 kW are necessary, completely reflected to an RF load. For realistic excursions (Δx<1 mm) the power change is then still in the linear range

(11) $$\Delta P_{g,r} = \pm \tfrac{1}{2} \cdot V_{\perp} \cdot I_b \cdot k \cdot \Delta x$$

‡ a unique definition one day is not very probable

i.e. about 20 kW/mm. At 400 MHz for such *total* power values tetrodes are hardly usable, hence a (noisy) klystron has to be used.

KICK ERRORS

There are different types of crabbing kick-errors, each one with two resulting effects on the bunch: •modifying the 'enclosed' collision and •influencing the trajectory after 'compensation'. We consider here only compensated systems, not the 'global' unique system, and assume that 'on entry' the bunch is perfectly aligned. Evidently any remaining error will reappear at entry of the next turn, transformed by the optical transfer function of the machine. All the following errors are additive.

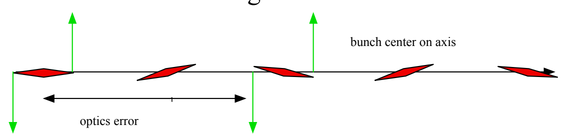

Fig. 7a: The optical transfer function between the two crab systems is not π (modulo 2π). The bunch centre always remains on axis but – if already crab1-IP is not π/2 – the tilt at the IP is not as designed. The bunch-inclination continues to oscillate after crab2.

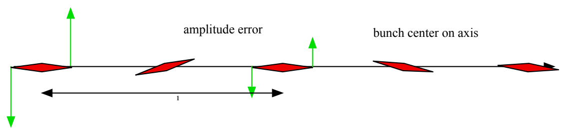

Fig. 7b: The kick amplitudes are not equal. The bunch centre always remains on axis but – if crab1 has not the design amplitude – the tilt at the IP is not as designed. The bunch-inclination continues to oscillate after crab2.

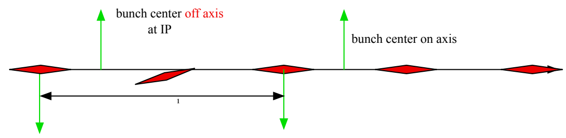

Fig. 7c: A *common* phase shift exists between crab1 and crab2. The bunch centre does not stay on axis at the IP, i.e. the collision is not central, but the bunch is perfectly aligned again after crab2 (if no other errors or beam-beam effects due to the not central collision).

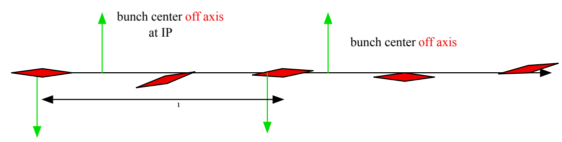

Fig. 7d: *Independent* phase shifts exist between crab1 and crab2. The bunch centre does not stay on axis at the IP, i.e. the collision is a slight miss, and the bunch line and centre of mass continue to oscillate after crab2. This seems to be the worst type of error.

RF NOISE CONSIDERATIONS

Before comparing requirements in different publications, one should be aware that there are two distinct applications of crab cavities. One is in linear colliders (ILC) with extremely small spot size but where only the single shot precision counts. The other is in circular colliders with less extreme spot size but where the beam may be blown up over many turns. Furthermore, the latter case splits into electron colliders that are synchrotron radiation dominated – bunches have only a short memory – while e.g. the hadron collider LHC has a (longitudinal) synchrotron radiation time of about 12 hours, i.e. practically negligible damping.

Using the table of [19], based on simulations [20] for LHC, for independent phase noise an average statistical excursion of 0.002 ps is claimed as the tolerable limit (during the present workshop in [21] these limits were somewhat relaxed). These values are difficult to achieve.

One solution [22], similar to a design by J. Frisch for ILC, is to use a single (noisy) high power klystron, split the power and send one half to the left and one half to the right (group of) crab cavity(s). In this way, whatever the klystron's noise contribution, both crab systems are fed with a coherent power wave which would not be the case for two local klystrons driven by a split low power signal.

But this design makes a fast vector feedback (e.g. to fight CBI) around cavities very difficult. Furthermore, instead of thin cables bulky 400 MHz waveguides have to run along the tunnel and around the detector, one set for each (group of) pair of cavities.

It is furthermore proposed [22] to look for answers to a catalogue of questions and then try to solve unsettled items.

• What are the phase noise properties of power amplifier systems (caution AM/PM conversion) typically used to drive such cavities. → CW operation is foreseen, but beam loading requires the transmitter to react, i.e. change its amplitude to some degree.

• To what precision can phase noise be measured? → see the discussion above on precision

• To which precision can it be controlled? → not better than measured; a possible actuator not introducing significant additional noise is an open question. Furthermore, to obtain the measurement precision as stated above, long integration times (seconds) are required, hence any counter-action has intrinsically this delay while the initial noise persists.

• Which technology should be used (klystrons, solid state)? → for the necessary power level at 400 MHz with classical technology only klystrons can be used, possible new developments in high power RF transmitters may give other options.

• Where is the limit between jitter and drift? → the betatron frequency is expected to define the most sensitive time scale

• How about the impact of amplitude noise (AM/PM conversion) → still an open question

• What are the phase noise properties of the beam itself (e.g. from power supply ripple, parametrically excited modulation etc.)? → phase is something relative between two waves. But even cooled beams – that behave very well – have a noise spectrum orders of magnitude larger than the above requirements [22] and there might be the suspicion that the asked precision is too large. Therefore true tests (as planned in KEKB) are vital to compare theory and practice.

Individual bunch phases

For the LHC RF system it is foreseen [23] to let bunches longitudinally slide to such a position (Fig. 8) that the RF power spikes are much reduced. This avoids running the klystron into saturation during spikes at very high beam current and in general reduces the klystron trip rate. The shift in bunch position is negligible compared to the bunch length, hence transparent for the LHC detectors. But either this bunch-by-bunch phase offset is transmitted to the crab RF system – probably inducing more noise – or the centre of tilt will always be slightly shifted away from the bunch centre. Whether this is a problem is also still an open question.

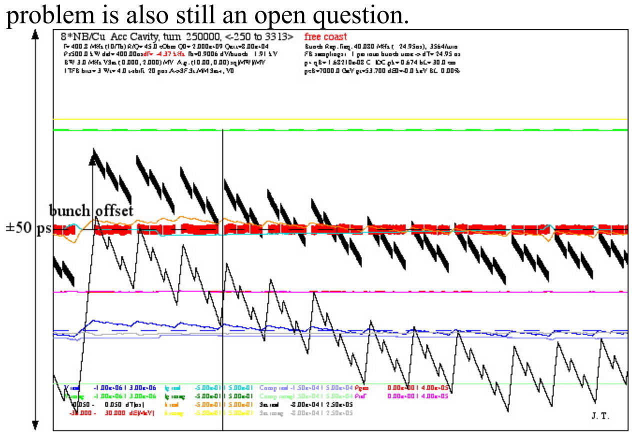

Fig. 8: Complete 'individualized' stable bunch positions at 7 TeV coast after smoothing: vertical position of black bars (±50 ps range) present stable bunch position. More details in [23].

SUMMARY

• At 400 MHz a horizontal kick with the present horizontal beam-beam distance is not possible: one needs different cavity shapes or more beam-line separation (see [12])

• Nb/Cu technology might be an option but R&D to verify film quality for the various shapes proposed is necessary

• (low) N-cell and M cavities per transmitter is possible if space and financial requirements push for it. But such a system is more complex with probably higher RF noise.

• A limited beam excursion in LHC cannot be exploited for low power consumption: the system BW would be too low. $Q_{ext}=10^6$ with 400 Hz BW would require an installed power of at least 100 kW per 2-cell cavity [18] including dynamic reserve.

• The role of different types of noise (amplitude, phase; does coherence between both crab systems help) has to be analyzed in more detail to find the best technical options.

• The question as to whether each bunch having its 'private phase' is a real problem or only a nuisance should be addressed?

• The required noise level as announced is about a factor 10 (see also [21]) below present technology, but ideas seem to exist to solve the problem.

In any case caution should be kept when extrapolating technology: for the *integrated* luminosity in LHC *reliability* is a cornerstone. Therefore one should not extrapolate from today's best laboratory technology what might be the best laboratory performance in a few years and assume that it can be reproduced without fault any day, around the clock, in an accelerator environment full of high power equipment of all sorts.

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REFERENCES

[1] R. B. Palmer, SLAC-PUB 4707 (1988)
[2] K. Oide and K. Yukoya, Phys. Rev. A40, 315 (1989)
[3] H. Padamsee et al., Proc. Pac91, 6-9 May 1991, San Francisco, CA, USA, p 2423
[4] K. Akai et al., Proc. 15th Int. Conf. On High Energy Accel., p 757 (1992)
[5] K. Akai et al., Proc. PAC93, 17-22 May 2003, Washington, DC, USA, p. 769
[6] K. Akai, talk at KEKB review committee, 22 March 2006
[7] K. Akai and Y. Morita, Proc. PAC05, 16-20 May 2005, Knoxville, Ten., USA
[8] K. Hosoyama et al., Proc. APAC98, 23-17 March 1998, Tsukuba, Japan
[9] K. Hosoyama, talk in KEK Crab Cavity R&D Group, KEK, Tsukuba, Japan
[10] W. K. H. Panofsky and W. A. Wenzel, Rev. Sci. Instr. **27**, 967 (856).
[11] S. Vaganian and H. Henke: The Panofsky-Wenzel theorem and general relations for the wake potential, Part. Acc., Vol. 48 (1995), pp. 239-242.
[12] R. Tomas Garcia, this workshop
[13] The TESLA technical design report, http://tesla.desy.de/new_pages/TDR_CD/start.html
[14] The International Linear Collider, http://www.linearcollider.org/cms/
[15] S. Calatroni, CERN – private communication
[16] H. Frischholz et al., "First Results with a Fast Phase and Amplitude Modulator for High Power RF Application ", CERN-AB-2004-052
[17] Conceptual design of the SPL II (draft) http://project-spl.web.cern.ch/project-spl/Documentation/spl2.pdf
[18] R. Calaga, this workshop
[19] F. Zimmermann, Proc. CARE-HHH-APD LHC-Lumi-05 Workshop, Arcidosso, 31 Aug.-3 Sept. 2005
[20] K. Ohmi, Proc. CARE-HHH-APD LHC-Lumi-05 Workshop, Arcidosso, 31 Aug.-3 Sept. 2005
[21] K. Ohmi, this workshop
[22] F. Caspers, CERN, private communication
[23] J. Tückmantel, "Adaptive RF Transient Reduction for High Intensity Beams with Gaps", Proc. EPAC06, 26-30 June 2006, Edinburgh, Scotland http://accelconf.web.cern.ch/AccelConf/e06/PAPERS/MOPLS006.PDF