### Low Level RF

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### ILC Feedback Block Diagram



### **CERN LHC Feedback Block Diagram**



## SLAC - PEP-II Feedback Block Diagram



### Very similar

- Basic design very similar!
- Beam stability limitations differ, so emphasis is different in each machine.
- We will look at the ILC requirements and limitations and then the feedback systems for the LHC and LINAC4.

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#### Cavity Based Loops

- Power Amplifier limits and cure
- Beam Loading
- Coupled-bunch longitudinal instabilities
- Beam loading and coupled-bunch instabilities cure

### Cavity Resonance Loops

Design Example

### **ILC** requirements

### **ILC requirements**

- CM energy: 500 GeV. Range 200-500 GeV. Upgradable to 1 TeV
- Luminosity and reliability of the machine should allow L<sub>eq</sub> = 500 fb<sup>-1</sup> during first four years
- Energy scans between 200 GeV and 500 GeV. Energy change should take less than 10% of data taking time
- Beam energy stability and precision should be below the tenth of percent level

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### Scope of Main Linac RF

total number of klystrons / cavities per linac	~ 280/ 7,280
per rf station (klystron):	
# cavities / 10 MW klystron	~ 26
<pre># of precision vector receivers (probe, forward, reflected power, reference line, beam)</pre>	~78
# piezo actuator drivers / motor tuners	~ 26/26
# waveguide tuner motor controllers	~ 26
# vector-modulators for klystron drive	1
Total # of meas. /control channels per linac	~22,000 / ~22,000

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LLRF System Requirements Overview

- Maintain Phase and Amplitude of the accelerating field within given tolerances
  - up to 0.07% for amplitude and 0.24 deg. for phase
- Minimize Power needed for control
- RF system must be reproducible, reliable, operable, and well understood.
- Other performance goals
  - build-in diagnostics for calibration of gradient and phase, cavity detuning, etc.
  - provide exception handling capabilities
  - meet performance goals over wide range of operating parameters

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LLRF System Requirements – Field Stability

- · Derived from beam properties
  - energy spread
  - Emittance
  - bunch length (bunch compressor)
  - arrival time
- Different accelerators have different requirements on field stability (approximate RMS requirements)
  - 1% for amplitude and 1 deg. for phase (example: SNS)
  - 0.1% for amplitude and 0.1deg.for phase (linear collider)
  - up to 0.01% for amplitude and 0.01 deg. for phase (XFEL)
- Note: Distinguish between correlated and uncorrelated errors

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## Non-Functional Requirements

- Reliability
  - not more than 1 LLRF system failure / week
  - minimize LLRF induced accelerator downtime
  - Redundancy of LLRF components
  - ...
- Operability
  - "One Button" operation (State Machine)
  - Momentum Management system
  - Automated calibration of vector-sum
  - ...
- Reproducibility
  - Restore beam parameters after shutdown or interlock trip
  - Recover LLRF state after maintenance work
  - ...

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# Non-Functional Requirements (C'tnd)

- Maintainability
  - Remote diagnostics of subsystem failure
  - "Hot Swap" Capability
  - Accessible Hardware
  - ...
- Well Understood
  - Performance limitations of LLRF fully modelled
  - No unexpected "features"
- · Meet (technical) performance goals
  - Maintain accelerating fields defined as vector-sum of 26 cavities within given tolerances
  - Minimize peak power requirements

### Sources of Field Perturbations

#### o Beam loading

- Beam current fluctuations
- Pulsed beam transients
- Multipacting and field emission
- Excitation of HOMs
- Excitation of other passband modes
- Wake fields

#### o Cavity drive signal

- HV- Pulse flatness
- HV PS ripple
- Phase noise from master oscillator
- Timing signal jitter
- Mismatch in power distribution

#### o Cavity dynamics

- cavity filling
- settling time of field

#### o Cavity resonance frequency change

- thermal effects (power dependent)
- Microphonics
- Lorentz force detuning
- o Other
  - Response of feedback system
  - Interlock trips
  - Thermal drifts (electronics, power amplifiers, cables, power transmission system)

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- Cavity Based Loops
  - Power Amplifier limits and cure
  - Beam Loading
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### Cavity Resonance Loops

Design Example

# 2. Beam based loops for Synchrotrons

Loops that use signals from beam Pick-ups, either longitudinal (beam phase) or transverse (beam position) and that act on all bunches

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# 2.1 Beam Phase Loop

- Motivation:
  - Transients will be triggered by energy/voltage mismatch at capture
  - RF noise will excite the synchrotron oscillation of each particle individually.
- In electron machines the synchrotron light provides a natural damping mechanism and will be sufficient in most cases except for the injection transient
- In proton and ion machines the injection oscillations will last, resulting in emittance blow-up due to filamentation. The bunch lengthening caused by the RF noise may lead to beam loss when particles reach the separatrix (major concern in colliders where beams are kept colliding for 10 hours).

 Let us first consider the synchrotron oscillation in presence of a small dw<sub>RF</sub> modulation of the RF frequency. The kinematic relation for the RF phase at cavity crossing time becomes

$$\frac{d\widetilde{\phi}}{dt} = -2\pi h \Delta f_{rev} + \delta \omega_{RF}$$

The first term is the effect of the momentum error and the second term is the cavity RF frequency modulation.

 Following the derivation of the previous section, the linearised synchrotron oscillation equation becomes

$$\frac{d^{2}\widetilde{\phi}}{dt^{2}} + \Omega_{s}^{2} \quad \widetilde{\phi} = \frac{d\,\delta\omega_{RF}}{dt}$$

# Phase Loop

- We measure the phase error between Cavity Sum and the Beam (Longitudinal PU) averaged over all bunches
- This error is used to correct the RF frequency via the Phase Loop amplifier. The simplest regulation is proportional only.
- We have

$$\delta \omega_{RF} = -k_{\varphi} \langle \tilde{\phi} \rangle$$

and the differential equation becomes

$$\frac{d^{2}\langle \widetilde{\phi} \rangle}{dt^{2}} + k_{\varphi} \frac{d\langle \widetilde{\phi} \rangle}{dt} + \Omega_{s}^{2} \langle \widetilde{\phi} \rangle = 0$$

the synchrotron frequency is not changed but we have introduced the desired damping term



The phase loop effect is similar to radiation damping but...it acts on the average phase error only

#### T. Mastoridis

#### Damping of injection transient:

- The phase loop must be fast compared to the synchrotron period to avoid filamentation
- It damps the average phase oscillation of the bunch. This is called dipole mode as the bunch moves back and forth in the bucket without shape change
- It is very effective on injection phase and energy errors





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Sept 12, 2008. First capture of LHC ring 2 beam with Phase Loop ON. Left: Phase error. Rigth: Mountain range dislay. Notice the rapid damping of the injection phase error and the lasting quadrupole oscillations caused by voltage mismatch (see next slides). Courtesy of T. Bohl

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#### Preventing emittance blow-up:

- In colliders phase noise is much more damaging than amplitude noise because the beam sits at stable phase 0 or 180 degree
- Beams must be kept colliding for > 10 hours. So effects of noise is critical
- The Phase Loop was essential in the SPS proton-antiproton collider and it is essential in the LHC



LHC single bunch at 3.5 TeV 1E10 p. Evolution of bunch length with time as a function of the Phase Loop gain. Fixed 8 MV RF (T. Mastorides, P. Baudrenghien, May 2010). LHC BQM system.

- But how can this work?
  - The Phase loop measures the bunch average only and there is no coherent dipole oscillation in bunch lengthening...
  - The explanation is that the phase loop reduces the phase noise in the cavity sum signal in the synchrotron band. In this band, the beam gives a coherent response that is measured by the loop and damped via the modulation of the VCXO
  - Outside the synchrotron band the phase loop does nothing...except inject noise in the cavity, as there is no response from the beam
  - Note that it acts on the first synchrotron band only



PSD of the phase noise in dBc/Hz in a LHC cavity with circulating 3.5 TeV bunch, for various phase loop gains (in s<sup>-1</sup>), 1.66 MV. The synchrotron frequency is ~ 24 Hz

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Reciprocity: Phase noise with narrowband spectrum at the Synchrotron Frequency of the core of the bunch, can be injected for controlled emittance blow-up



LHC single bunch at 450 GeV 2E10 p. Evolution of bunch length during emittance blow-up with a 0.6 deg rms phase noise covering the 36-42Hz band (42 Hz = W<sub>s0</sub>). The bunch length grows quickly from 1.1 to 1.4 ns then settles (June 7, 2010. E. Chapochnikova, J. Tuckmantel, G. Papotti, A. Butterworth, M.E. Angoletta, P. Baudrenghien)

# ... and now a bit of discipline

- Motivation: In the phase loop, the beam is the Master. The RF will do its best to please it. If there is an energy error at injection, the RF will change its frequency. If there is noise in the cavity in the delicate synchrotron band the RF will be modulated to minimize this noise. That will preserve emittance but... it is not a stand-alone solution because:
  - If there are several injections, the RF must be restored to an injection frequency after transient to prepare for the next injection
  - When we start ramping, the RF must track the B field to keep the beam centered
  - If we transfer to another machine, the RF must be synchronized to the buckets of the receiving machine
  - There is no mechanism to keep the beam centred
- Solution: we will add a slower loop that will "discipline" the beam. It will be gentle enough so that it does not perturb the all-important phase loop. Gentle means adiabatic = "slow compared to the synchrotron period".
- Several options. Two big classics:
  - Radial Loop: We slowly adjust the RF to keep beam centered as measured in one or several PUs
  - Synchro Loop with frequency program reference: We keep the RF softly locked onto a Synthesizer whose frequency tracks the B field to keep the beam centered

# 2.3 Radial Loop

- We measure the radial position error average
- This error is used to correct the RF frequency via the Radial Loop amplifier. The simplest regulation is proportional only.
- We have

$$\delta\omega_{RF} = -k_{\varphi} \left\langle \widetilde{\phi} \right\rangle - k_{R} \,\delta R$$

 At constant B, the radial position error is proportional to a momentum error

$$\frac{\delta R}{R} = \frac{1}{\gamma_t^2} \frac{\left< \Delta p \right>}{p}$$

We have

$$\delta\omega_{RF} = -k_{\varphi} \left\langle \widetilde{\phi} \right\rangle - k_{R} \frac{R}{\gamma_{t}^{2} p_{s}} \left\langle \Delta p \right\rangle$$

and the differential equation becomes

$$\frac{d^2 \langle \widetilde{\phi} \rangle}{dt^2} + k_{\phi} \frac{d \langle \widetilde{\phi} \rangle}{dt} + \left( \Omega_s^2 + k_R \frac{q V \cos \phi_s}{2\pi p_s \gamma_t^2} \right) \langle \widetilde{\phi} \rangle = 0$$



A classic combination for proton and ion synchrotrons: Phase loop and Radial loop

$$\frac{d^{2}\langle \widetilde{\phi} \rangle}{dt^{2}} + k_{\varphi} \frac{d\langle \widetilde{\phi} \rangle}{dt} + \left(\Omega_{s}^{2} + k_{R} \frac{qV\cos\phi_{s}}{2\pi p_{s}\gamma_{t}^{2}}\right) \langle \widetilde{\phi} \rangle = 0$$

- The radial loop does not provide damping. It only increases the frequency of oscillation
- The sign of the gain must be changed at transition because cos f<sub>s</sub> changes sign there. It is the preferred loop for crossing transition
- Recall that, at constant B we have

$$\frac{\Delta f}{f} = \left(\frac{\gamma_t^2}{\gamma^2} - 1\right) \frac{\Delta R}{R}$$

the radial loop amplifier must have positive gain below transition and negative gain above

- It reduces the effect of frequency errors on the radial position
- Its gain must be small enough that its effects on the beam remain adiabatic
- Limits: It couples the two planes using transverse measurements to estimate momentum and correct the frequency. This causes problems:
  - Betatron oscillations interpreted as momentum error. Can be minimized by using two pick-ups at 180 degrees in betatron phase
  - Typically looks at one or few PUs only -> centers the beam in one location only instead of the average orbit
  - Position measurements are more noisy and more sensitive to intensity than frequency measurements

# 2.4 Synchro Loop

- We measure the phase of the RF (or beam) and compare it to a reference generator
- This error is used to correct the RF . frequency via the Synchro Loop amplifier
- The reference generator will be set at . the injection frequency during filling, then follow the frequency program during ramping and finally be locked to the receiving machine if needed for transfer
- The overall system is described by a third order differential equation. Its analysis is easier if we use Laplace Transforms
- First the beam transfer function . (undamped resonator at  $W_{c}$ )

$$\widetilde{\phi}(s) = \frac{s}{s^2 + \Omega_s^2} \,\delta\omega_{RF}(s) = B_{\phi}(s)$$



Another classic combination for proton and ion synchrotrons: Phase loop and Synchro loop



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### Beam Based Loops



### Cavity Based Loops

- Power Amplifier limits and cure
- Beam Loading
- Coupled-bunch longitudinal instabilities
- Beam loading and coupled-bunch instabilities cure



### Design Example

# A simplistic RF system (Synchrotron or Linac)

**Cavity Field Loops** 

- Simplest system: A cavity driven by a power amplifier whose drive is amplitude modulated and whose frequency comes from a synthesizer (fixed for Linacs, ramped for Synchrotron)
- What will go wrong:
  - The TX will inject amplitude and phase noise that will blow-up the emittance
  - The TX gain and phase shift will drift resulting in poor control of the cavity field
  - The cavity tune will drift resulting in field amplitude and phase change
  - Same effect when the cavity will vibrate with water cooling (Cu) or He pressure (SC)
  - The beam current will modify the cavity field
  - The beam can become unstable above some current threshold



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### Beam Based Loops



### Cavity Based Loops

### Power Amplifier limits and cure

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### Cavity Resonance Loops

Design Example

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# 4. Power amplifier limits

Tetrode, klystrons and IOTs are usually operated close to saturation for good efficiency. This makes them very nonlinear. Their parameters are also very sensitive to fluctuations in the HV. In addition they are noisy.



- When the TX saturates we observe
  - AM-AM distortion: gain drops with drive level
  - AM-PM distortion: the delay (negative phase shift) increases with drive level
  - If overdriven a klystron will have a negative differential gain
- A tetrode will also be non-linear at very low drive
- Large sensitivity to HV. For the LHC klystrons we have 8.4 degree @ 400.8 MHz per percent HV drift @ 50 kV.
  - In pulsed Linacs the HV will droop during the pulse
  - In both CW and pulsed, the HV will have ripples from rectifiers or switching

Klystron Power Sweep



LHC 330 kW klystron. Group delay 130 ns @ 400.8 MHz. ~50 kV, 10A DC





The modulator control keeps overall gain and phase shift constant 

- Correction BW depends on the overall loop delay. That includes waveguides/cables (layout) . and TX/circulator group delays (BW)
- The TX Polar Loop will be an inner loop inside the RF feedback (see later). Time constants must be optimized.
- Intended at PEPII but not implemented (P. Corredoura). This Klystron Polar Loop is operational on the LHC CW klystrons (the loop controller is a simple integrator). It will be implemented on the Linac4 pulsed klystrons as well
- Note that the HV ripples create multiplicative noise. This changes the klystron beam b and thereby acts on RF phase shift (and gain). A polar loop is therefore more appropriate a non-lation than an addition foodbool laan

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# Performances in static conditions (LHC)

# Pout vs DC parameters (HV and Icath)

HV or Icath	Pg Loop Open	Pg Loop Closed
Icath = 6.4 A		
HV=51.5 kV	123 kW	109 kW
HV=46.4 kV	117 kW	109 kW
HV=41.3 kV	102 kW	109 kW
HV=50 kV		
Icath=4.4 A	44 kW	109 kW
Icath=5.1 A	67 kW	109 kW
Icath=5.8 A	94 kW	109 kW
Icath=6.3 A	126 kW	109 kW

# Pout vs DC parameter (HV)

нv	Phase Shift @ 400.8 MHz	Phase Shift @ 400.8 MHz
Icath = 6.4 A	Loop Open	Loop Closed
HV=52.9 kV	34 degrees	-0.2 degrees
HV=51.9 kV	17.4 degrees	0.0 degrees
HV=50.9 kV	0 degrees	0.0 degrees
HV=47.8 kV	-74.4 degrees	0.0 degrees

Left: Keep modulator input constant, observe klystron output power @ 400 MHz when varying HV or Cathode current Right: Keep modulator input constant, measure klystron phase shift @ 400 MHz when varying HV



Left: Loop open. Phase noise Ig-Ref: Mainly 100 Hz and 600 Hz due to HV ripples. Calib 10 mV/dg @ 400 MHz. ~3.5 dg pkpk (10 mV/div, 5 ms /div) Rigth: Loop closed. Red trace = phase noise Ig-Ref. Calib 10 mV/dg @ 400 MHz. ~0.2 dg pkpk (2 mV/div, 5 ms /div). Blue trace = phase compensation.



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### Beam Based Loops



### Cavity Based Loops

- Power Amplifier limits and cure
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### Cavity Resonance Loops

Design Example
The beam current induces a voltage when crossing the cavity. To keep accelerating voltage constant, that calls for adapting the generator output

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### Mechanism

- Beam= charged particles in motion = current
- Cavity=resonant impedance
- Beam Crossing the cavity -> Beam induced electro-magnetic wave called wakefield
- The total voltage seen by the beam is the vector sum of the voltage due to the generator and the beam loading

$$V_t = V_{RF} + V_b = Z_{RF} I_g + Z_b I_b$$

 For high intensity machines the beam loading can be greater than the RF voltage



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$$V_t = V_{RF} + V_b = Z_{RF} I_g + Z_b I_b$$

#### Consequences:

 In stationary conditions, V<sub>RF</sub> must compensate V<sub>b</sub>, to keep V<sub>t</sub> at the desired value. This calls for extra RF power

#### In transient situations the voltage V<sub>t</sub> will vary. Transient Beam Loading:

- At injection it must settle to the stationary value in a time short compared to the synchrotron period to avoid mismatch, filamentation and emittance blow-up
- If the beam contains holes (beam dump hole for example), V<sub>t</sub> will vary along the batch and the stable phase and bucket area will not be correct for the bunches in the head of the batch

#### It may make the LL Loops go unstable.

In the 70s the PSB LLRF consisted of the classic combination of cavity amplitude and phase loops plus tuning loop. These early LLRF systems were much inspired by AM and FM demodulation. Perfect at low beam current, as the cavity voltage is then predominantly determined by the generator, the system showed its limits when the beam induced voltage became comparable to the total cavity voltage. In this situation a variation of the amplitude of generator current also modifies the phase of the cavity voltage. The loops become coupled and go unstable. Note that this is not a beam instability but an instability of the LLRF loops. Pedersen gave a full analysis [Pedersen]. The PSB LLRF is still based on amplitude/phase/tuning loops but the impact of Beam Loading has been reduced using RF feedback and 1-T feedback (see below). In modern high current machines I/Q Demodulation is now used instead of amplitude and phase loops.

[Pedersen] F. Pedersen, Beam Loading effects in the CERN PS Booster, IEEE Transaction on Nuclear Sciences, NS22,

# Example: The SPS at injection

**Cavity Field Loops** 

Beam loss due to uncompensated transient beam loading in the CERN SPS. The beam consists of one batch of 81 bunches (0.5E11/bunch) filling 2 ms out of the 23ms period. The cavity filling time is 800 ns. Each trace shows the envelope of the bunch intensity along the batch. The bottom trace is the first turn. Traces are separated by 200 turns. The capture voltage is 550 kV, similar to the beam induced voltage. The cavity response to the beam current step distorts the buckets resulting in loss at some locations along the batch



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#### Spectrum of the Beam Induced Voltage

**Cavity Field Loops** 

#### in a Synchrotron

In a circular machine, stable, uniformly filled, the spectrum of the beam current would be a series of lines at multiples of the RF frequency. Only the fundamental at the RF frequency couples to the cavity  $\rightarrow$  a single line at  $f_{RF}$ 

$$i_b(t) = I_0 \cos(2\pi f_{RF} t)$$

 Most machines are not uniformly filled. The beam current spectrum will be the spectrum of the beam envelope, sampled at the revolution frequency and its harmonic, and shifted at f<sub>RF</sub>



Spectrum of the beam current with a batch that covers only  $\frac{1}{4}$  of the ring. The rectangular envelope has a sinx/ x spectrum that is sampled by the Frev lines

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$$i_b(t) = I_0 \cos(2\pi f_{RF} t) [a_0 + a_1 \cos(2\pi f_{rev} t) + a_2 \cos(4\pi f_{rev} t) + \dots]$$

 Compensation of beam loading is therefore only needed around the frequencies

 $f = f_{RF} \pm \eta f_{rev}$ Revolution frequency
line index

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#### Cavity Resonance Loops

Design Example

### 6. Longitudinal Instabilities in Synchrotron

Above a certain current threshold, the bunch(es) start developing oscillations in the bucket(s). These can be rigid oscillations (dipole mode), or shape oscillations (quadrupole mode and higher). If not damped these oscillations cause emittance blow-up through filamentation and finally loss when the bucket is full

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## 6.1 Mechanism $I_b \rightarrow V_b \rightarrow I_b \text{ loop}$

- If the wakefield created by the passage of the bunch in the cavity has not decayed to zero by the next passage, it will act back on the bunch
- If the gain/phase shift of this natural beam/ cavity feedback is unfavorable, instability will arise: The bunch starts a oscillating in the bucket
- The situation gets worse if we have many bunches in the machine. The wakefield created by one bunch will act on the following one when it crosses the cavity, thereby creating coupling between the synchrotron oscillations of the individual bunches
- This effect, very important in high intensity synchrotrons, can lead to coupled-bunch longitudinal instability



Dipole mode. MR of the e+ bunch in the SPS. Horiz 10 ns. 10 turns between traces. Instability grows to 3 ns max, then is damped by radiation damping as energy increases.

The beam current is the sum of the motion of all particles present in the accelerator. The coupled-bunch instability is a Collective effects: All particles in a bunch start oscillating coherently or even successive bunches start oscillating with a fixed pattern. It will be enhanced if all particles have the exact same

**Cavity Field Loops** 

### Spectrum of Oscillating Beam

In the previous section we have derived, the beam current for a stable non-uniformly filled machine

$$i_b(t) = I_0 \cos(2\pi f_{RF} t) [a_0 + a_1 \cos(2\pi f_{rev} t) + a_2 \cos(4\pi f_{rev} t) + \dots]$$

When the bunches start oscillating in dipole mode at  $f_{s_1}$  their time of passage in the cavity is modulated at that frequency: phase modulation. The current becomes

 $i_{b}(t) = I_{0} \cos(2\pi f_{PE} t) [a_{0} + a_{1} \cos(2\pi f_{PE} t + \varepsilon \sin(2\pi f_{e} t)) + a_{2} \cos(4\pi f_{PE} t + \varepsilon \sin(2\pi f_{e} t)) + \dots]$ 

- In the frequency domain the phase modulation will appear as  $+-f_s$  side-bands around . each revolution frequency line
- Finally, considering also higher modes of oscillation: guadrupole at twice the synchrotron frequency, sextupole...each revolution frequency harmonic is surrounded by a series of synchrotron sidebands. The spectrum contains lines at

$$f = f_{RF} \pm n f_{rev} \pm m f_s$$
Revolution frequency
line index
Mode index: m=1 is
dipole, m=2 is
quadrupole

Conclusion: To prevent coupled-bunch instability the cavity impedance must be reduced on the synchrotron sidebands of the revolution frequency lines

line

### Modes and growth rates

- We will consider a machine with M uniformly spaced bunches, undergoing a small oscillation in dipole mode only (m=1)
- Let us take a picture of the bunches at instant t, and observe the phase error f<sub>k</sub>(t) of bunch k
- If all bunches oscillate in phase, we get

$$\phi_k^{(0)}(t) = \sin\left(2\pi f_s t\right)$$

**Cavity Field Loops** 

and the beam induced voltage shows  $f_s$  sidebands around  $f_{RF}$ . This is the (only) mode that the Phase Loop (lecture 1) damps

For a phase advance of 2p/M between successive bunches, we get

$$\phi_k^{(1)}(t) = \sin\left(2\pi f_s t + 2\pi k \frac{1}{M}\right)$$

and the beam induced voltage shows  $f_s$  sidebands around  $f_{RF}$ +-  $f_{rev}$ 

Generalizing, for a phase advance of 2pp/M between successive bunches, we get

$$\phi_k^{(p)}(t) = \sin\left(2\pi f_s t + 2\pi k \frac{p}{M}\right)$$

corresponding to the  $f_s$  sidebands around  $f_{RF}$ +-  $p.f_{rev}$ 

With M uniformly spaced bunches, we have M eigenmodes of dipole oscillation. Any pattern can be reproduced as a linear combination of these eigenmodes. The advantage of this decomposition is that it is easy to compute a growth rate for each eigenmode





### 6.2 Threshold. Electron machines

- Electron synchrotron are very relativistic. Due to radiation damping the bunches are very short and the dominant bunch mode is dipole (m=0)
- If the impedance of the machine elements is known, (and that is normally the case for the resonant structures - RF cavities, kickers - and the vacuum chamber), one can compute the growth rates for all M dipole modes
- For example if the dominant impedance is the cavity impedance around the fundamental, the growth rate of p<sup>th</sup> mode is approximated

$$\frac{1}{\tau^{(p)}} \approx -\frac{\Omega_s I}{2V \cos \phi_s} \begin{cases} \operatorname{Re} \left[ Z_{eff} \left( 2\pi f_{RF} + 2\pi p f_{rev} + \Omega_s \right) \right] \\ -\operatorname{Re} \left[ Z_{eff} \left( 2\pi f_{RF} - 2\pi p f_{rev} - \Omega_s \right) \right] \end{cases}$$

The beam will be stable if there is no growth rate faster than the radiation damping time (below 5 ms in LEP at 104.5 GeV/beam)



PEP II, SLAC. Shown are growth rates for various dipole modes of the PEPTT e+e- collider The -3 mode has growth time ~600 ms. The PEPII radiation damping time is 19 ms (HER) and 30 ms (LER). The Longitudinal Damper provided the needed extra damping (~150 ms time). Courtesy of T. Mastorides.

### 6.3 Threshold. Proton machines,

**Cavity Field Loops** 

- There is virtually no radiation damping (24 hours damping time in the LHC at 7 TeV) because g is too low
- Bunches are long and we can observe high order bunch modes (quadrupole, sextupole,...)
- The only natural damping is the Landau damping due to the energy and synchrotron frequency spread: The particles in the bunches do not all oscillate coherently, thereby reducing the collective effect
- For a given beam current, one can compute a threshold on the maximum cavity impedance, valid on all f<sub>rev</sub> sidebands [Shaposhnikova]

$$R_{\max} \propto |\eta| \frac{E}{I_b} \left(\frac{\Delta E}{E}\right)^2 \frac{\Delta \Omega_s}{\Omega_s}$$

- Observations:
  - □ *R<sub>max</sub>* decreases with energy. In an acceleration cycle, instabilities are first appearing at top energy
  - *R<sub>max</sub>* increases with the relative synchrotron tune spread DW<sub>s</sub>/W<sub>s</sub>. The relative Energy spread is also stabilizing. Large and almost full buckets are more stable. But caution with loss...



Narrow-band impedance threshold Rsh (solid line) during the LHC acceleration ramp Reproduced from [Shaposhnikova]



Synchrotron Tune vs. pk deviation (Lecture 1)

[Shaposhnikova] E. Shaposhnikova, Longitudinal beam parameters during acceleration in the LHC, LHC project Note 242, Dec 8, 2000

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#### Beam Based Loops



#### Cavity Based Loops

- Power Amplifier limits and cure
- Beam Loading
- Coupled-bunch longitudinal instabilities
- Beam loading and coupled-bunch instabilities cure

#### Cavity Resonance Loops

#### Design Example

- "... with feedback it is possible to reduce the distortion generated by the amplifier, to make the amplification substantially independent of the electrode voltage and tube constants, and to reduce greatly the phase and frequency distortion" F. Terman.
- Feedback reduces the effects of beam loading by reducing the effective cavity impedance. It reduces the effect of other noise sources as well (TX ripples, tune variations, microphonics) and it improves precision by making the RF voltage independent of amplifiers non-linearity, gain and phase drifts
- It is the preferred method wherever feasible

Works on all sources of perturbations Works for Synchrotrons and Linacs

Cavity Resonance Loops

- Principle: Measure the accelerating voltage in the cavity, compare it to the desired voltage and use the error to regulate the drive of the power amplifier
- It is a real RF feedback, not an amplitude and phase loop
- but it can be implemented using I/Q Demodulators





 A SWC near resonance can be represented as an RLC circuit

$$Z(\omega) = \frac{R}{1 + j \, 2Q \frac{\Delta \omega}{\omega_0}}$$

$$\Delta \omega = \omega - \omega_0$$

With the feedback loop, the beam loading voltage is

$$V_t(\omega) = \frac{Z(\omega)}{1 + GAe^{-iT\Delta\omega}Z(\omega)} I_b(\omega)$$

 A large gain G.A means good impedance reduction. Stability in presence of the delay T will put a limit. Outside its bandwidth the cavity is purely reactive and its impedance can be approximated

$$Z(\omega) \approx \frac{R}{j \, 2Q \frac{\Delta \omega}{\omega_0}}$$



RF or Direct Feedback

 To keep a 45 degrees phase margin the open-loop gain must have decreased to 1 when the delay has added an extra -45 degrees phase shift, that is at Dw=p/(4T)



- The final performances depend on Loop delay T and cavity geometry R/Q. It does not depend on the actual Q
- Lesson: Keep delay short and TX broadband to avoid group delay

#### Advantages:

- Relatively insensitive to small drifts in amplifier gain and phase
- Broadband impedance reduction achievable if the total loop delay T is small -> Place the amplifier next to the cavity
- Easy for a single-cell cavity

#### Limitations:

- Can be complex for multicell cavities. Cluster of resonances with different phase shifts
- Gain limited by the loop delay T
- Caution:
  - We have considered the TX response as a linear gain G. Not very realistic...
  - TX non-linearity will degrade the performances of the feedback. Best is to simulate using a TX model including saturation
  - For regulation we need extra TX power. Rule of thumb: TX must not be operated above ~70% power saturation level (SNS 76%, JPARC 66%, Linac4 76%)
- One TX feeding several independent cavities:
  - The RF feedback can only regulate the voltage sum. We loose much freedom
  - Power to individual cavities can be adjusted with Power I/Q Modulator, but we now have regulation at the MW level, instead of mW...Reduced regulation BW
  - The decision of splitting klystron power must consider field stabilization issues. Simulations needed

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Loop delay 650 ns, R/Q=45 ohm.

The LHC cavities are equipped with movable couplers and  $Q_L$  can be varied from 10000 to 100000. But, with feedback,  $Q_{aff} \sim 600$  in all positions.

### 7.2 The 1-Turn Feedback

### or Long-Delay feedback or Comb-Feedback To reduce the effective cavity impedance,

**Cavity Field Loops** 

- the RF feedback is the best solution. But it is not applicable if the loop delay is long
- The SPS was designed in the 70's as a 300 GeV proton accelerator. When increasing beam current in the early 80's, the impedance of the cavities at the fundamental appeared as a limit. Their amplifiers were located on the surface, far away from the tunnel. With this 2.6 ms loop delay, the RF feedback would only cover the first two revolution sidebands ( $f_{rev}$ =43 kHz)
- In 1985 D. Boussard implemented the first 1-Turn Delay Feedback on that machine [Boussard]

Good for beam loading and instabilities (if cavity impedance at fundamental is the source)



SPS Traveling Wave Cavity in the SPS tunnel, Backward Wave Structure, 90 degrees phase advance/cell, 200.22 MHz centre freq

[Boussard] D. Boussard. Control of cavities with high Beam Loading, PAC1985, Vancouver, May 1985

### 1-T Feedback. Why?

- For transient beam loading compensation and prevention of instabilities we only need to damp the cavity impedance on (transient beam loading) or around (long. Instabilities) the revolution frequency sidebands
- Idea:
  - Provide large open-loop gain and 0 degree phase shift on the revolution frequency sidebands
  - Reduce gain between sidebands so that wrong (180 degree) open-loop phase shift does not lead to loop instability



Trivial: simple IIR filter plus 1-T delay

$$H_{comb}(z) = G \frac{1-a}{1-az^{-M}} z^{-M}$$
  
with  $f_{ck} = M \cdot f_{rov}$ 

- Two parameters to be chosen: openloop gain G and geometric ratio a
- a fixes the bandwidth -> related to the synchrotron frequency (dipole) or its harmonics

$$\Delta f_{-3dB} = \frac{1}{2\pi} (1-a) f_{rev} > f_s$$

 a governs the decay of the transient at injection



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- G is limited by stability considerations:
  - Halfway between peaks the phase shift is 180 degrees
  - And the gain must be below 1/3 to respect the canonical 10 dB gain margin
  - Thus:

$$G\frac{(1-a)}{2} < \frac{1}{3}$$

- In the SPS:
  - G= 10, a = 15/16 thus G(1-a)/2 = 10/32 < 1/3
  - -3 dB BW = 428 Hz (single-sided)
  - Synchrotron frequency between 100 Hz and 400 Hz for LHC beam (but as high as 1 kHz for FT)
- In the LHC:
  - $f_s/f_{rev} < 5 \ 10^{-3}$  and we use a= 15/16 and G=10

**Cavity Field Loops** 

We have not considered the cavity response in the derivation. If narrow-band it will modify the openloop response (+- 90 degrees phase shift) and the 1-T fdbk cannot extend much beyond the cavity BW

- Solution: Flatten the cavity • response with an RF feedback, then increase the gain on the revolution frequency lines with the 1-T feedback
- Caution: TX linearity will limit the performances. In PEPII cavity impedance reduction was actually limited by the TX driver nonlinearity. Measure, model and simulate



Combined RF feedback and 1-T feedback

### Example: The LHC



Effective Cavity Impedance with RF feedback alone (smooth trace) and with the addition of the 1-T feedback (comb). The cavity centre frequency is 400.789 MHz. We look at a band offset by +200 kHz to +300 kHz. Frev= 11 KHz. The 1-T feedback provides ~ 20 dB additional impedance reduction on the Frev lines.

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- 7.3 1-T Feedforward
- Idea: Measure the beam current I<sub>b</sub> with a pickup and feed it back via the generator to compensate for the beam loading
- Recall that

$$V_t = V_{RF} + V_b = Z_{RF} I_g + Z_b I_b$$

so we want the generator to produce a current  $I_{a,comp}$  such that

$$Z_{RF} I_{g,comp} = -Z_b I_b$$

- For a SWC, Z<sub>RF</sub> and Z<sub>b</sub> are proportional. It is thus very easy to implement
- A 1-T delay must be inserted in the feed-forward path. As the synchrotron frequency is much smaller than the revolution frequency, the PU signal does not change significantly between successive turns

Fair for beam loading and instabilities (if cavity impedance at fundamental is the source) Works for Synchrotrons only



Limitations:

- Sensitive to drifts in TX gain and phase
- Difficult to set-up for a varying RF frequency. The fixed PU to cavity delay must be compensated continuously as the revolution period changes to keep the overall delay equal to exactly one turn

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### 7.4 Adaptive Feedforward (AFF)

**Cavity Field Loops** 

- The RF feedback will take some time to react to a transient, this time being at the minimum the Loop Delay (see above)
- In pulsed Linacs, the beam loading compensation at the head of the batch will not be very good because the first injected bunches will induce a voltage that will be compensated after the Loop Delay only
- As this effect is clearly reproducible from pulse to pulse, a Feed-forward compensation will help
- Other repetitive sources of perturbation can also be corrected with the feed-forward
- These repetitive sources of perturbation will slowly change from pulse to pulse. Adaptive Feedforward (AFF) aims at tracking these changes to best anticipate the correction on the next pulse



Good for all repetitive disturbances, including beam loading, TX ripples, source current fluctuations, and Lorentz force detuning. Developed and in operation in pulsed Linacs (SNS and FLASH)

#### SNS Feed-forward compensation

Beam-Loading compensation



At the SNS, the switching of the HV modulators is synchronized with the rep rate. So the klystron ripples are also repetitive from pulse to pulse and corrected by the Feed-Forward



The Lorentz force detuning is also synchronous with the rep rate and can be compensated by the AFF

NOTE: Detuning implies more power for a given field. In the SNS the power margin is sufficient to cope with it.



2 kHz resonance in medium beta cavities





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 Fast piezzo tuners were installed at the SNS start-up but are NOT used anymore. The ~1 kHz detuning can be dealt with by the RF feedback and AFF and... the klystron power margin...

Above plots and info from Sang-Ho Kim, SNS, ORNL

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To my knowledge, AFF is presently operational at Flash (Free Electron Laser), Desy and at SNS, with the help of Desy For scientific publications on the subject query on keywords: "Stephan Simrock" and "Adaptive Feed-Forward"

### 7.5 Longitudinal damper (dipole mode)

- For each bunch, we measure its phase with respect to the RF, and generate a momentum kick at the correct time (act on the same bunch), that is 90 degrees phase shifted with respect to the phase measurement to produce damping
- Let  $f_k(t)$  be the phase of the RF when the  $k^{th}$  bunch crosses the cavity. We have  $\widetilde{\phi}(t) = \phi(t) - \phi$

$$\phi_k(t) = \phi_k(t) - \phi_s$$

 We rewrite the synchrotron oscillation with the momentum kick Dp<sub>k</sub>(t) as driving term

$$\frac{d^2 \,\widetilde{\phi_k}}{d \,t^2} + \Omega_s^2 \,\widetilde{\phi_k} = -2\pi \frac{\eta \, h \, f_{rev}^2}{p_s} \,\Delta p_k$$

 To get damping we now make the momentum kick proportional to the derivative of the phase error Idea: mimic e-machines radiation damping but...only bunch per bunch



And the equation becomes

$$\frac{d^2 \widetilde{\phi_k}}{dt^2} + 2 \alpha_1 \frac{d \widetilde{\phi_k}}{dt} + \Omega_s^2 \widetilde{\phi_k} = 0$$

The damping time constant is  $\tau_{I} = \frac{1}{\alpha_{I}}$ 

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- The Feedback filter
  - We first derive the filter H(z) with sampling clock  $F_{rev}$
  - □ It must provide ~90 degrees phase shift at the synchrotron frequency for damping
  - It must have gain around the synchrotron frequency (BPF characteristic)
  - It must have zero gain at DC so that the damper does not attempt to reduce the static bunch phase
  - Designs from J. Fox (SLAC) for PEPII, DaFne, ALS were implemented using a bank of DSPs, each processing a few bunches.
- Nowadays, series processing in an FPGA is preferred
  - □ For *M* bunches, we sample at *F*<sub>ck</sub>=*M F*<sub>rev</sub>
  - And we process the data stream with filter  $H(z^M)$
  - Then we must add a delay z<sup>-p</sup> so that measurement and kick correspond to the same bunch
- Remark
  - Large BW required for the acquisition and the power amplifier. The phase of each bunch is sampled independently
  - The synchrotron frequency is much smaller than the revolution frequency (respectively 60Hz and 11 kHz in the LHC at injection). For a given bunch the momentum kick need not be re-computed at each turn. Decimation/interpolation possible

Good for injection transients and dipole instabilities no matter what the source... Works

- Variant. Poor man's damper (LHC, PEPII woofer)
  - In the absence of a broadband kicker we can act via the RF cavities
  - Dp is generated by adding to the cavity voltage, a small correction in quadrature with the accelerating voltage (phase modulation)
  - The BW is limited to the Cavity Field control BW
  - Used in the LHC for damping injection phase/energy error in multi-batch injection mode. Not needed for stability (Landau damping sufficient)
  - Needed in PEPII for stability



LHC filling: It takes 12 injections from the SPS. The transients will be damped
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#### Cavity Based Loops

- Power Amplifier limits and cure
- Beam Loading
- Coupled-bunch longitudinal instabilities
- Beam loading and coupled-bunch instabilities cure

#### Cavity Resonance Loops

#### Design Example

# Lorenz Force Detuning

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Cavity Deformation by Electromagnetic Field Pressure

· Radiation pressure

$$P = \frac{\left(\mu_0 \left| \vec{H} \right|^2 - \varepsilon_0 \left| \vec{E} \right|^2\right)}{4}$$

· Resonance frequency shift

$$\Delta f = -K \cdot E_{acc}^2$$



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## Lorenz Force Detuning

- Effects of Lorenz force detuning
  - Change cavity voltage and phase during RF pulse
  - Generate more reflection power
  - Limit maximum repetition rate of RF pulses
- Properties
  - Gradient dependent
  - Predictable from pulse to pulse
  - Perturbations are correlated from cavity to cavity

### Measurement of Lorentz Force Detuning



# **Microphonics**

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 Mechanical vibrations caused by the accelerator environment are always present and may be transferred to the cavity.



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### **Microphonics**

- Effects of microphonics
  - It mainly influences the resonance frequency of the cavity and therefore the RF phase with respect to the beam
- Properties
  - Slow perturbation
  - Not predictable
  - Uncorrelated along the Linac

## **Cavity Frequency Tuner**

- Motor tuner (slow), used to
  - Large range frequency tuning, such as by-pass ( $\Delta \omega > 10$  times of bandwidth) the cavity or set the pre-detuning
  - Can not be tuned frequently because the motor lifetime
- Piezo tuner (fast), used to
  - Fine tuning of the cavity
  - Lorenz force detuning or microphonics compensation

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## Motor Tuner

The **Motor tuner** is used to tune the cavity resonance frequency by deforming the whole cavity along the axis. It uses a stepper motor and is considered as a slow control (compared with the piezo tuner).



## **Piezo Tuner**



## Control of Cavity Detuning

- Lorenz force detuning control
  - Feed forward control is suitable
    - Coupling of Lorenz force and piezo actuator to cavity detuning must be similar
    - Slow parameter changes can be corrected with adaptive feed forward
- Microphonics control
  - Feedback control
    - Transfer function from piezo actuator to detuning must allow controller design which allows stability of closed loop
    - Transfer function must be stable for timescale of adaptation of controller
  - Adaptive feed forward control
    - · Noise cancellation with adaptive filters

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#### Cavity Based Loops

- Power Amplifier limits and cure
- Beam Loading
- Coupled-bunch longitudinal instabilities
- Beam loading and coupled-bunch instabilities cure

#### Cavity Resonance Loops

#### Design Example

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- 160 MeV H<sup>-</sup> Pulsed Linac
- PSB injector
- 40 mA average current (nominal)
- Normal Conducting cavities, 352.2 MHz operation
- ~ 1 MW/cavity (except DTL2 and DTL3 ~ 2 MW/cavity) with 40 mA
- 2 Hz rep rate
- Commissioning in 2013. Injection in PSB in 2015
- Proposed LLRF is much inspired from SNS

20-30% klystron power margin for regulation

### Cavity Controller Functionalities

For each cavity:

- A Tuner Loop to keep the structure on resonance
- An RF Feedback, and an Adaptive Feedforward (AFF) to keep the accelerating voltage at the desired value in the presence of beam transient
- A Klystron Polar Loop to compensate the variation of klystron gain and phase shift caused by High Voltage (HV) supply fluctuations and droop
- A Conditioning System monitoring the Cavity Vacuum while feeding the Line with Frequency Modulated bursts of RF power of increasing amplitude
- A Klystron Drive Limiter that prevents from driving the klystron over the saturation limit during loop transients.

# Architecture

T. Mastoridis

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## Klystron Loop

- Klystron HV pulse
  - Flat-top 1.2 ms
  - Precision 1%
  - Ripple 0.1 %
- LEP klystron:
  - 1 % HV -> 8.4 degree phase shift @ RF
- Linac4 Klystron loop:
  - Expect < 50 ms risetime</p>





3 MeV Test \$tand. RF Off. Pulsing the P.S: 100 kV/23 A at 2 Hz rate. Zoom at flat-top: Ch1 - Cathode voltage (2kV/div); Ch2 - Cathode current (0.8A/div); Ch3 - Anode voltage to ground (1 kV/div).

- Improved PS understudy
  - □ Reduced ripples...but at higher frequency
  - Simulations must tell whether it is desirable.

 HV ripple hopefully reduced by AFF if synchronized with rep rate

### RF feedback

- Loop Delay: 1100 ns
  - 160 m Cable/Waveguide=550 ns
  - Klystron 250 ns
  - Circulator 50 ns
  - Driver 50 ns
  - LLRF 200 ns
- With Fdbk Closed we expect
  - ~ 150 KHz single-sided Loop bandwidth
  - <10 ms response time</li>



LHC: 100 KV IN 3 ms, 2 ms per div, 1=000 hs Linac4 reaction should be two times slower



PIM: Cavity impedance without feedback, QL=7000 (red) and with PI feedback (blue) .P gain ~3.



feedback. Same as above. Single-sided -3 dB BW ~ 150 kHz

#### T. Mastoridis

#### LLRF, November 5th 2015



- The beam pulse is 400 ms long but it can be later extended to 1.2 ms
- We have 300 ms for LLRF loops stabilization. We will use a sequence as at SNS
  - 1. Filling of the cavity open-loop but with feedforward from the result of the previous pulses. Cavity filling time < 20 ms (Q\_L<20k)
  - 2. Switch the RF feedback ON. Ramp fdbk gain. Allow ~ 100ms for stabilization.
  - 3. Switch the AFF ON and the Chopping Compensation ON
  - 4. Beam ON
- 2 Hz rep rate



- Step 1: Is the klystron power sufficient for the intended voltage/phase manipulations (set point)?
- Step 2: Coarse adjustment of the loop parameters (Feedback, Klystron Polar Loop, AFF) to keep the ensemble "well behaved"
- Step 3: Introduce perturbations: klystron noise, beam loading, source current ripples. Derive expected field stability. Optimization of the algorithms. Modifications to other parts of the machines: Power Converter, source, beam current, voltage distribution among the structures (beam dynamics)...

# Hardware

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# Digital I/Q Demodulator

- In a feedback system with high loop gain, the guality of the measurement front-end sets the quality of the ensemble: In the frequency band where the loop gain is high, the LLRF will adjust the klystron drive so that the Measured Cavity Field is equal to the setpoint. Measurement error will be directly reflected in the cavity field
- In large Synchrotrons and Linacs, the RF frequency is too high to allow for direct sampling of the cavity field and waveguide coupler signals. But the needed BW is typically very small as the signals come from narrow-band elements such as cavities or klystrons
- A typical front-end will therefore contain a Mixer that shifts the RF signal to an IF frequency that can be conveniently sampled by an ADC
- Amplitude/phase loops can be used in low current machines. In a high beam loading configuration they become unstable and (I,Q)implementations are preferred



 Amplitude A(t), phase f(t) and cartesian coordinates (I(t),Q(t)) are slowly varying signals. Their BW is much smaller than the RF frequency. They are related by

$$I(t) = A(t) \cos \phi(t)$$
$$Q(t) = A(t) \sin \phi(t)$$



The RF signal is shifted to the IF frequency band using a mixer

$$V_{RF}(t) = A(t)\sin(2\pi f_{RF} t + \phi(t))$$
$$V_{IF}(t) = A(t)\sin(2\pi f_{IF} t + \phi(t))$$

 The sampling frequency is chosen to be four times the IF. Let x<sub>n</sub> be the sampled signal, with n the time index, we get

$$x_{n} = A(nT_{CK})\sin(2\pi n f_{IF} T_{CK} + \phi(nT_{CK}))$$

$$x_{n} = A_{n}\sin\left(n\frac{\pi}{2} + \phi_{n}\right)$$

$$x_{n} = (-1)^{\frac{n}{2}}A_{n}\sin(\phi_{n}) = (-1)^{\frac{n}{2}}Q_{n} \quad \text{for n even}$$

$$x_{n} = (-1)^{\frac{n+1}{2}}A_{n}\cos(\phi_{n}) = (-1)^{\frac{n+1}{2}}I_{n} \quad \text{for n odd}$$

- The demodulator generates the data  $\{Q_{0r}-I_{1r}-Q_{2r}I_{3r},Q_{4r}...\}$  from which we derive, after sign correction and decimation, the data flow  $\{(I_{nr},Q_{nr})\}$  at the rate  $f_{CK}/2$
- Note that the I and Q are measured at alternate samples. The decimation introduces an error that increases with frequency. The I/Q demodulator is therefore narrow-band
- For Linac4 we use  $\begin{aligned} f_{RF} &= 352.2 \text{ MHz} \\ f_{LO} &= 330.1875 \text{ MHz} \\ f_{IF} &= 22.0125 \text{ MHz} \\ f_{CK} &= 88.05 \text{ MHz} \end{aligned}$

and we get an (I,Q) pair at 44.025 MHz rate that we interpolate to do the Signal Processing at the full 88.05 MHz FPGA clock

- Except for its narrow BW, the I/Q demodulator has many advantages: The effect of ADC offset can be nulled. The ADC gain is not critical as I and Q are affected in the same way. For slow applications (tuning for example), the very large oversampling leads to extremely good SNR after decimation.
- It was first proposed for PEP2 [Ziomek]. It is now used most everywhere...
- Much more on I/Q Demodulator in CAS Digital Signal Processing, June 2007, T. Schilcher, RF Applications in digital signal processing

[Ziomek] C. Ziomek, P. Corredoura, Digital I/Q Demodulator, PAC95



#### LLRF, November 5th 2015

# FPGA design and Visual Elite

- Signal Processing in FPGA
  - **Fixed Point Arithmetic**
  - Caution: scaling to avoid overflow but preserve SNR
  - Use embedded fixed point multipliers
  - Much "inspiration" from U. Meyer-Baese, Digital signal Processing with Field Programmable Gate arrays, Sringer Verlag, 2001
- Design with Visual Elite. Advantages:
  - Generates Device independent portable VHDL code.
  - Code reusability
  - Graphical Interface. Accept State-Diagram, Truth Tables, Processing Blocks (Adder, Logics, Multiplier, Memory) or VHDL code
  - Hierarchical
  - Graphics to text, text to graphics conversion
  - Powerful auto-documenting creates html п

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# Digital I/Q Demodulator



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Courtesy of John Molendijk

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# Decimating filters

- The signals are sampled at 88.05 MHz. But in some application (tuning) the closed loop response is a few seconds only (mechanical part)
- Oversampling is good for Signal to Noise Ratio (SNR): The quantization noise of the ADC is (assumed to be) white noise extending from DC to the Sampling Frequency, and with a Standard Deviation of 1-2 Least Significant bits.
- After filtering, the noise power is reduced by the ratio filter BW/sampling frequency. Potentially a very significant improvement...
- But brute-force implementation of a few Hz LPF FIR clocked at 88.05 MHz will ask for a lot of resources (taps -> multipliers)
- The classic solution is Decimation: We Low-Pass filter the signal and reduce the sampling rate at the same time.
- Good fixed-point architectures are the Cascaded Integrator Comb (CIC) filter and the Half-Band filters

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Cascaded Integrator-Comb filters. Classic decimating filter that uses accumulators only (no multiplier). Proposed by Hagenauer ~ 1985





# Cross Product as Phase Discri

$$u x v = u_x v_y - u_y v_x$$

- $|\mathbf{u} \times \mathbf{v}| = |\mathbf{u}| \times |\mathbf{v}| \sin\theta = \varepsilon \text{ IcFwd}$
- u = Vacc, v = IcFwd

Used to measure phase shift Vcav-Icfwd for Tuning



# Limiting Adder

Very important: elegant saturation in case of adder output overflow



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# Coordinate Rotation Digital Computer (CORDIC)

Imagine computing an Arctan[x] in fixed-point arithmetics....and with any desired precision...

No problem with the CORDIC....iterative algorithm...you set the number of digits...

- Iterative hardware algorithm for the computation of trigonometric functions
- Can also be used to compute square roots and divisions
- Uses shifts and adds only -> well suited for fixed-point FPGA implementation
- Pipe-lined implementation possible for higher throughput
- Proposed in late 1950s by J.Volder
- (To my knowledge) first use in an accelerator LLRF: RHIC (BNL) Beam Phase loop (M. Brennan, J. Delong, early 2000s)

Consider a rotation by angle f

$$x' = x\cos\phi - y\sin\phi = \cos\phi[x - y\tan\phi]$$

$$y' = x\sin\phi + y\cos\phi = \cos\phi[y + x\tan\phi]$$

- If the rotation angle is restricted to +-arctan[2-i] the multiplication by the tangent term is reduced to a simple shift operation
- Arbitrary rotation can be achieved by a series of rotations of amplitudes arctan[1], arctan[2<sup>-1</sup>], arctan[2<sup>-2</sup>],...
- Let d<sub>i</sub> be the decision whether to rotate in the positive or negative direction at iteration i (d<sub>i</sub>=+-1) then the i<sup>th</sup> iteration can be written

$$\begin{aligned} x_{i+1} &= K_i [x_i - y_i \, d_i \, 2^{-i}] \\ y_{i+1} &= K_i [y_i + x_i \, d_i \, 2^{-i}] \\ K_i &= \cos[\arctan(2^{-i})] = \frac{1}{\sqrt{1 + 2^{-2i}}} \end{aligned}$$

with  $d_i = \pm 1$ Let  $z_i$  be the rotation left to be done before iteration i we get

$$d_i = 1 \quad \text{if } z_i \ge 0$$
  
$$d_i = -1 \quad \text{otherwise}$$
  
$$z_{i+1} = z_i - d_i \arctan\left[2^{-i}\right]$$

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- The Rotation Form of CORDIC
- Example: rotation by 60.35 deg

i	Z (deg)	К	d	Arctan[2- <sup>i</sup> ] (deg)
0	60.35	0.707	1	45
1	15.35	0.894	1	26.56
2	-11.21	0.970	-1	14.03
3	2.82	0.992	1	7.12
4	-4.30	0.998	-1	3.57
5	-0.73	0.999	-1	1.79
6	1.06	0.999	1	0.89
7	0.17	1	1	0.45

Load the rotation angle in 
$$z_0$$
  
Iterate on  $i$ :  
 $d_i = 1$  if  $z_i \ge 0$   
 $d_i = -1$  otherwise  
 $x_{i+1} = K_i [x_i - y_i d_i 2^{-i}]$   
 $y_{i+1} = K_i [y_i + x_i d_i 2^{-i}]$   
 $z_{i+1} = z_i - d_i \arctan[2^{-i}]$   
 $K_i = \cos[\arctan(2^{-i})] = \frac{1}{\sqrt{1 + 2^{-2i}}}$   
untill  $z_n = 0$  or  $n \ge \max\_nbr\_iterations$ 

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- The values of arctan[2-i] must be stored in a table
- The Rotation Form can be used to compute Cosine and Sine
- The Vectorial Form of the CORDIC starts with a vector (x,y) and compute its angle with respect to the x-axis.

Both forms are used in the Klystron Polar Loop



Vectorial form: the original vector is rotated untill vn=0. The sum of the rotation

# PCBs

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#### Tuner module: RF front-end



IF out (8 channels, differential)

RF demodulators (8 channels)

Linac4 Tuner module RF Front-end card. J. Noirjean

### Tuner module: Processing card

Logging memory Post-Mortem

memory

Tiger Shark DSP. Slow Postprocessing (floating-point)

The Tiger Shark was scientifically selected as best fit to discipline Maurizio's zoo of low beta cavities



If interested, contact John Molendijk or Jose Noirjean

FPGA Fast Pre-Processing (fixed-point arithmetic), controls of the memories and VME interface

LHC Tuner module, processing card. J. Molendijk

# Installation

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#### LHC LLRF VME Chassis

#### Custom-designed VME crates used in the LHC and Linac4 (same crates) VXI is also a popular standard (PEP2, SNS)

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#### Thank you for your attention!