ANL: Tim Berenc, Hengjie Ma, Ned Arnold, Frank Lenkszus, Tom Fors, Bill Yoder

LBNL: Larry Doolittle, Gang Huang, John Byrd, Jim Greer, Kerri Campbell

Feb. 6, 2012
ASD Seminar
Outline

- Intro
- LLRF Receiver (prototype results)
- Deflecting Cavity Behavior (static and dynamic)
- LLRF Controller (benchtop performance tests)
- Storage Ring RF modification plans
- Summary
Goal: provide ~2 psec (presently 50-100 psec) X-ray pulses at 6.5 MHz rep. rate for time-resolved studies

RF at ~2815 MHz
(8th harmonic of Storage Ring RF)

Ideally, second cavity exactly cancels effect of first cavity

Correlation between vertical distribution of x-rays and time-distribution of electrons that generated them. Pulse can be sliced or compressed with an asymmetric cut crystal.

1 A. Zholents et al., NIM A 425, 385 (1999)
SPX0 = R&D System Proof of Principle (1 Sector, 2 cavities)

- Cavities counter-phased (180deg) to demonstrate tolerance requirements
- Cavities run in-phase to create a chirped beam around entire ring to have a look at short pulse x-rays
### SPX0 System Performance Requirements

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#### Common Mode

- Residual tilt
- Residual kick

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Cavity #1

Cavity #2

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3 SPX0 PRD, ICMS# APS_1423800 (1/17/12)
Low Level Radio Frequency (LLRF) System

Primary responsibility is to regulate the cavity field

\[ V_{\text{cav}} \cos(\omega_{RF} t + \phi_{\text{cav}}) \]

**Polar Coordinates**

**Cartesian Coordinates**

\[ V_I \cos \omega_{RF} t = V_Q \sin \omega_{RF} t \]

\[ V_{\text{cav}} = \sqrt{V_I^2 + V_Q^2} \]

\[ \phi_{\text{cav}} = \arg(V_I + jV_Q) \]
Receiver

You can’t regulate any better than your receiver

Regulate to a Designated Phase Reference

- Don’t let the LO assume the role of the phase reference
- Phase is a Differential Measurement
- Mixers preserve phase information, x’s and ÷’s preserve timing
- In theory, common mode LO and clock noise cancels
Receiver

ADC Quantization Noise

Variance
\[ \sigma^2 = \frac{q^2}{12} = \frac{1}{2^{2N} \cdot 12} \]

\[ SNR = 6.02 \cdot N + 1.76 - C \quad [dB] \]

N = # of ADC bits
C = dB carrier is below full scale
ADC Quantization Noise

Phase noise variance

\[ \sigma_{\phi}^2 = \int_0^{f_{\text{max}}} S_{\phi}(f) \, df \]

14 bit ADC

\[ \sigma_{\phi}^2 = -85 \text{ dB rad}^2 \]

\[ \sigma_{\phi} = 0.0032 \text{ deg rms} \]

16 bit ADC

\[ \sigma_{\phi}^2 = -97 \text{ dB rad}^2 \]

\[ \sigma_{\phi} = 0.0008 \text{ deg rms} \]
Receiver

ADC Aperture Jitter

\[
\cos(\omega_{IF}(t + \varepsilon)) = \cos(\omega_{IF}t + \omega_{IF}\varepsilon)
\]

Phase noise

\[
SNR_{jitter} = -20 \cdot \log(\omega_{IF} \cdot \sigma_{jitter}) \quad [\text{dB}]
\]

\(\sigma_{jitter}\) \hspace{0.5cm} \text{rms aperture jitter}
ADC Aperture Jitter

phase noise variance

\[ \sigma_\phi^2 = \int_0^{f_{\text{max}}} S_\phi(f) \, df \]

14 bit ADC, 0.5 psec rms

30 MHz IF \( \sigma_\phi \approx 0.008 \) deg rms

90 MHz IF \( \sigma_\phi \approx 0.023 \) deg rms
Receiver

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Receiver – Digital Receiver LLRF4 Board – Differential Phase Noise

58.68 MHz
IF

1378.98 MHz
CLK

Datasets:
- Dataset test_0_00.bin from 6/10/2011

Graphs:
- LLRF4 Single Channel vs. Phase Diff. PSD, IF=58.68MHz, CLKIN=1378.98MHz
- Cumulative Integrated Phase Noise

July 2011 SPX Workshop
Receiver - CW Drift Compensation

\[ \Delta \phi_{\text{meas}} = (\phi_{\text{cav}} - \phi_{\text{ref}}) + \Delta \phi_{\text{drift}} \]

\[ \Delta \phi_{\text{calTone}} = \Delta \phi_{\text{drift}} \]

\[ \Delta \phi_{\text{correct}} = \Delta \phi_{\text{meas}} - \Delta \phi_{\text{calTone}} \]

4 “Signal Processing for High Precision Phase Measurements”, G. Huang, L. Doolittle, J. Staples, R. Wilcox, J. Byrd, Proceedings of BIW10
receiver - CW drift compensation demonstration

\[ \Delta \phi_{\text{meas}} = (\phi_{\text{cav}} - \phi_{\text{ref}}) + \Delta \phi_{\text{drift}} \]

\[ \Delta \phi_{\text{calTone}} = \Delta \phi_{\text{drift}} \]

\[ \Delta \phi_{\text{correct}} = \Delta \phi_{\text{meas}} - \Delta \phi_{\text{calTone}} \]

LLRF4 Differential Phase Noise with & w/o Cal Tone Process

- Cal Tone Corrected Phase Difference
- Uncorrected Phase Difference

~ 0.118° rms

~ 0.023° rms

LLRF4 Cal-Tone Process Example Measurement at IF=58.68MHz

\[ \Delta \phi \approx 5° \]

\[ \Delta \phi \approx 0.09° \]

~ 35 dB
Receiver - Intermodulation Distortion
Receiver - Intermodulation Distortion

For simplicity assume a Taylor series approximation (in general should use Volterra series)

\[ v_o \approx a_o + a_1 v_i + a_2 v_i^2 + a_3 v_i^3 \]

For a 3-tone input signal:

- \( \omega_o \): RF carrier
- \( \omega_{LSB} \): Lower side-band cal-tone
- \( \omega_{USB} \): Upper side-band cal-tone

\[ \Delta \equiv \omega_o - \omega_{LSB} = \omega_{USB} - \omega_o \]

\[ v_o \equiv \left\{ a_1 V_{LSB} + a_3 \left[ \frac{1}{2} V_{LSB}^2 + V_o^2 + V_{USB}^2 \right] + \frac{1}{4} V_{LSB}^3 + \frac{3}{4} V_{USB}^2 V_o^2 + V_{LSB} V_o^2 + V_{LSB} V_{USB}^2 \right\} \cos \omega_{LSB} t \]

+ \[ \left\{ a_1 V_o + a_3 \left[ \frac{1}{2} V_o^2 + V_o^2 + V_{USB}^2 \right] + \frac{1}{4} V_o^3 + \frac{3}{2} V_{LSB} V_o V_{USB} + V_o V_{LSB}^2 + V_o V_{USB}^2 \right\} \cos \omega_o t \]

+ \[ \left\{ a_1 V_{USB} + a_3 \left[ \frac{1}{2} V_{USB}^2 + V_o^2 + V_{USB}^2 \right] + \frac{1}{4} V_{USB}^3 + \frac{3}{4} V_{LSB} V_o^2 + V_{USB} V_o^2 + V_{USB} V_{LSB}^2 \right\} \cos \omega_{USB} t \]
Marki T3-03MQP mixer measurements, Sine vs. Square Drive

Receiver - Intermodulation Distortion

Marki T3-03MQP mixer measurements, Sine vs. Square Drive

![IMD vs. RF Drive Graph](chart.png)
Receiver - Intermodulation Distortion

Marki T3-03MQP mixer measurements, Sine vs. Square Drive

- **Input TOI vs. LO Amp Input Level**
- **Input TOI (dBm)**
- **Input to LO Amplifier (dBm)**

- **Square +5V**
- **Square +6V**
- **Square +7V**
- **Sine**
Estimated -120 dB rad^2/Hz at -40 dBm input (~10 dB < F.S.)

> 20 dB improvement

**AFE Downconverter Comparison 2-Ch Differential Phase Noise**

- LBNL/SLAC -26 dBm in
- LBNL/SLAC -19 dBm in
- ANL -10 dBm in ~10 dB < F.S.
- ANL -1 dBm in

**ANL 2-Channel Down-Converter Prototype**

**LBNL/SLAC AFE Ver.1**
ANL 2-Channel Down-Converter Prototype

LBNL/SLAC AFE Ver.1

Graphs showing AFE Downconverter Comparison 2-Ch Differential Phase Noise with different input power levels for LBNL/SLAC and ANL.

Approximately 10 dB below full scale (F.S.)
ANL 2-Channel Down-Converter Prototype

LLRF4 + AFE, Single Channel vs. Differential Phase Noise

Limited by LLRF4 ADC's with ANL AFE

confirmed LBNL/SLAC AFE = -120dBrad²/Hz at -40dBm
Receiver - comparison (Susceptibility to Interference)
Low Level Radio Frequency (LLRF) System

Primary responsibility is to regulate the cavity field

Get to know the plant you are controlling – the cavity (deflecting not accelerating) …. 
Deflecting Cavity - Beam Loading

Longitudinal voltage

\[ V_{Z}(y) = V_{m} \cdot y \]

Vertical deflecting voltage

\[ V_{t} = j \frac{V_{m}}{\kappa_{o}} \]

Magnetic Field

Electric Field

Cavity Transverse Voltage

Cavity Longitudinal Voltage / \( \kappa_{o} \) (\( y > 0 \))
Deflecting Cavity - Beam Loading

Dipole loss factor: \( k_\perp \equiv \frac{U_{loss}}{q^2} = \frac{|V_z(y)|^2}{4U} = \frac{\omega_r}{2} \left( \frac{R}{Q} \right)' (\kappa_0 y)^2 \)

Circuit definition \( R/Q \): \[ \left( \frac{R}{Q} \right)' = \frac{V_t^2}{2\omega_r U} = 17.8 \Omega \]

\[ U_{loss} = q^2 k_\perp = \frac{1}{2} CV_t^2 \quad \Rightarrow \quad V_t^2 = \left( \frac{q \cdot \kappa_0 y}{C} \right)^2 \quad \Rightarrow \quad q_{eq} = \left| q \cdot \kappa_0 y \right| \]
Deflecting Cavity - Beam Loading\textsuperscript{5,6}

\[ i \kappa \left( y + j \theta \omega c \sigma_i^2 \right) e^{-j(\pi + \phi_h)} \]

\[ Z_{\text{cav}} \]

Phase (deg)

- Cavity Transverse Voltage
- Cavity Longitudinal Voltage
- Beam Induced Longitudinal Voltage ($y > 0$)
- Beam Induced Transverse Voltage ($y > 0$)

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5 Berenc, "An Equivalent Circuit Model ..", ICMS# APS_1405978
6 Decker, "...Tilt Monitor", DIAG-TN-2010-10, ICMS# APS_1417048
Deflecting Cavity - Beam Loading

\[ P_g^+ = \frac{V_t^2}{8\beta(R/Q)Q_o} \left[ \left( \beta + 1 + \frac{P_B}{P_{cav}} \right)^2 + \left( 2Q_o \frac{\Delta f + \delta f_m}{f_r} + \frac{P_B}{P_{cav}} \tan \phi_s \right)^2 \right] \]

\[ i_o = 2I_{dc} e^{-\frac{1}{2}(2\pi f_0 \sigma_t)^2} \]

For \( V_t \cdot y > 0 \)

\[ P_g^+ \text{ for } V_t \cdot y > 0 \text{ and } 0_{yz} = 2\text{deg} \]

\[ I_{DC} = 100mA \quad V_{cav} = 0.5MV \]

For \( V_t \cdot y < 0 \)

\[ P_g^+ \text{ for } V_t \cdot y < 0 \text{ and } 0_{yz} = 2\text{deg} \]

SPX LLRF R&D - 2/6/2012 ASD Seminar
Deflecting Cavity - Dynamic Behavior

\[ I_T(t) = I_r \cos \omega_{RF} t + i_I(t) \cos \omega_{RF} t - i_Q(t) \sin \omega_{RF} t \]

\[ V_{\text{cav}}(t) = V_r \cos(\omega_{RF} t + \phi_Z) + v_I(t) \cos(\omega_{RF} t + \phi_Z) - v_Q(t) \sin(\omega_{RF} t + \phi_Z) \]

In general I/Q modulations of \( I_T \) each cause both I/Q modulations of \( V_{\text{cav}} \)

For example: see P. Wilson, SLAC-PUB-2884, p. 26, prob 4.4
Deflecting Cavity - Dynamic Behavior

\[ I_I(t) = I_r \cos \omega_{RF} t + \alpha_I(t) I_r \cos \omega_{RF} t - \phi_I(t) I_r \sin \omega_{RF} t \]

\[ N_{polar} = |Z(j \omega_{RF})| e^{+j\phi_Z} = Z(j \omega_{RF}) \]

\[ G_{\alpha\alpha}(s) = G_{\phi\phi}(s) = \frac{\sigma(s + \sigma(1 + \tan^2 \phi_Z))}{s^2 + 2\sigma s + \sigma^2(1 + \tan^2 \phi_Z)} \]

\[ G_{\alpha\phi}(s) = -G_{\phi\alpha}(s) = \frac{-\sigma \tan \phi_Z s}{s^2 + 2\sigma s + \sigma^2(1 + \tan^2 \phi_Z)} \]

classical “Pedersen/Boussard Equations”

\[ I_T(t) = I_r \cos \omega_{RF} t + \alpha_I(t) \cos \omega_{RF} t - i_\phi(t) \sin \omega_{RF} t \]

\[ N_{Cartesian} = e^{+j\phi_Z} \]

\[ G_{ii}(s) = G_{qq}(s) = \frac{\sigma R \cos \phi_Z (s + \sigma(1 + \tan^2 \phi_Z))}{s^2 + 2\sigma s + \sigma^2(1 + \tan^2 \phi_Z)} \]

\[ G_{iq}(s) = -G_{qi}(s) = \frac{-\sigma R \sin \phi_Z}{s^2 + 2\sigma s + \sigma^2(1 + \tan^2 \phi_Z)} \]

Modern I/Q Equations
Deflecting Cavity - Dynamic Behavior

Polar Coordinates
for discussion “NO DETUNING”

\[ G^G_{\alpha\phi}(s) = -G^G_{\phi\alpha}(s) = 0 \]

\[ G^G_{\alpha\alpha}(s) = G^G_{\phi\phi}(s) = \frac{(1+Y)\sigma}{s + \sigma} \]

\[ Y = \text{Beam Loading Factor} \text{ which can be negative for deflecting cavities.} \]

Amp/Phase control can be lost when beam offset drives the cavities to full field (there is no drive carrier). This doesn’t happen for I/Q control.

Cartesian Coordinates
for discussion “NO DETUNING”

\[ G^G_{iq}(s) = -G^G_{qi}(s) = 0 \]

\[ G^G_{ii}(s) = G^G_{qq}(s) = \frac{\sigma R}{s + \sigma} \]

Use vector projection techniques to find the transfer functions from generator current and beam current modulations. Generator Current in-phase modulation is shown here. Total of 15 transfer functions describe the cavity.
Deflecting Cavity - Dynamic Behavior

**Controller**

\[ C_i(s) \]

\[ C_q(s) \]

**Klystron**

\[ I^{\text{driver}}_{\text{noise}} \]

\[ I^{\text{kly}}_{\text{noise}} \]

**Cavity Loop**

\[ G_{u}^{\text{GN}}(s) \]

\[ G_{qL}^{\text{GN}}(s) \]

\[ G_{yL}^{\text{BN}}(s) \]

\[ G_{\phi}^{\text{BN}}(s) \]

\[ G_{\xi}^{\text{BN}}(s) \]

**Beam Loading Variations**

\[ \phi_{S,n} \]

\[ \phi_{Z,n} \]

\[ \phi_{L} \]

\[ \theta_{\gamma z,n} \]

\[ \gamma_{n} \]

\[ \alpha_{n} \]

**Q-component Loop**

\[ G_{q}^{\text{GN}}(s) \]

\[ G_{qq}^{\text{GN}}(s) \]

\[ G_{\phi}^{\text{BN}}(s) \]

\[ G_{\xi}^{\text{BN}}(s) \]

\[ \Omega_{\phi}^{N}(s) \]

**Q-det**

\[ Q_{\text{det}} \]

**Noise**

\[ I_{\text{det}} \]

**Lorentz Force**

\[ L_{w}(s) \]

**Detuning**

\[ \delta \omega \]

**Microphonics**

\[ V_{I} \]

\[ V_{Q} \]
Deflecting Cavity - Dynamic Behavior

Phase Transfer Functions

Amplitude Transfer Functions

Phase Transfer Functions

Amplitude Transfer Functions
Deflecting Cavity - Dynamic Behavior

No cross-coupling when cavity is tuned to resonance, except through Lorentz Force Detuning (minimal if stiff cavity)

Pursue R&D benchtop tests with a cavity emulator to quantify the LLRF system contribution to the system error budgets.
Low Level Radio Frequency (LLRF) System

Primary responsibility is to regulate the cavity field

The Controller....
Controller – Benchtop Tests

LLRF4 Receiver Chassis Prototype

Diagram showing the LLRF4 + Analog Front End with signals divided by 2, CLK, and a prescaler. Connections include LO, Reference, Cav, Drive, and OUT 1.
Controller – Benchtop Tests

Cavity Emulator

Frequency Generation Chassis

Controller – Benchtop Tests

Cavity Emulator

Frequency Generation Chassis
Controller – Single System Benchtop Test

- Frequency Generation Chassis
  - 351.94 MHz
  - x8
  - 2815.52 MHz
  - BPF
  - 58.66 MHz
  - 1/6
  - 2756.86 MHz

- LLRF4 + Analog Front End
  - CLK
  - Divide by 2
  - Prescaler
  - LO
  - ch1
  - cal
  - ch2
  - ch3
  - ch4
  - OUT 1

- FFT Analyzer
- Out-of-Loop Phase Noise Measurement

- Cavity Emulator
- Out in
- In out

- REF
- 2815.52 MHz
- LO
- 2756.86 MHz

- LLRF4 + Analog Front End
- Controller – Single System Benchtop Test
Noise sources include an independent LO generator used for cavity emulator. This is not something that exists in the ‘real’ system.

What matters is the noise suppression capability in combination with our expected noise sources.
What matters is the noise suppression capability in combination with our expected noise sources.
Controller – Noise Suppression Model

\[ C(s) = K_P \left( 1 + \frac{\sigma_z}{s} \right) = K_P \left( \frac{s + \sigma_z}{s} \right) \]

\[ G_{qq}(s) = \frac{\sigma_{cav}}{s + \sigma_{cav}} \]

\[ \phi_{cav} = \frac{1}{1 + C(s) G_{qq}(s) e^{-s \tau_d}} \]

\[ \phi_E = \frac{\sigma_{cav}}{s + \sigma_{cav}} \]

\[ \sigma_{cav} = 2 \pi \cdot 1e3 \text{ rad} / \text{sec} \]

\[ \tau_d = 1.8 \mu\text{sec} \]

\[ K_P = 2 \]

Noise Suppression - LLRF4 Cavity Emulator Test 8/19/2011

- red: zero = 53.76 kHz
- green: zero = 25.30 kHz
- blue: zero = 12.65 kHz
- pink: Zero Integral

Noise Suppression [dB]

Frequency [Hz]
Controller – 2 System Benchtop Test

**Frequency Generation Chassis**

- 351.94 MHz
- Divided by 8
- 43.99 MHz
- Bandpass Filter (BPF)
- 58.66 MHz
- Divided by 6
- 9.78 MHz
- 2815.52 MHz
- LO

**LLRF4 + Analog Front End**

- CLK Prescaler
- Divide by 2
- CLK
- LLRF4
- ch1
- cal
- ch2
- ch3
- ch4
- OUT 1

**Out-of-Loop Phase Noise Measurement**

- FFT Analyzer
- Residual Phase Noise Test Set

**Controller – 2 System Benchtop Test**

- Frequency Generation Chassis
- 351.94 MHz
- 2815.52 MHz
- LO
- 2756.86 MHz
- Divide by 2
- CLK Prescaler
- LLRF4 + Analog Front End
- OUT 1

**FFT Analyzer**

**Residual Phase Noise Test Set**

**Controller – 2 System Benchtop Test**
Controller – 2 System Benchtop Test

- **Residual Phase Noise Test Set** (measure noise between cavity emulators)
- **Cavity Emulators #1 and #2**
- **Freq. Generation Chassis**
- **LLRF Receiver #1**
- **LLRF Receiver #2**

**LLRF4 Two Cavity Emulator Test 9/29/2011**

- **Phase Noise (dB/Hz)**
- **Price paid for capability to suppress low freq. noise (i.e., beam loading & microphonics)**

**LLRF System contribution ~ 20 fsec rms [0.1 Hz – 1MHz]**
LLRF R&D Outlook (overly simplified)

- Adding the calibration tone scheme into the cavity control gateware. Currently these are 2 separate code bases, parts need to be merged.

- Preparing for real single cavity testing to begin ~ June 2012

- Modifications to Storage Ring RF System ...
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**Residual tilt**

**Residual kick**

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[Diagram of Cavity #1 and Cavity #2](#)
Present Storage Ring Beam Jitter

\[ \sim 1.65 = \sqrt{0.7^2 + 1.5^2} \]
\[ 0.86 = \sqrt{0.7^2 + 0.5^2} \]
\[ 0.72 = \sqrt{0.7^2 + 0.15^2} \]

Sereno et. al, “Storage Ring Phase Noise Studies …” AOP-TN-2012-001
Proof of Principle Feed Forward Experiment

Experiment with 360Hz Feed-Forward correction of Storage Ring Klystron High-Voltage Power Supply (HVPS) induced noise

AM & PM suppression at Both Stations

Horizontal BPM Data

Feed Forward OFF

Feed Forward ON
Adaptive Noise Cancellation Concept

Fig. 1. The adaptive noise cancelling concept.

From [9]
Adaptive Noise Cancellation Concept


\[ N_I \cos \omega_N t - N_Q \sin \omega_N t \]

\[ (Y_I - N_I)^2 + (Y_Q - N_Q)^2 \]

Fig. 6. Single-frequency adaptive noise canceller.

From [9]
Summary

- Digital LLRF system shows promise of femto-second level synchronization [0.1 Hz – 1MHz] with proper attention to common source distribution

- Great design improvement demonstrated for Analog Front End with T3 mixers

- New I/Q small-signal baseband model developed for SRF Deflecting Cavities

- Adaptive noise cancellation of Storage Ring main 352MHz RF system AM/PM noise is being pursued to reduce present beam jitter