# E-Clouds / TMCI : Simulations and Feedback Models, MD Preparation and Preliminary Results

C. H. Rivetta[1]
Ecloud / TMCI US-LARP CERN Contributors:
J. D. Fox[1], O. Turgut[1], S. Uemura[1], M. Pivi[1], I. Rivetta[1],
W. Hofle[2], U. Wehrle[2], G. Romulo[2],
R. Secondo[3], J.-L. Vay[3]

[1]Accelerator Research Division, SLAC
[2]BE-RF Group CERN
[3]LBNL

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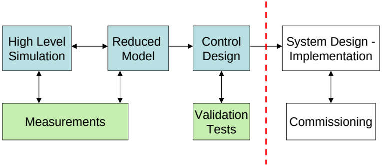
# High Bandwidth Feedback Project - (CERN - US LARP)

- Motivation: - Control E-cloud and TMCI effects in SPS and LHC via GHz bandwidth feedback
  - Intrabunch Instability: Requires bandwidth sufficient to sense the vertical position and apply correction fields to multiple sections of a nanosecond-scale bunch.
- US LHC Accelerator Research Program (LARP) has supported a collaboration between US labs (SLAC, LBNL) and CERN
  - Large R & D effort coordinated on: Non-linear Simulation codes (LBNL - CERN - SLAC), Dynamics models/feedback models (SLAC - Stanford STAR lab), Machine measurements - SPS MD (CERN - SLAC - LBNL) and Hardware technology development (SLAC)



# Macro - Particle Simulation codes : Feedback System

## Generalities

The macro-particle simulation code solves

$$\frac{d^2\vec{x}_{p,i}(s)}{ds^2} + \mathbb{K}(s)\vec{x}_{p,i}(s) = \Delta P_{e,i}(\vec{x}_{p,i}(s)) + Ki_k(<\vec{x}_{p,i}(t,s_{BPM})>_k, s_{ki})$$

$$\frac{d^2\vec{x}_{e,j}(s)}{ds^2} = \Delta P_{p,j}(\vec{x}_{e,j}(s))$$

where

$$\Delta P_{e,i}(\vec{x}_{p,i}(s)) = -\frac{e}{\gamma m_p c^2}\sum_{n=0}^{n_{IP}-1} E_e[\vec{x}_{p,i}(s); f_e(x,y,t)]\sigma(s-ns_{el})$$

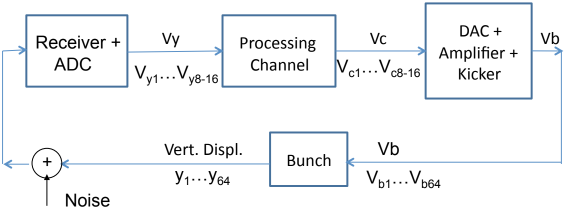
$$\Delta P_{p,j}(\vec{x}_{e,j}(s)) = -\frac{e}{m_e}E_p[\vec{x}_{e,j}(s); f_{pSL}(x,y,t)],$$

$Ki_k(<\vec{x}_{p,i}(t)>_k, s_{ki})$ : feedback signal based on $<\vec{x}_{p,i}(t,s_{BPM})>_k$

We have a stochastic system represented by a limited number of macro-particles - Statistical errors - Limitations due to feedback hardware.

# Macro - Particle Simulation Codes : Realistic Feedback

## Add realistic representing feedback system

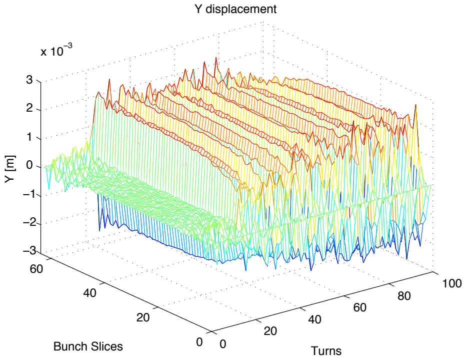


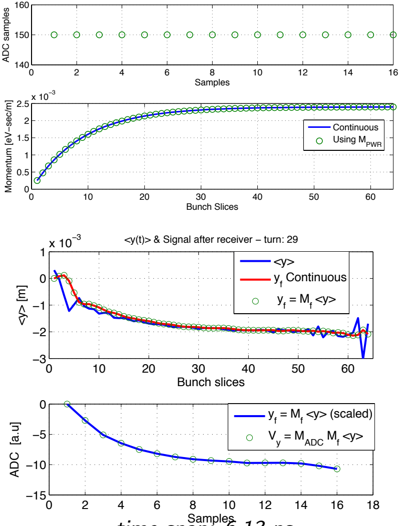

- $V_{b_k} = Ki_k(< \vec{x}_{p,i}(t) >_k, s_{ki}),\ y_k =< \vec{x}_{p,i}(t, s_{BPM}) >_k$
- Receiver, processing channel, amplifier, kicker include frequency response, signal limits and noise.
- $[V_{b_1} \ldots V_{b_{64}}]^T = M_{PWR}\ [V_{c_1} \ldots V_{c_{16}}]^T$
- Validate with measurements : Macro-particle simulation codes are our test-bench for control algorithm - Test stability and performance of the feedback system.

# Macro-Particle Simulation Codes : Realistic Feedback

## Results from C-MAD

Kick at turn 20, free vertical oscillation of the bunch. (out of scale)



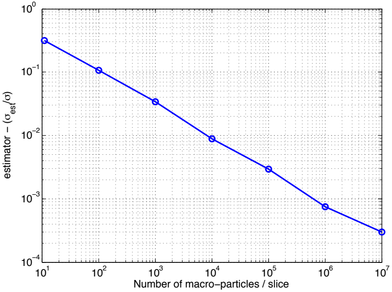

*time span: 6.13 ns.*

# Macro - Particle Simulation Code : Statistical Errors

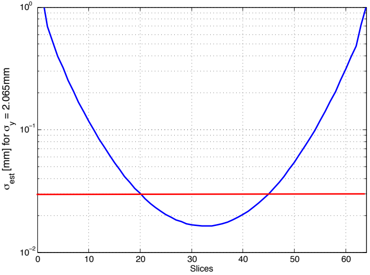
## Estimation of the vertical position

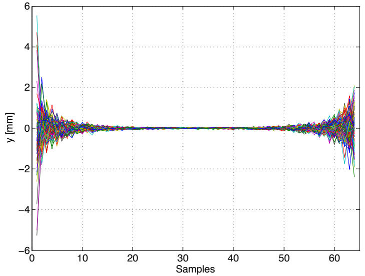
$$\hat{y}_k(s) = \sum_{i=1}^{N_k} y_{p,i}(s) \rightarrow$$

$$\sigma_{\hat{y}} = \sigma_y / \sqrt{N_k}$$




For a bunch with 300K macro-particles...
(red: equal number of particles per slice,
blue: regular slice space)



# Macro - Particle Simulation Code : Next steps

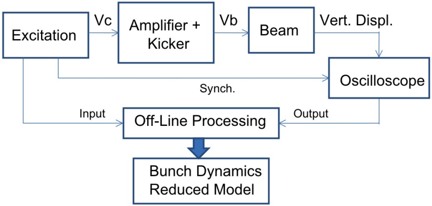
### Error bounds for stochastic variables

- Estimate the error bounds for $\hat{y}_k$ and $\hat{V}_{b_k}$
- Validate feedback models with measurements
- Benchmark C-MAD, WARP, Head-tail for different operations in SPS.
- Include realistic feedback channel in Head-tail code
- Estimate kicker strength for different operation conditions.

# MD preparation

## Goal: Drive individual sections of the bunch - Estimate Models

- Hardware development - Excitation - Power Stage - Vertical displacement measurement.
- Analyze and estimate using macro-particle simulation codes the signal levels and outcomes of MD measurements.
- Estimate bunch reduced dynamical model in open loop- Below e-cloud instability threshold.




- Drive individually different areas of the bunch (Excitation - Amplifier - Kicker)
- Measure with scope the receiver signals $\Delta - \Sigma$. Estimate vertical displacement for different sections of the bunch.
- Based on Input-Output signals, estimate bunch reduced model.

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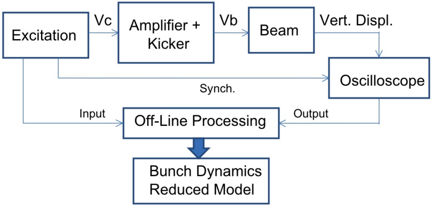


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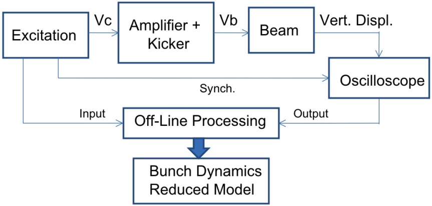


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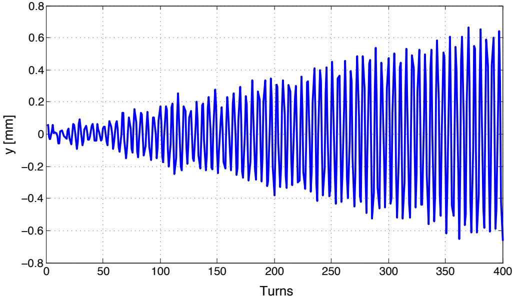
# MD preparation

## Simulation Results - Estimation of Vertical Displacement.

- SPS Kicker: Max. $V_{\Delta} = 200V$, Max. Momentum $= 4.10^{-6}$ eV.s/m, Kick in single turn $\rightarrow y_{max} = 3.27\mu m$ at 26 GeV
- It is necessary to kick the beam using a periodic excitation near the betatron frequency (frac. tune = 0.185)

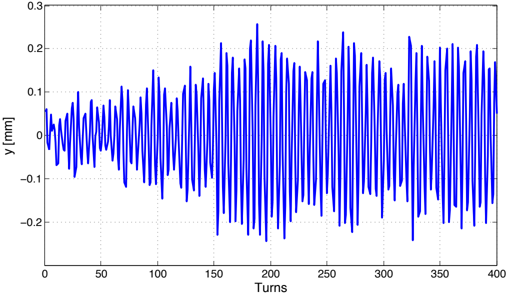



Kicker signal for all the slices: $V_b = 4.10^{-6} sin(2\pi 0.185 Turns)$ eV.s/m. C-MAD result: Vertical displacement of center of the bunch.

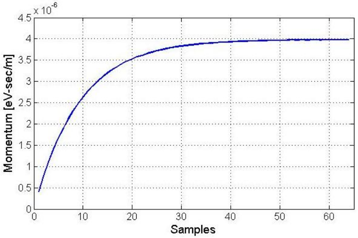
# MD preparation and preliminary results

## Simulation Results - Excitation signal: Sweep around betatron frequency

- C-MAD simulation includes the frequency response of the kicker.
- The frequency of the excitation signal sweeps between $0.185 \pm 5\%$.

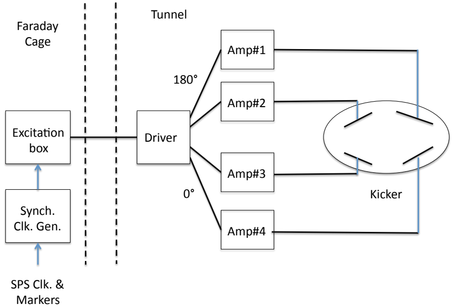



Momentum applied to the bunch at turn 50.




*time span: 6.13 ns.*

# MD Hardware


Faraday
Cage
Tunnel
Excitation
box
Synch.
Clk. Gen.
SPS Clk. &
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Driver
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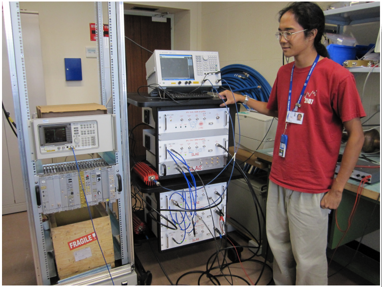
Amp#2
Amp#3
Amp#4
Kicker

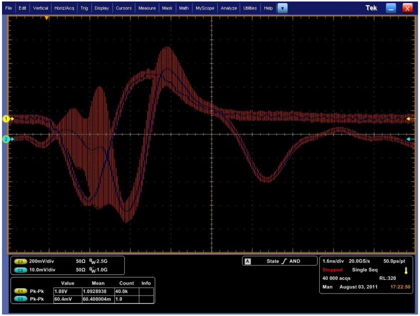

FRAGILE


K 028

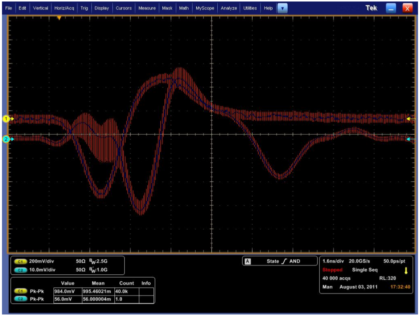
# MD Preliminary Results

## Single bunch driven by sine wave

- Bunch was driven by continuous sine waves at 200.272680MHz, 300.404676MHz and 400.537404MHz (no phase synchronization between excitation signal and SPS ring).
- Pictures: SUM (SIGMA) signal and DIFF (DELTA) signal for multiple turns




SUM/DIFF signals when bunch is driven by 200.272680 MHz sinewave

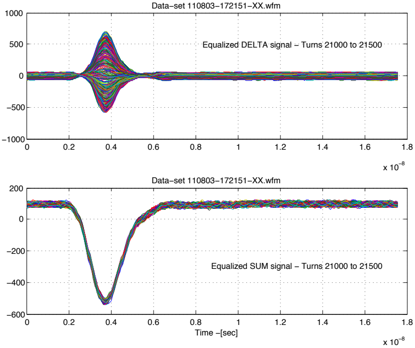



SUM/DIFF signals when bunch is driven by 400.537404 MHz sinewave

# MD Preliminary Results

## Single bunch driven by sine wave

- Movies: SUM (SIGMA) and DIFF (DELTA) signals are processed by equalizing the frequency response of the pick-up and cables and subtracting the mean value along the turns. e.g. Equalized SUM/DIFF signals for turns 21000 to 21500




- Movies: (top) RMS value of the vertical dipole motion, (bottom) sliding window showing the Vertical dipole motion of 25 turns. (Driven by 200.272680MHz sinewave)

# Conclusions

## Conclusions - Further plans

- Introduced realistic models for the feedback system in macro-particle simulation codes (C-MAD, WARP), next Head-tail.
- Quantifying statistical / estimation errors in the variables used in the macro-particle codes.
- Continue with the preparation of SPS MD and the estimation of signals to be measured.
- Drive the bunch with different modal signals to analyze the vertical motion of the bunch in response to those signals
- First steps toward more specific MDs based on driving the bunch: Identification of bunch dynamics, bunch dynamic behavior near e-cloud instability and TMCI thresholds, effects of synchrotron motion of bunch centroid, etc..

.Many thanks to all the people from CCC, OP crew and collaborators that helped conducting the Aug 03 MD, Metral, Yannis, Kevin, Thomas, ... and many more!.

.

.Thanks to the audience for your attention!, ....Questions?

# Extra slides

## Excitation Box


Injection trigger (magenta), Rev-Markers (yellow), Excitation signal (light blue ) (fifth bucket)

# Extra slides

## Excitation Box


Injection trigger- (magenta), Rev-Markers (yellow), Excitation signal (light blue ), 200MHz reference signal (SPS ring - green)