LCLS-II

Cryomodule-on-Chip (CMOC) Simulation Engine

L. Doolittle & C. Serrano, LBNL

SLAC NATIONAL ACCELERATOR LABORATORY

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Jefferson Lab

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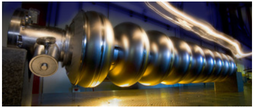
Outline/Summary

- Math and physics of Mechanical and Electromagnetic modes, with nonlinear coupling
- Eventually lands in state-space formalism
- Can numerically integrate equations in software or FPGA
- FPGA is nice because it can run in same chip as controller(s)
- Match parameters to experimental evidence

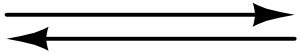
Physics

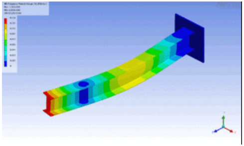
Electromagnetic world

Mechanical world



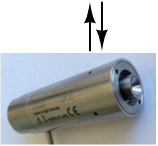
coupling





EM fields store energy
power flows in and out

deflections store energy
power flows in and out



Physics converted to math

Decompose dynamics into eigenmodes that store energy
use $\sqrt{\mathrm{Joule}}$ as universal amplitude coordinate (thanks, Olof!*)

Electromagnetic

$$\frac{d\vec{x}}{dt} = \mathbf{A}\vec{x} + \mathbf{B}\vec{k} + \mathbf{C}i_B$$

$$\mathbf{A} = \mathbf{A}_0 + \mathbf{G}\vec{y}$$

Mechanical

$$\frac{d\vec{y}}{dt} = \mathbf{D}\vec{y} + \mathbf{E}\vec{w} + \mathbf{F}|\vec{x}|^2$$

Linear Time Invariant (LTI) until red nonlinear coupling terms are added.
$\vec{k}$ are RF drives
i_B is the beam
$\vec{w}$ are actuators and environmental forces

- Using eigenmode coordinates makes **A** and **D** diagonal
- **F** and **G** are both based on the same $B^2 - E^2$ surface integral

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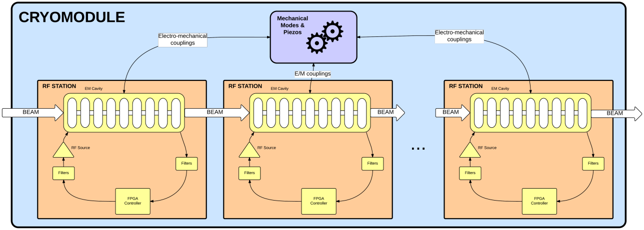
*Olof Troeng, *Modeling of accelerating cavity modes*, in preparation.

Translate to hardware

Abstract state space equation, unifying $\vec{x}$ and $\vec{y}$ as $\vec{S}$

$$\frac{d\vec{S}}{dt} = f(\vec{S}, \vec{k}) \qquad \text{or} \qquad z\vec{S} = \vec{S} + f(\vec{S}, \vec{k}) \cdot dt$$



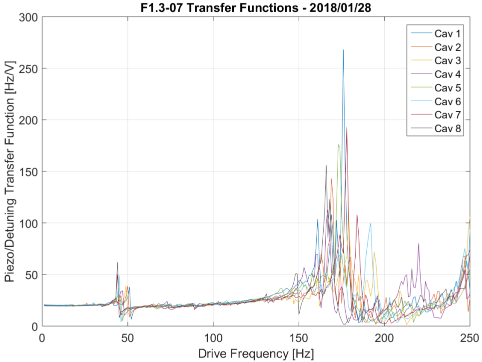
FPGA clock tick ∼5 ns

∼10 ns per electromagnetic time step (parallel DSP)

∼250 ns per mechanical time step (serial DSP)

- Fixed point arithmetic, unlike floating point typical for software
- 22% of XC7K160T, configured for 2 cavities, 3 electrical modes each

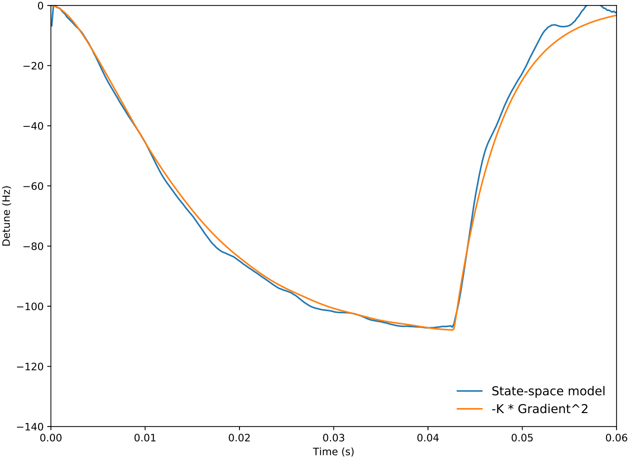
Measurements



$$\sum_k \frac{G_{1k} E_{k1}}{1+\frac{1}{Q_k}\frac{s}{\omega_k}+\left(\frac{s}{\omega_k}\right)^2}$$

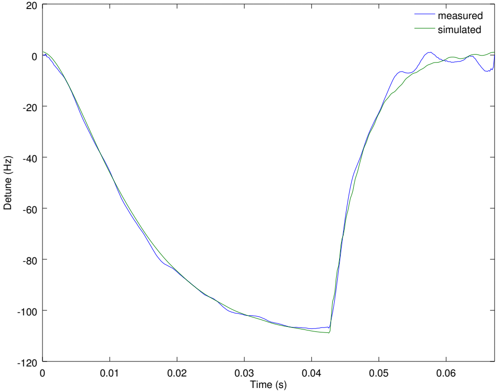
Also need $\Delta f/|V_{\mathrm{cav}}|^2$; want $I_{\mathrm{piezo}}/V_{\mathrm{piezo}}$, and $I_{\mathrm{piezo}}/|V_{\mathrm{cav}}|^2$ as a cross-check. All physics based on the same set of second-order low-pass resonances (f_0 and Q, embedded in **D**), but with different coupling constants (**E**, **F**, **G**).

Measurements



Simple RF pulse response provides some info about Lorentz detuning

Simulation



Using same resonances as meausred with transfer function, fitting coupling coefficients, driven by $|V|^2$
Would be far preferable to frequency-sweep $|V|^2$

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Conclusion

- Physics of the electro-mechanical system is easily understood (if the dynamical part stays linear).
- Numerical treatment is also not hard.
- Acquiring and interpreting data to fit the model involves more work.
- Having a complete controller/model running in real time opens up many possibilities for software development and operator training.
- Specifically has proved useful during development of the automated cavity bring-up process for LCLS-II .

https://github.com/BerkeleyLab/CMOC

https://github.com/BerkeleyLab/Global-Feedback-Simulator

LLRF'15 Shanghai poster: **Accelerator-On-Chip Simulation Engine**

ICALEPCS'17 talk/paper: **Cryomodule-on-Chip Simulation Engine**

Thank You!