Longitudinal Beam Dynamics and LLRF Requirements for the Project X Pulsed Linac

A. Vivoli*, G. Cancelo, B. Chase, N. Solyak and P. Varghese

Fermilab

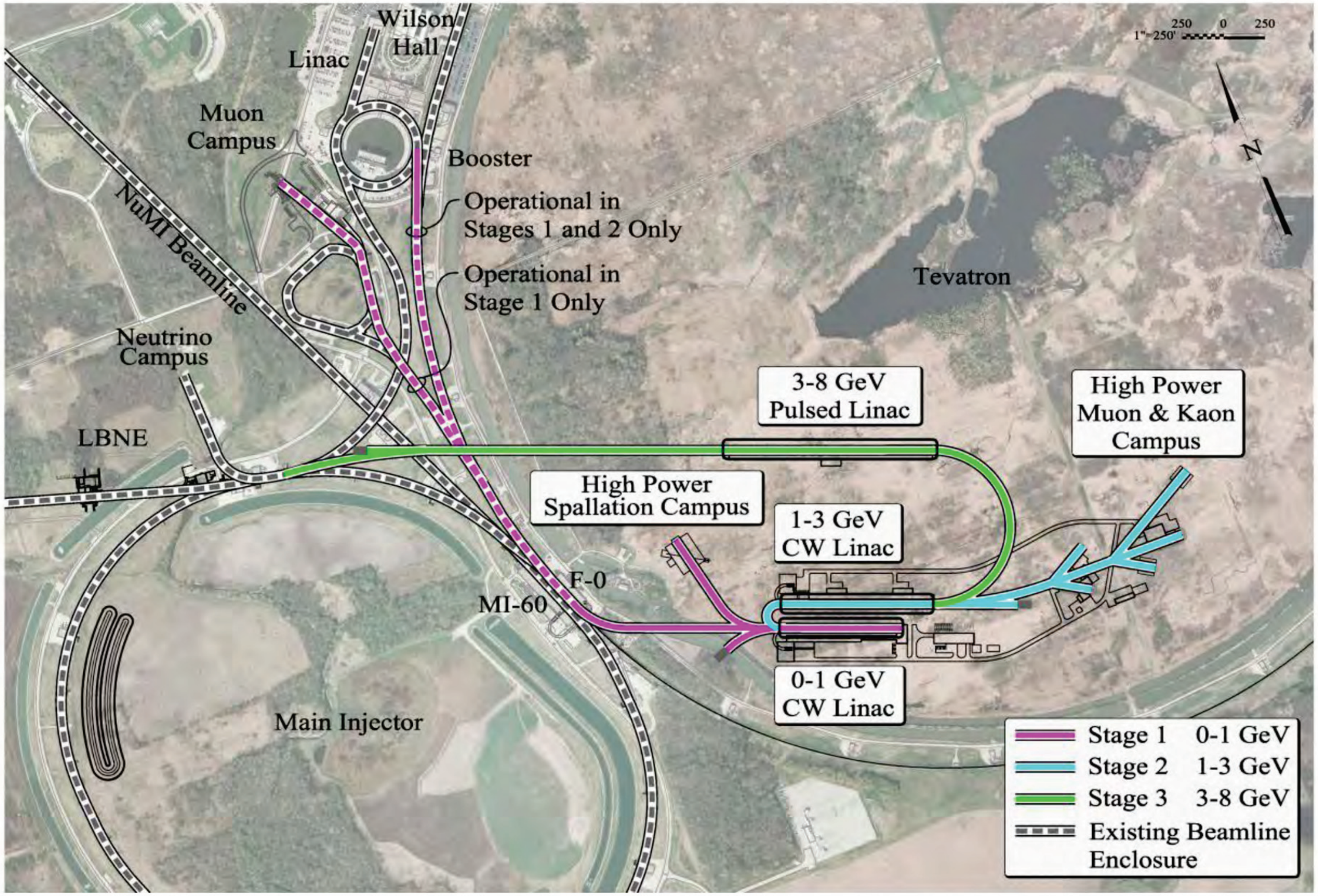
Thanks to Y. Eidelman, C. Ginsburg, I. Gonin, D. Johnson, T. Khabiboulline, I. Kourbanis, R. Pasquinelli, Y. Pischalnikov, J. Reid, W. Shappert, V. Yakovlev (Fermilab)

*vivoli@fnal.gov

Contents

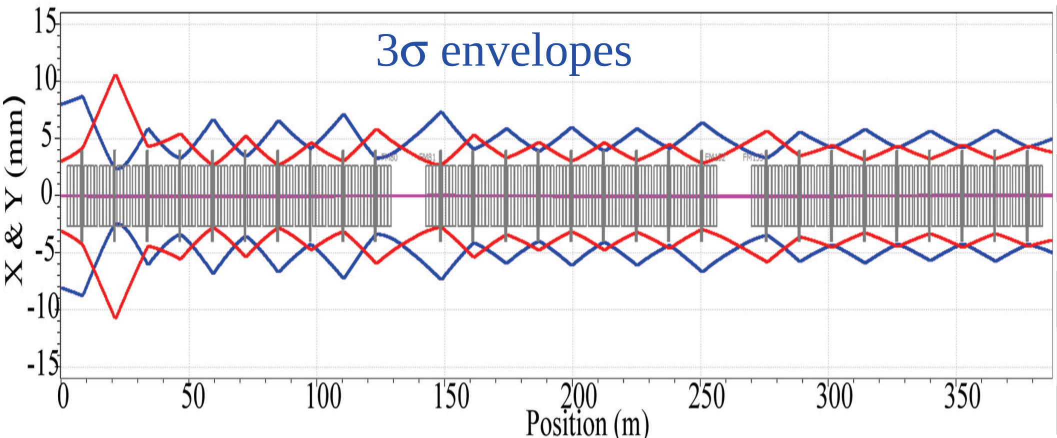
- Layout of Project X and the Pulsed Linac
- Lattice and parameters
- Multi-bunch simulations
- Detuning models
- LLRF schematic design & baseline parameters
- Simulation results
- Conclusions

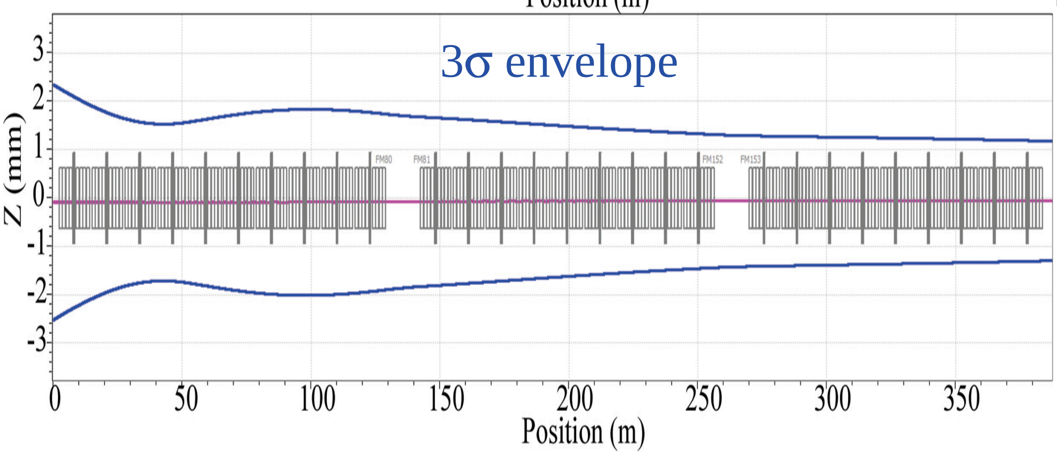
Project X layout



Pulsed Linac lattice and parameters

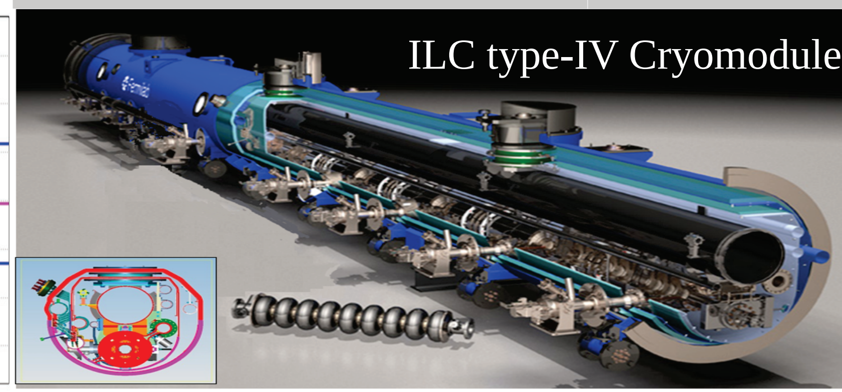
Single bunch simulations using TraceWin

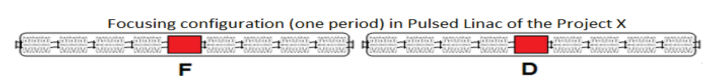




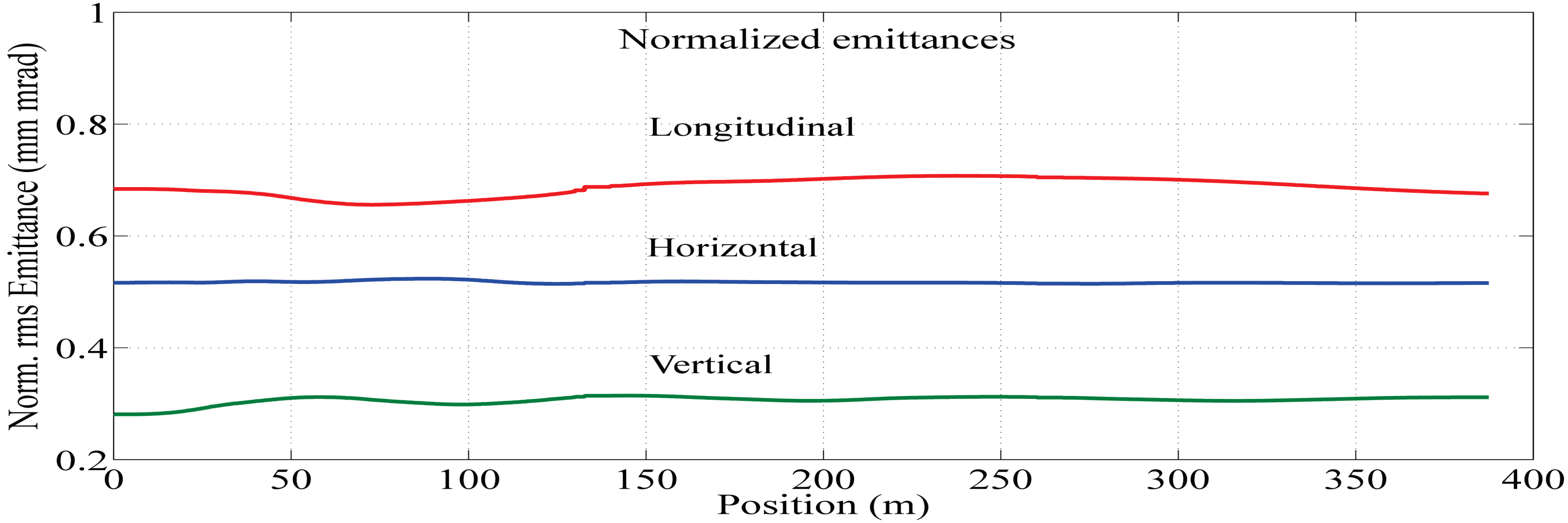
Lattice segmentation

Number cryo strings (CS)	3
Cryomodules (CM) per CS	10/9/9
Cryomodules length	12.652 m
Cavities per CM	8
Number of room temperature sections	2
Room temperature section length	7.652 m
Number of service boxes for cryogenics	6 (2.5 m each)
Total length	388 m





Pulsed Linac lattice and parameters



Lattice parameters

Cavity gradient (MV/m)	14/24/25.1
Synchronous phase (deg)	-4.5/-6.5/-5
N. cavities	224
N. quadrupoles	28
Quadrupole gradient (T/m)	1.42 -- 2.42

Beam parameter	Initial value	Final value	Requirement
Energy (MeV)	3000	8000	8000
Norm. hor. rms emit. (mm mrad)	0.5163	0.5159	< 0.6
Norm. vert. rms emit. (mm mrad)	0.2811	0.3114	< 0.6
Rms bunch length (ps)	2	1.3	< 100
Rms energy spread (MeV)	0.9	1.6	< 4

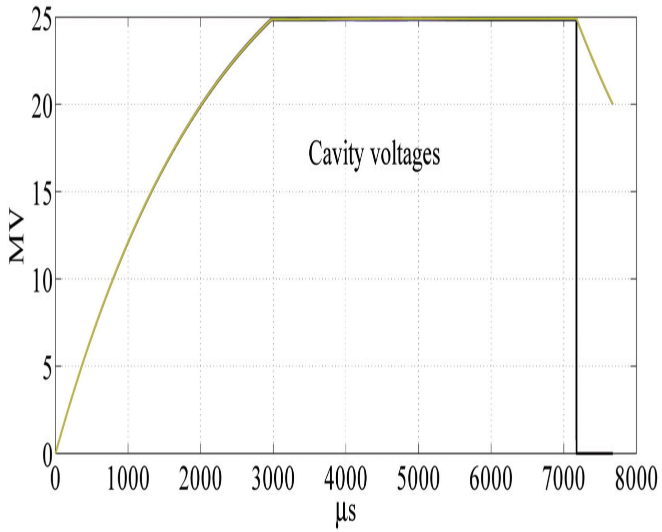
Multi-bunch simulations

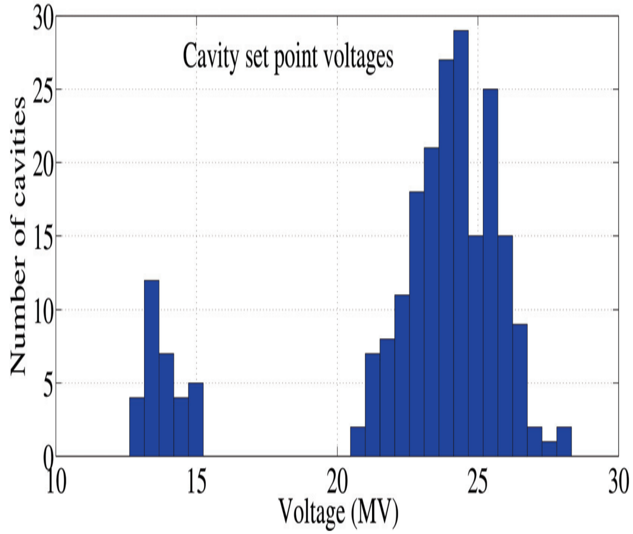
Goals of multi-bunch simulations:

- Assure that the Pulsed Linac performance fulfill the requirements during all the beam pulse (4.3 ms) and on multi-pulse time scale in presence of cavity detuning (LFD+microphonics).
- Set constraints for the parameters used in order to consistently perform at an acceptable level.
- Study the impact of cavity gradient spread in cryomodules (not all cavities can reach design gradient) on performance.
- Evaluate different RF configurations (1 RF station for 1 or 2 cryomodules).
- Validate current design and point out possible improvements.

Code features:

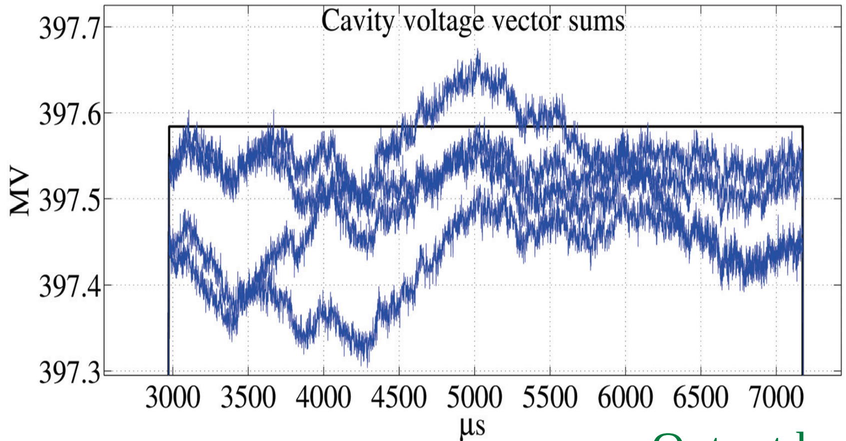
- Only longitudinal motion is considered.
- Only cavities and drifts in beamline.
- Only fundamental mode in cavities.
- Non interacting particles.
- Accepts in input positions, voltage and synchronous phase of cavities and beam parameters.

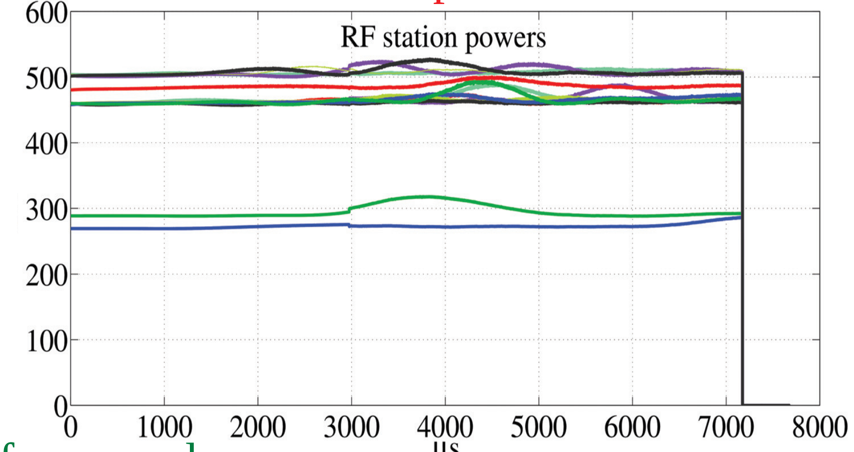




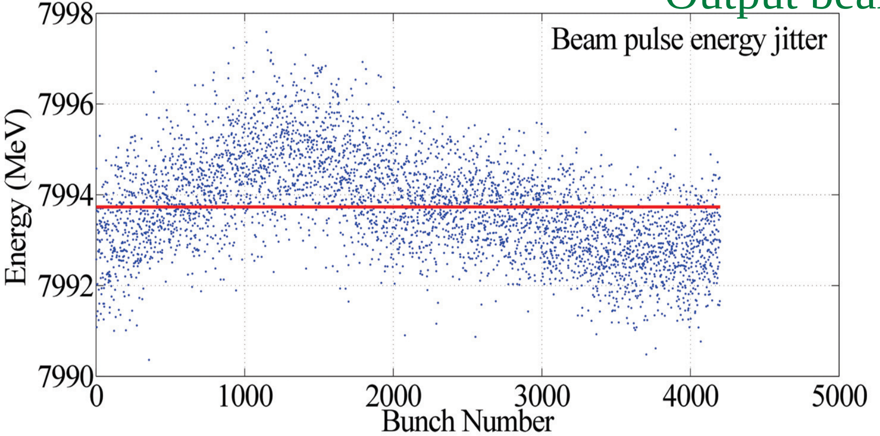
Code output

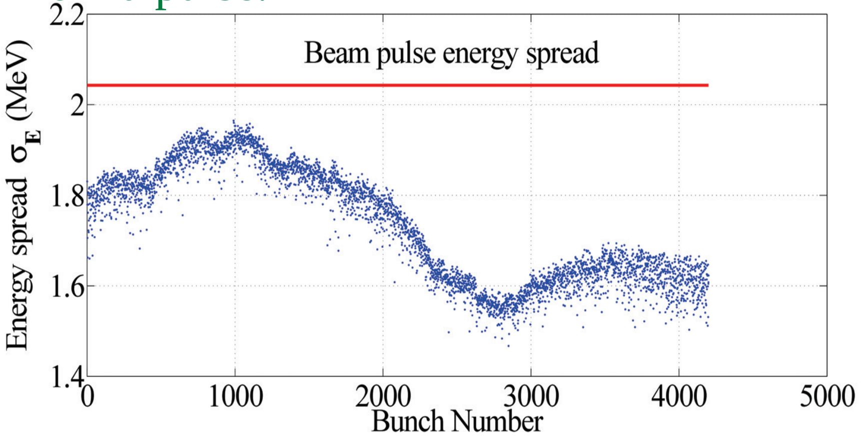
Control of vector sums by regulation of RF stations' power.



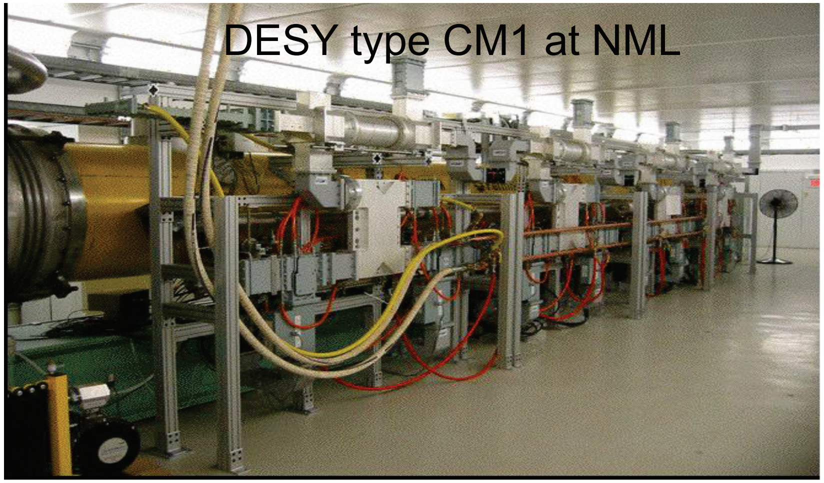


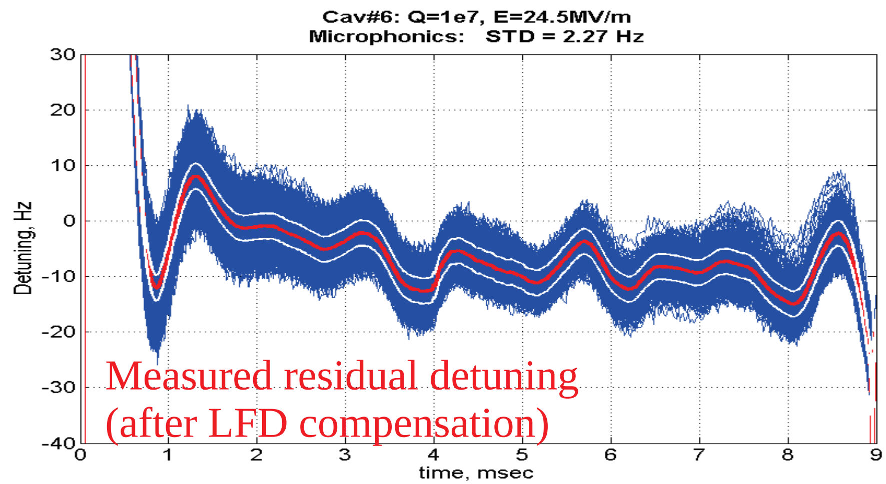
Output beam from a pulse.

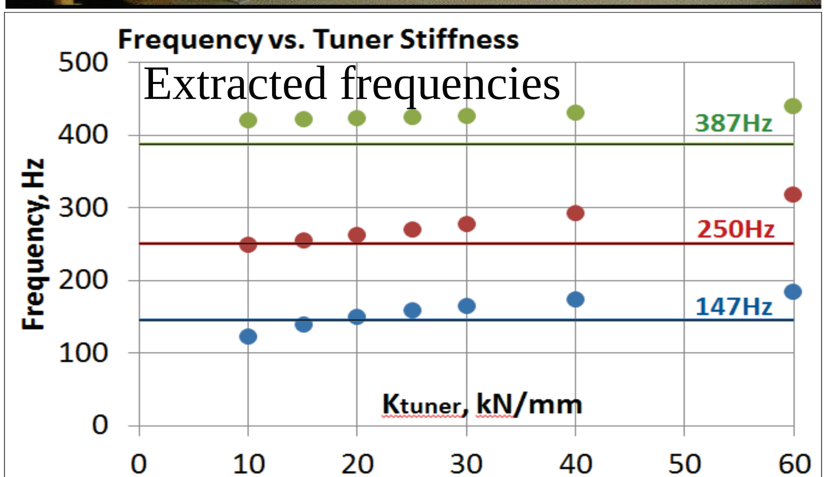




Detuning Model







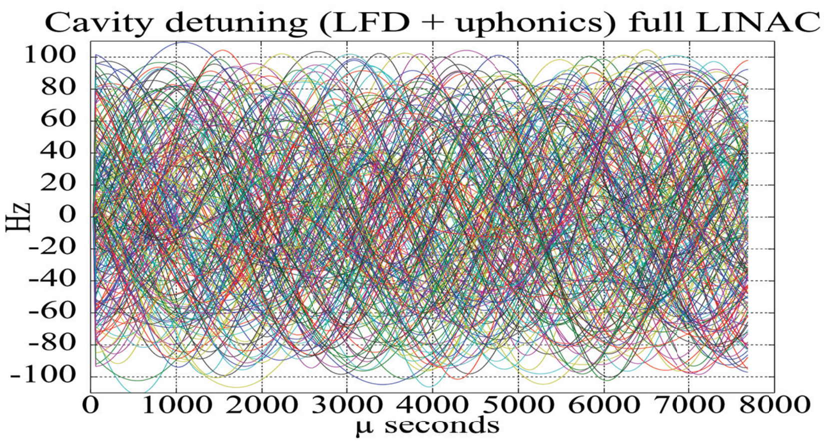
DETUNING MODEL

$f_{1,i}, f_{2,i}, f_{3,i} \rightarrow \omega_{1,i}, \omega_{2,i}, \omega_{3,i}$	cavity mechanical modes
$\alpha_{1,i}, \alpha_{2,i}, \alpha_{3,i}$	amplitudes of LFD modes
$\varphi_{1,i}, \varphi_{2,i}, \varphi_{3,i}$	phases of LFD modes
$\alpha_{0,i}$	microphonics

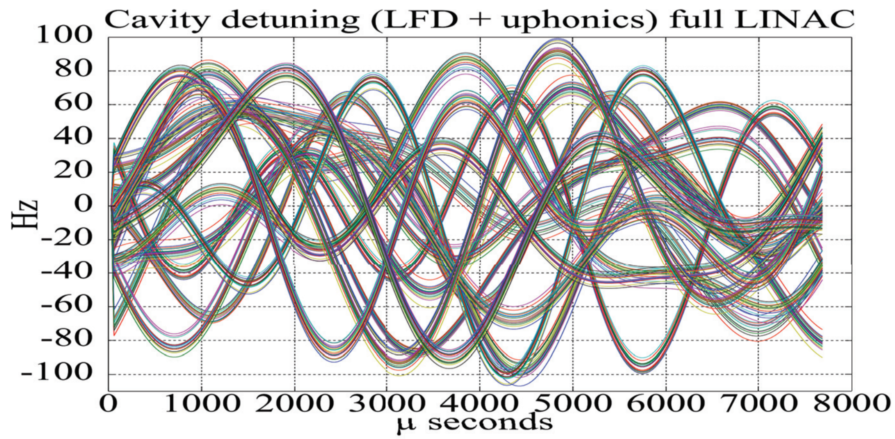
$$\Delta f_i = \alpha_{0,i} + \alpha_{1,i}\sin(\omega_{1,i}t + \varphi_{1,i}) + \alpha_{2,i}\sin(\omega_{2,i}t + \varphi_{2,i}) + \alpha_{3,i}\sin(\omega_{3,i}t + \varphi_{3,i})$$

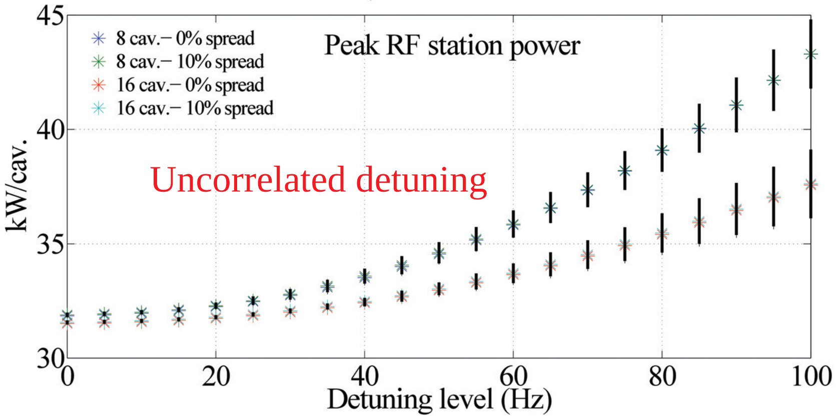
Detuning study

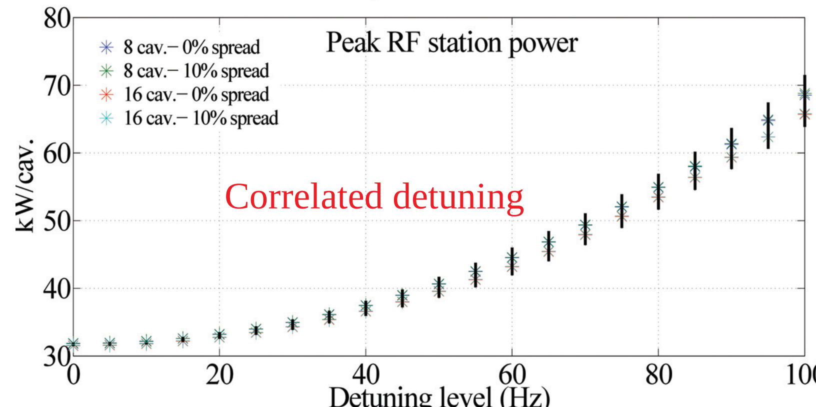
Model A: phases, amplitudes uncorrelated



Model B: phases, amplitudes correlated



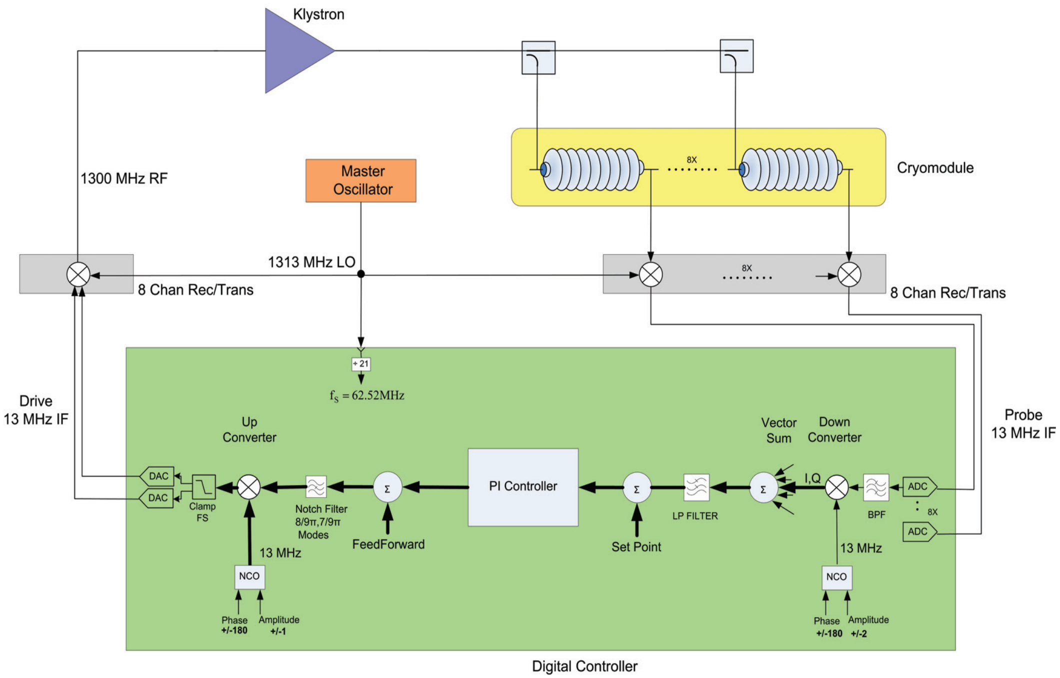




Final energy spread also bigger for correlated model.

LLRF control

Klystron delivers requested power and phase with RF station's errors and delay given by loop delay at 1MHz.



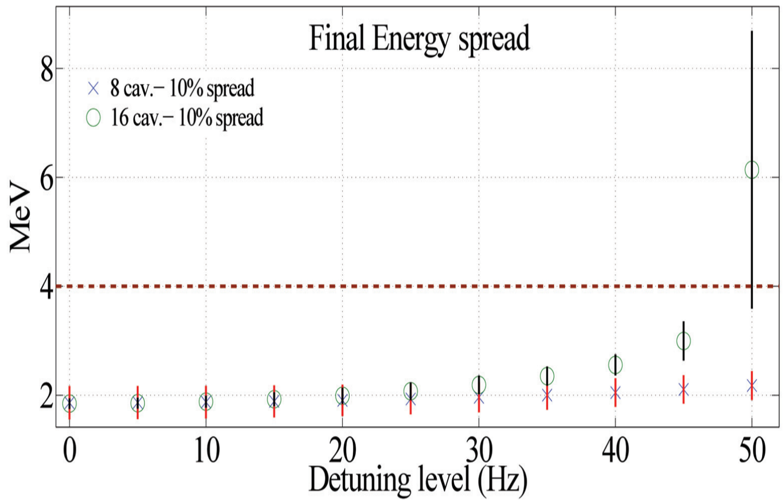
Control system receives voltage amplitude and phase with receiver's errors at f=1 MHz.

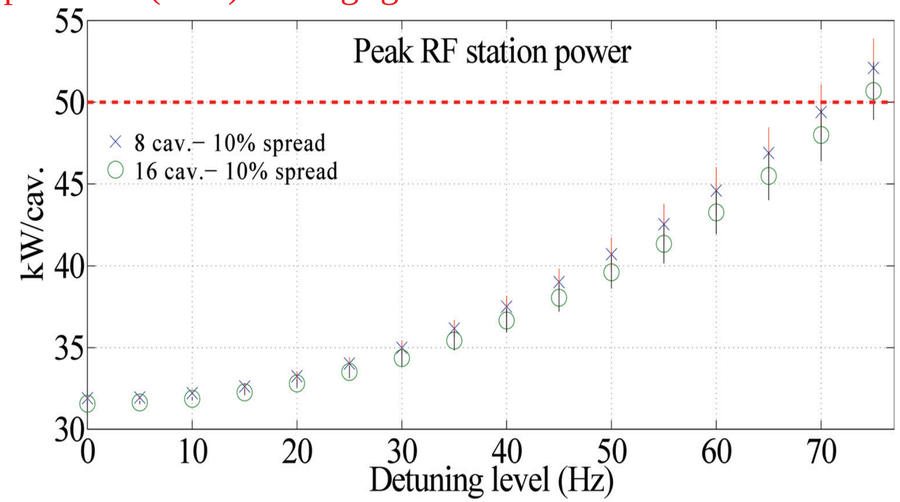
Number of RF stations	28/14
Cavities for RF station	8/16
Total detuning level (peak)	30 Hz
Receiver amp. rms error (static/dynamic)	0.67/0.009%
Receiver phase rms error (static/dynamic)	0.667/0.005 deg
Proportional gain	250
Klystron gain	1
Loop delay	1 µs
Generator amp. rms error (static)	0.2%
Generator phase rms error (static)	1 deg
RF pulse length	7.2 ms
Repetition rate	10 Hz
Beam pulse length	4.3 ms
Pulse current	1 mA
Initial rms bunch time jitter (ps)	1
Initial rms bunch energy jitter (MeV)	0.25
Bunch to bunch intensity jitter (max-min) (%)	3
Pulse to pulse intensity jitter (rms) (%)	3

RESULTS

Simulations performed varying one parameter and keeping the rest at nominal.

Effects of gradient spread up to 10% (total) are negligible.





Other LLRF parameters

Parameter	Nominal	Constraint	σ_E increase	Power increase
Generator amp. rms error (static)	0.2%	<2%	<1%	<1%
Generator phase rms error (static)	1 deg	<10 deg	<15%	<2%
Receiver amp. rms error (dynamic)	0.009%	<0.09%	<1%	<4%
Receiver phase rms error (dynamic)	0.005 deg	<0.05 deg	<1%	<14%

Conclusions & Outlook

- Beam dynamics study of the Project X pulsed linac has been carried out for single bunch simulations and an optimized design has been found.
- Simulations of longitudinal beam dynamics and LLRF control have been performed with a Matlab based code developed at Fermilab.
- Configurations of 8 and 16 cavities per RF station have been compared in presence of gradient spread in cryomodules.
- According to simulations gradient spread up to 10% (total) has no impact on performance.
- Simulations show '16 cavities' configuration more sensitive to detuning level (<50 Hz for acceptable energy spread < 4 MeV).
- LLRF parameters space have been preliminary studied, showing greater impact of phase errors in generator and receiver on results.
- Other LLRF parameters don't seem to have strong impact on performance in the range explored.
- Exploration of parameters space will be completed soon.
- Improvement of the code speed is desirable to have more accurate simulations.