Project X

WG-2: Pulsed Linac Summary

J.F. Ostiguy
(for N. Solyak)

Project X

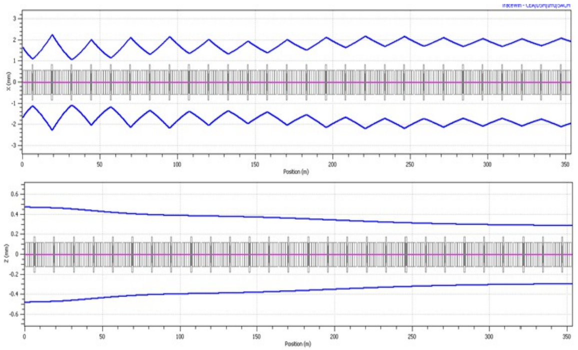
General

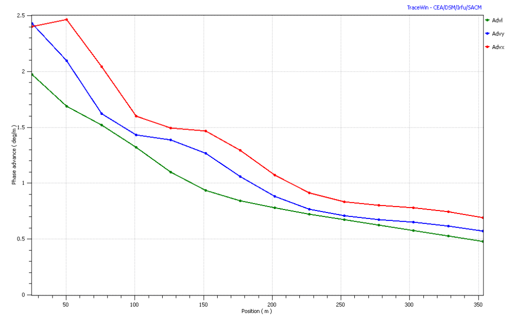
- One session, Tue 15:00-17:30, 15-20 participants
- Eight presentations, 3 main topics
  - status and general plans for FY 2012
  - transfer lines
  - LL and HL RF challenges, experimental results and modeling
- The pulsed linac is still at the conceptual level
  – Modest manpower & resources for FY12
  – Many issues in common with ILC, XFEL, SPL, ESS, SNS etc … Much interest in communications and exchanges with these groups.

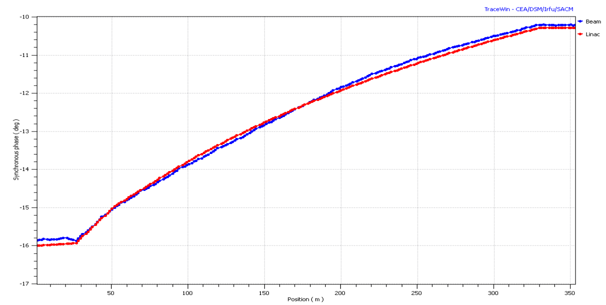
Project X

Overview

(N.Solyak)







Focusing : FODO Lattice; each quad has x/y correctors and BPM

Cavity: *Average Gradient 25 MV/m; max spread ±10% Q0=$10^{10;}$ Qload=1 • 107*

(Note: Q_L for a matched cavity at 25MV, Ib=1mA is 2.5•107 => BW1/2 =26Hz, too small to deal with LFD and microphonics)

Filling time = 4 ms, flat-top = 4.3 ms

RF source:

Pulse length = 8.3 ms; Rep. rate = 10 Hz

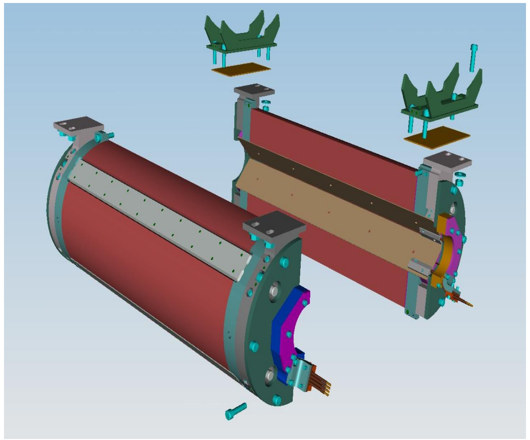
0.4 (0.8) MW klystron per 1(2) CM's (5o kW/cav with ~60% overhead)

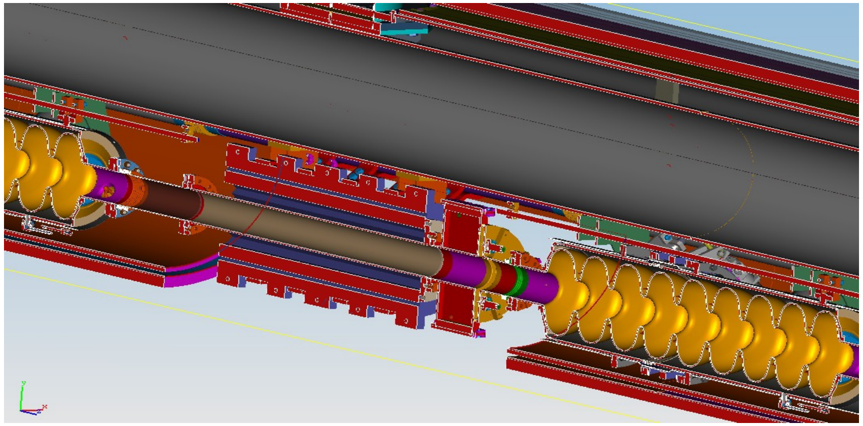
H- beam: *Current = 1 (2) mA; (10 mA peak @ 162.5 MHz)- Energy 3GeV; emittance~ 0.25 mm*mrad; σE/E=0.5MeV(init), < 10 MeV (exit)*

- Synchronous phase -10°

Splitable Quadrupole Concept For Pulsed Linac
(N. Solyak)

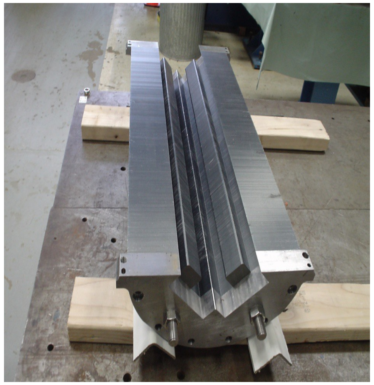
V. Kashikin

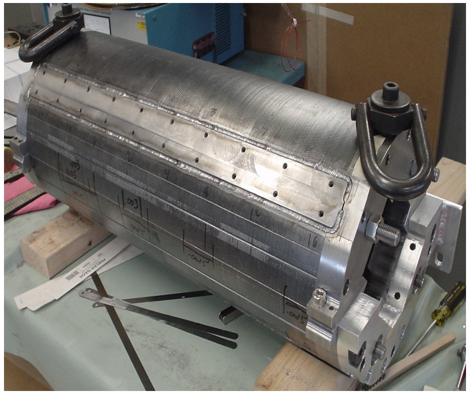


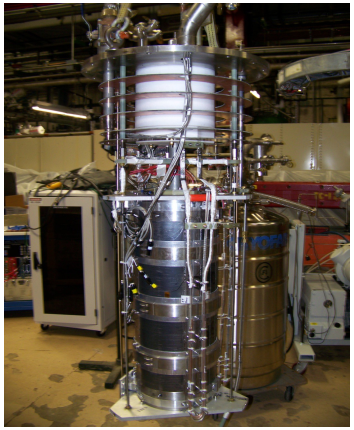


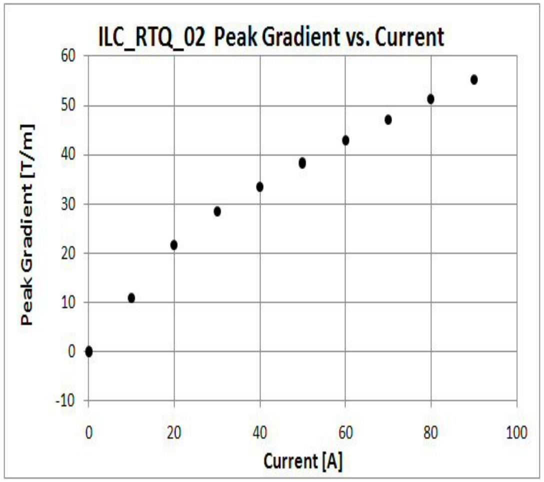
Magnet was developed for ILC, but in principle is ready for use in PX pulsed linac.
Can be simplified in view of more modest requirements for
PX PL (max gradient (4 vs 54 T/m), magnetic center stability etc)

Splittable Quadrupole Prototype









At 90 A the quadrupole reached the specified peak gradient 54 T/m.

Summary of Preliminary Studies for 3-8 GeV Linac
(N. Solyak)

- LLRF control
  - Static simulations for scheme with 1 klystron per 2 CM
    - With VS control at the level below~0.5 % and 0.5 deg (individual cavity error ~10% and 10 deg) allow keep energy jitter at 8 GeV below 10 MeV. (needed for injection)
  - Dynamics simulations with LFD/microphonics and Acc. gradient spread underway (see presentations: G.Cancello, B.Chase, Y.Eidelman)
- Beam losses are smaller than for CW linac
  - Intra-beam stripping is well below 0.1 W/m
  - Magnetic stripping is small for reasonable beam displacement (<20mm)

FY2012 R&D Plan

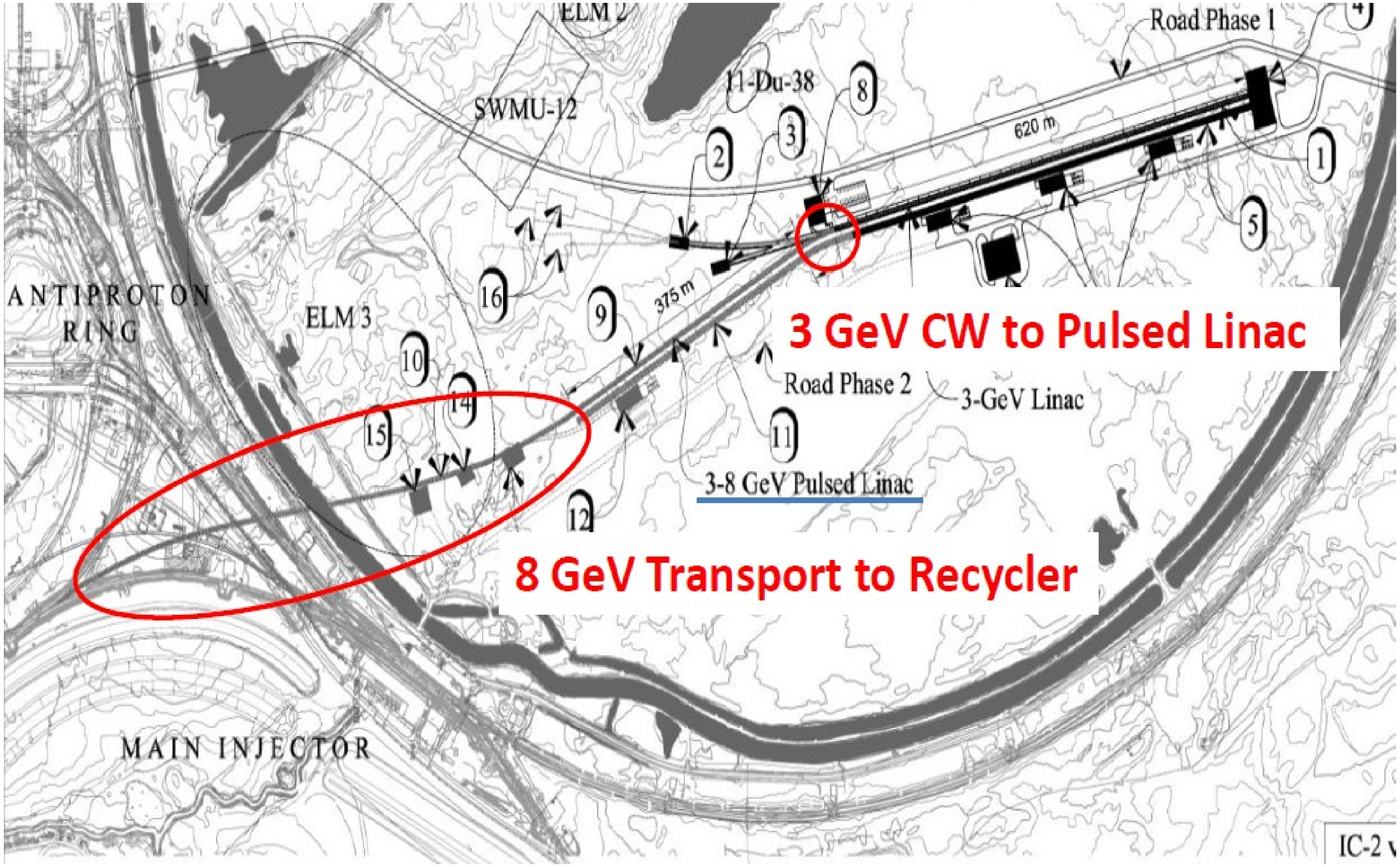
(N. Solyak)

- Complete lattice design and specifications for misalignments and RF tolerances (N.Solyak)
  - Beam dynamics, losses, system specifications
  - Failure analysis
  - Long-pulse operation stability requirements
  - Concept Design of the beam collimation system and Radiation issues, Specs
  - Develop specs for linac components
  - Review modified ILC like CM design (cavity, coupler,magnets,cryo) as a baseline for pulse linac
- Design of the transport lines to and from pulsed linac, functional specs (D.Johnson)
- Develop conceptual design of the HLRF system (modulators, klystrons, PDS, controls) – J.Reid
  - Define baseline configuration and alternatives based on requirements and cost analysis
  - Write specifications and cost estimations for HLRF system
- LLRF performances study and development of specifications for long pulse operation regime (B.Chase)
  - Develop LLRF control system for cavity, operating in long-pulse regime, based on multiple tests of ILC like cavities in HTS and NML cryomodule
  - Develop models and software for long-pulse operations with LLRF controls
  - Develop specifications and costing of LLRF system.
- Complete conceptual and EM design of splittable SC magnet (V.Kashikhin)
- Conceptual design of the cryogenic systems and specifications (A.Klebaner)
- Create specifications for beam diagnostics in Linac and transport lines (M.Wendt)

TOTAL= 4.3 FTEs

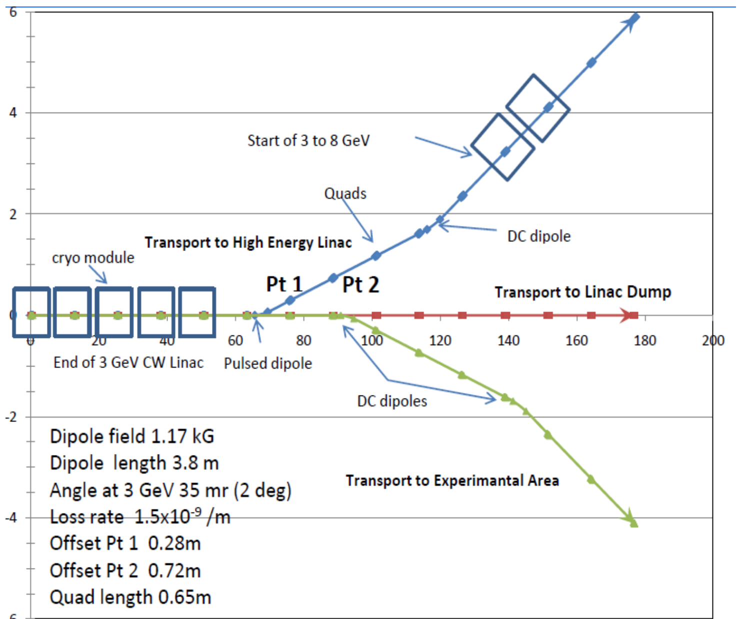
Pulsed Linac Transfer Lines

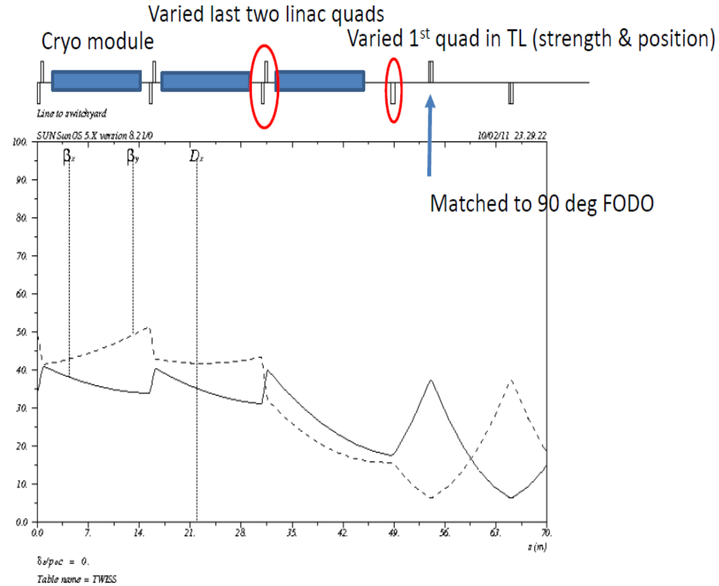
(D. Johnson)



CW Linac to Pulsed Linac

(D. Johnson)





At 10 Hz Intensity is 2.7×10^{14} particles/sec

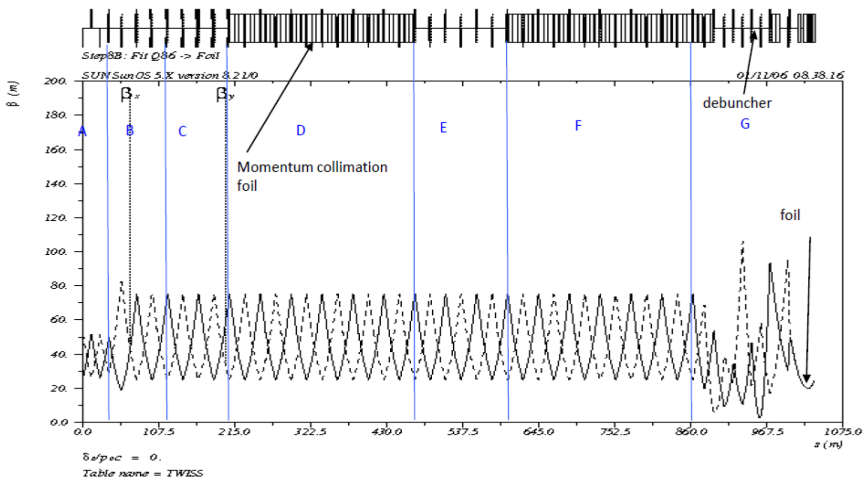
Beam Power 130 kW

Loss Mechanism	3 GeV 130 kW		
	Value	loss/m	W/m
Black body	300°K	1.30E-07	1.690E-02
Lorentz	1.17 kG	1.52E-09	1.976E-04
Vacuum	1×10^{-8}	1.30E-08	1.690E-03
Total		1.45E-07	0.019
Residual activation bare beam pipe [mrem/hr]			2.787

"Fairly straightforward; should be no issues
- Don't foresee the need for collimation or Cold beam tube."

8 GeV Transport
(D. Johnson)

8 GeV transport line from Proton Driver design showing basic layout



Details of design change according to

–**which ring we inject into**

–Operational scenarios (i.e, maximum beam intensity)
- Full 10 Hz operation (2.7E14 particles/sec) for 345 kW
- Just 6 linac pulses for 120 GeV neutrino program (170 kW)

–**Elevation of transport line and the requirement for vertical achromat**

Proton Driver and Project X Initial Configuration contained an 8 GeV beam dump line
–needs re-evaluation

•Injection and transport line design will ultimately determine the footprint of the Project X facility

HLRF Parameters
(J.Reid)

3-8 GeV Pulsed Linac

Two scenarios at present

1. Inject into recycler @ 8 GeV – 8 mSec RF pulse, 10Hz
   - Requires Linac output energy to match 8 GeV recycler input
   - Must have sufficient rf overhead to overcome failed rf station

2. Inject directly into MI 6-8 Gev ~ 30mSec RF pulse, 2 Hz

28 cryomodules

8 Cavities + one focusing magnet per cryomodule

Beta = 0.97 at the input

Based on ILC / XFEL type cryomodules

R/Q = 1036

Loaded Q = 1e7 to reduce the effects of both Lorentz force detuning and microphonics

Cavity Gradients all greater than 25 MV/m

Table of Parameters

Table of RF Parameters - 1.3GHz Pulsed Linac

	Recycler/MI	Direct Injection into MI
Frequency:	1.3GHz	1.3 GHz
Loaded Q:	1e7	1e7
RF Pulse width:	8.0 mSec	30 mSec
Cavity Gradient:	25 MV/m	25 MV/m
Beam Current:	1 mA	1 mA
Repetition rate:	10 Hz	2 Hz
Cavity Power +losses +regulation +EOL:	50 kW	50 kW
Power required per Cryomodule:	400 kW	400 kW
Cryomodule average RF Power:	32 kW	24 kW

Losses ~ 1.10, Regulation overhead ~1.15, Klystron EOL ~ 0.80

Klystron Parameters

(J. Reid)

Klystron Parameters

- Number of cryomodules per klystron (1 or 2) for a total of 14 or 28 klystrons
- Possible klystron parameters:

Klystron Type	**SBK**	**MBK**	**SBK**	**MBK**
Klystron Power (kW)	400	400	800	800
Voltage (kV)	54	33	71	44
Current (Amps)	12	20	19	30
Efficiency (%)	60-62	62-64	60-62	62-64
Average Power (kW)	32	32	64	64

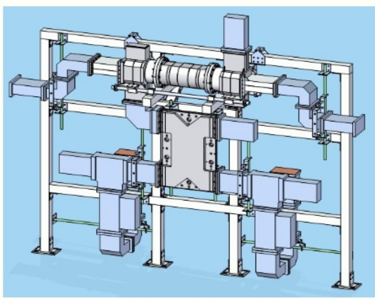
- Modulator Type (solid state), V&I criteria, No HV pulse transformer
  - Solid state multiple stage modulators, etc. (Lower voltage requirements make it cheaper)
- Power distribution system: Equal powers or Proportional power distribution

Power Distribution Schemes How many Cavities/ Klystron ?

(J. Reid)

CM1 at NML

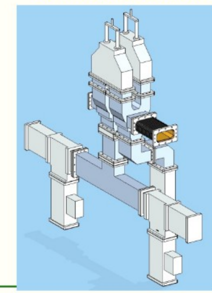
VTO (Variable Tap-OFF) – manually adjustable power dividers to adjust rf split to cavity pairs (requires pair sorting).



Developed as part of collaboration with SLAC

CM2 Distribution Scheme

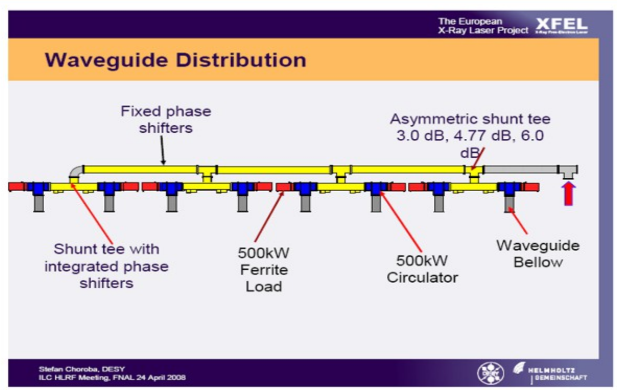
- Alternate Scheme with folded Magic –T's and motorized U-bend phase shifters.
  - Remotely adjustable by pairs (requires pair sorting).



Developed as part of collaboration with SLAC

October 25, 2011 John Reid 1

XFEL Distribution



LLRF Requirements
(B. Chase)

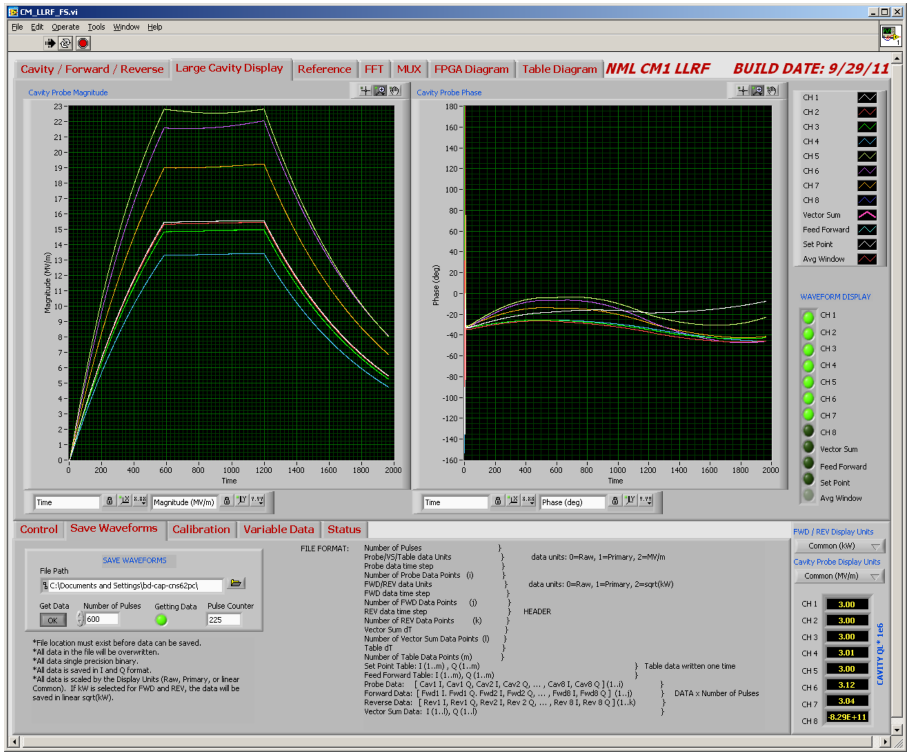
RF Control Requirements

	Inject RR	Inject MI	Comments
Cavities per RF Station	16	16	Discussion on 8 vs 16
Pulse width	8.3ms	30ms	Same difficulty
Rep rate	10 Hz	~1 Hz	
Beam current	1mA	1mA	
Gradient	25 MV/m	25 MV/m	
Loaded Qs	1E7	1E7	Simulations -> lower Qls
Regulation (RF Station VS)	0.5 deg. 0.5%	0.5 deg. 0.5%	Early simulation efforts
Individual cavities within an RF station	10 deg 10%	10 deg 10%	Early simulation efforts Complex issues…
Tolerance to piezo failure	Not tolerant	Not tolerant	Detune cavity
Gradient spread of cavities within RF group	10%	10%	Not yet achieved – see simulations

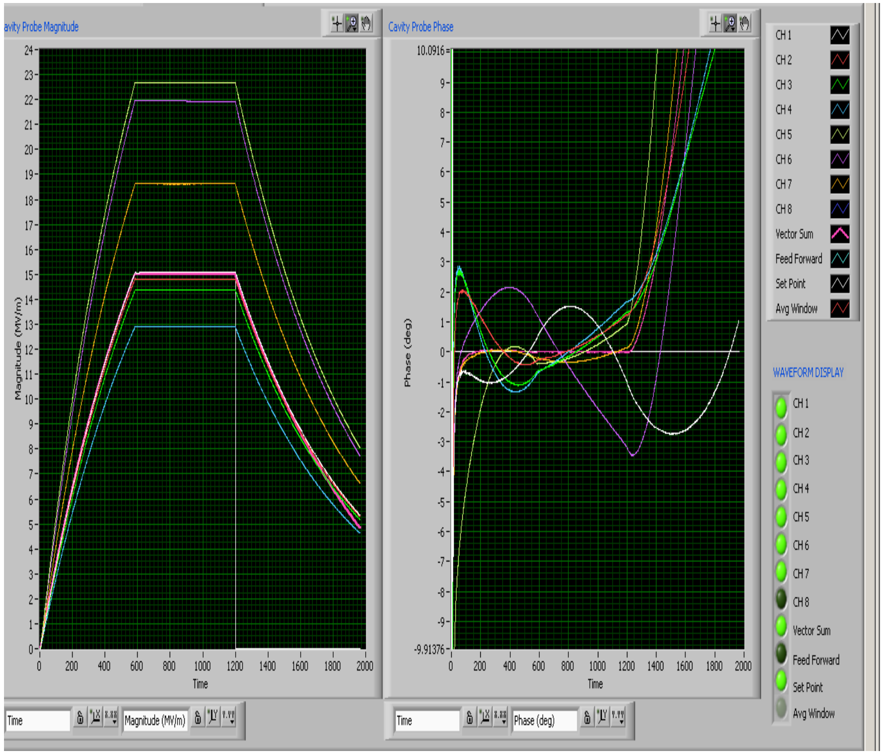
Main Points

- LLRF can do a great job of controlling the Vector sum
  - Regulation errors 10-4
  - VS calibration beambased predicted errors 5x10-3
    - Noise in measurements, R/Q value, Microphonics
- Gradient spreads cause cavity tilts
- Piezo resonance control must work
- Resonance control errors drive power overhead requirements

Experimental Results NML CM1 Feedback + Piezo Detuning Compensation (B. Chase)



Feedback OFF

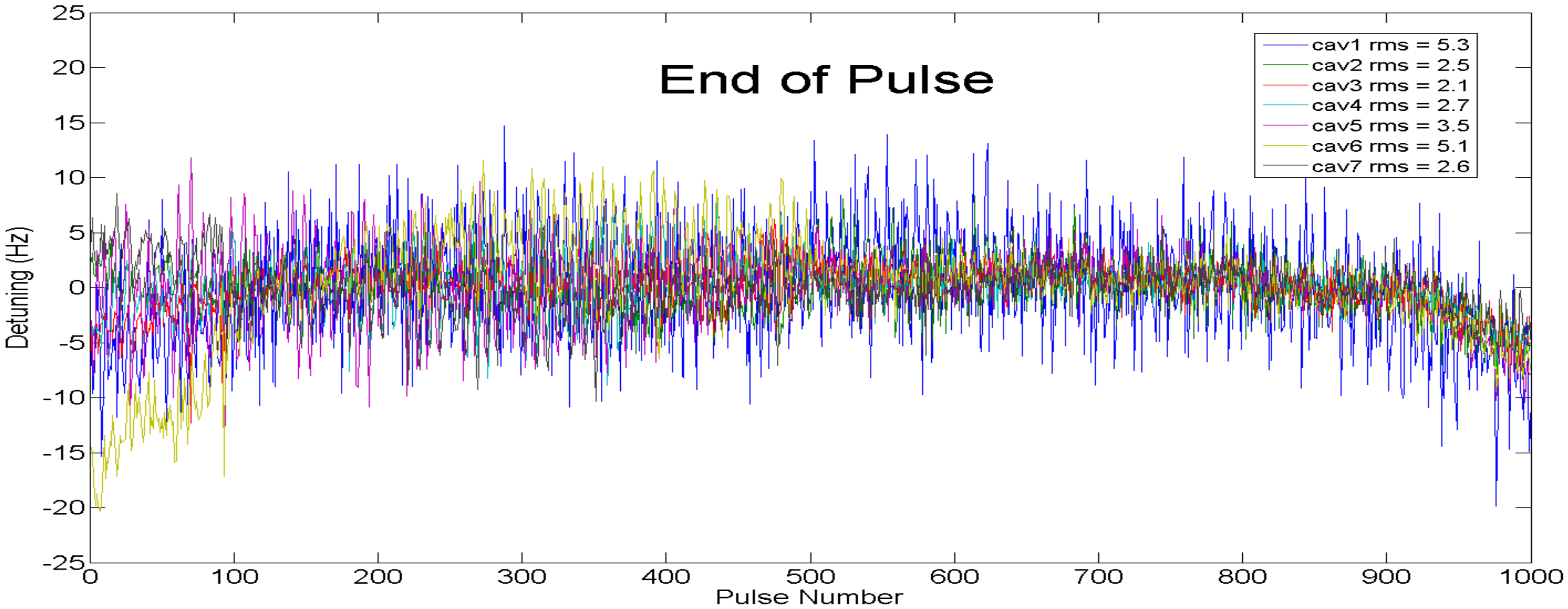


Feedback ON

Microphonic Detuning for 7 Cavities

1000 second period, 1 Hz rep rate

Cavity 1 does not have active detuning compensation (control case)

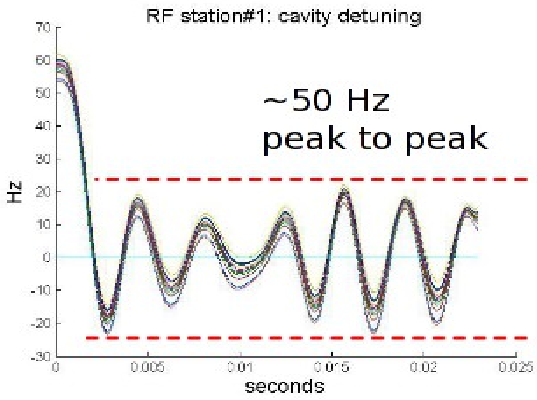


Detuning and Fill Time

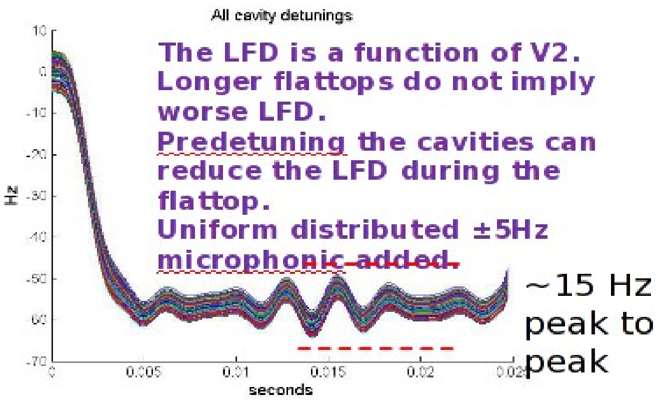
Detuning for 4.2ms vs. 2.4ms fill time

- ILC type 9-cell niobium cavities detune about 600Hz at 25MV by effect of LFD. This number would prohibitive in terms of RF power required. We assume that LFD can be reduced to 50Hz peak to peak or better.
- In this simulation we assume a cavity to cavity uniform random microphonic detuning of ±5Hz.

2.4 ms fill



4.2 ms fill

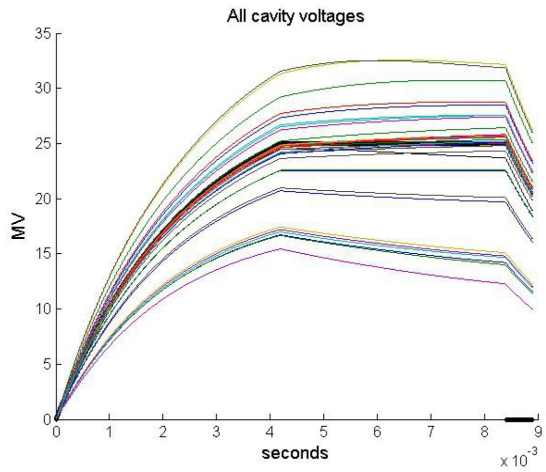


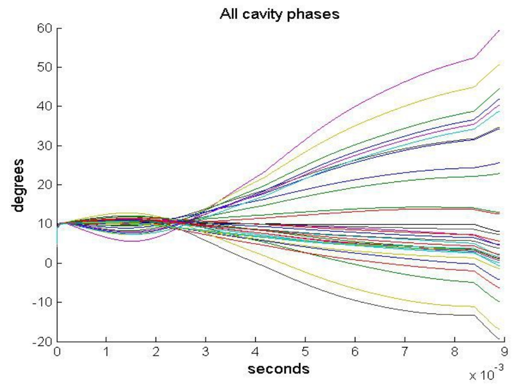
The size of the Δω oscillation is proportional to electrical bandwidth ω12. I.e. inversely proportional to the electrical QL and also to the fill time.

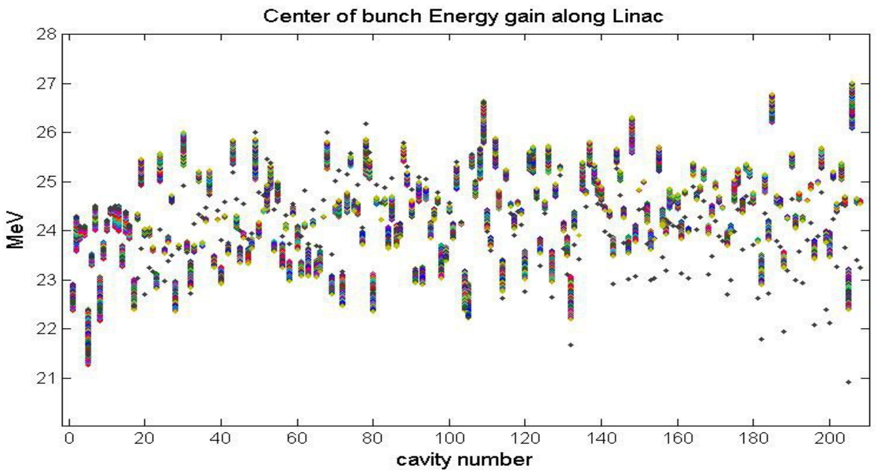
Dynamic Simulations with LLRF Stabilization: 20% gradient spread, LFD, u-phonics, beam and coupler errors (G. Cancelo)

- 1st RF station is DESY-FLASH ACC6-7
- All other 12 RF stations have 2 low gradient cavities at 18MV and 14 cavities at 26MV.

- Simulation assumptions:
  - LFD: ~ 60 Hz at 25 MV.
  - μ-phonics: ±5Hz uniformly distributed.
  - Beam errors:
  - Coupler error: 10% uniformly distributed.

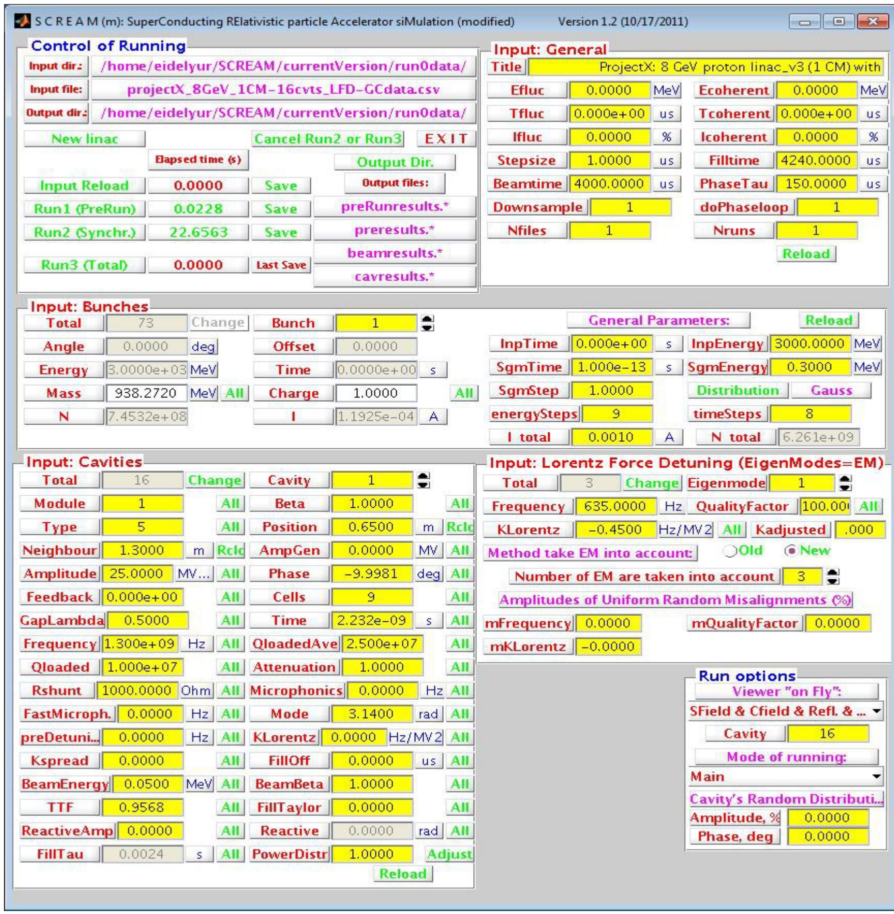






SCREAMm : Improved version of SCREAM

(Y.Eidelman et al.)



Main new features:

- More realistic expression for the vector-sum;
- Friendly GUI;
- More realistic modeling of Lorentz detuning

Concerns for 3-8 GeV Pulsed Linac

3-8 GeV pulsed LINAC: Major concerns

- Only VS is regulated (flat), individual cavity gradients tilt (A & φ)
  - Non constant beam energy gain along bunch train.
  - Potential emmitance grow and beam loss due to tilts in amplitudes and phases.
  - How do we fix cavity tilts?
- LFD: peak to peak detuning, in particular for long pulses.
  - Impact of fill time in LFD.
  - Active compensation or stiffer mechanical systems?
- Gradient spread.
  - Reduce gradient spread or minimize impact.
  - Find optimum QL for a given gradient spread.
- Bringing up the LINAC
  - How much gradient overhead is needed to go from Ib=0 to Ib=max?

Lorentz Detuning Model

(Y.Eidelman et al.)

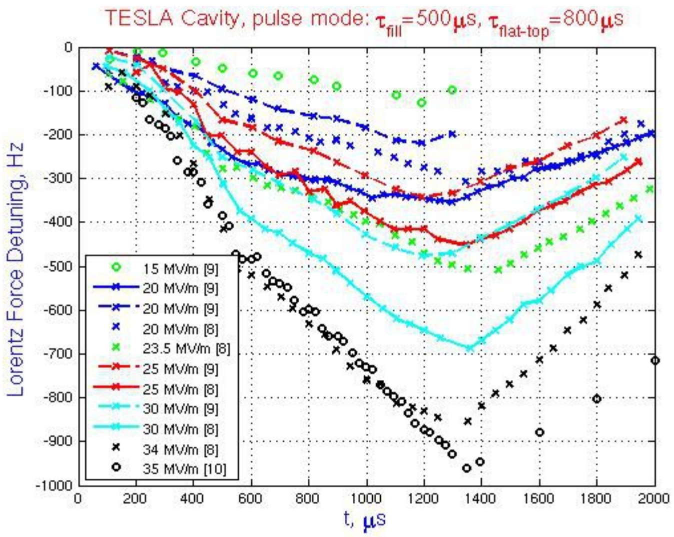
$$\Delta\omega''_m + \frac{\omega'_m}{Q_m} + \omega_m^2 \Delta\omega = 2\pi\omega_m^2 K_m V^2(t)$$

$$V(t) = V_0 t/\tau \quad t \leq \tau$$

$$V_0 \quad \tau < t \leq T$$

$$V_0 \mathrm{e}^{-\gamma_{RF}(t-T)/2} \quad t > T$$

LFD Model Based on N-mode Fit



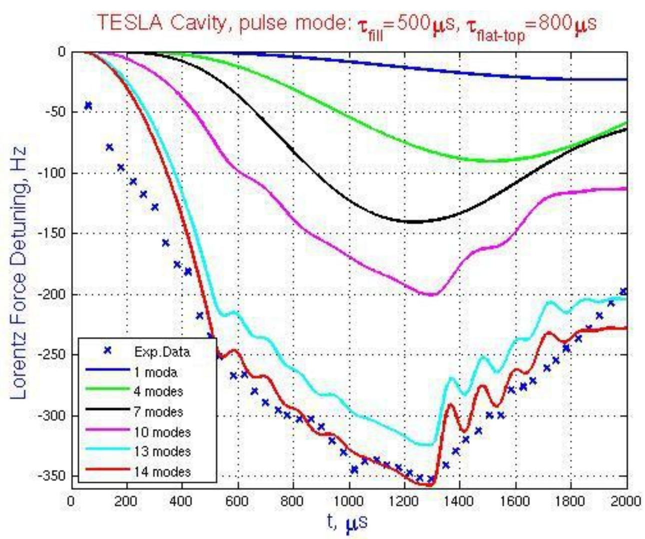
Experimental Data: LFD Measurements

Short pulse:

$$\tau_{fill} = 500\ \mu s,$$

$$\tau_{flat} = 800\ \mu s$$

Simulation of LFD taking into account increasing number of the eigenmodes



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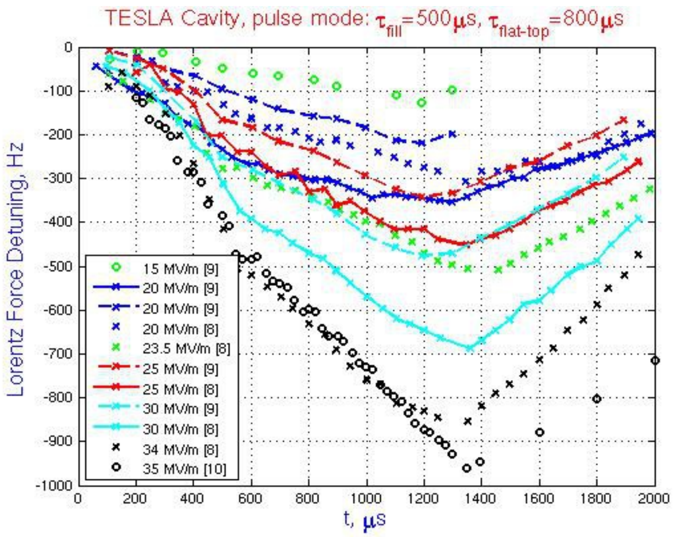

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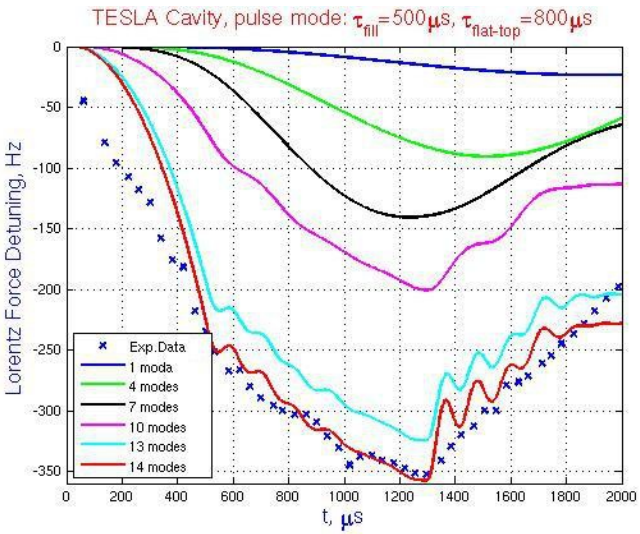


FNAL Adaptive LFD

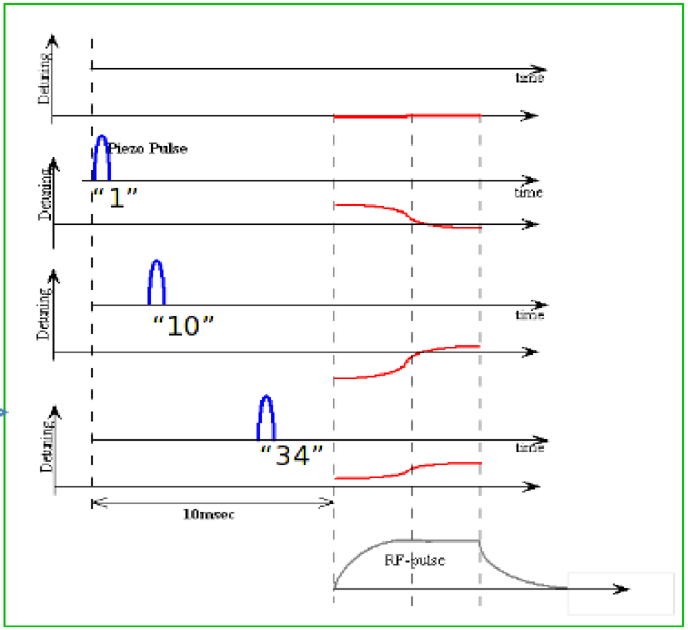
(Y. Pischalnikov)

Adaptive Least Square LFD Algorithm

has been developed at Fermilab as a part of SRF Resonance Control R&D program
(Developed by Warren Schappert.)

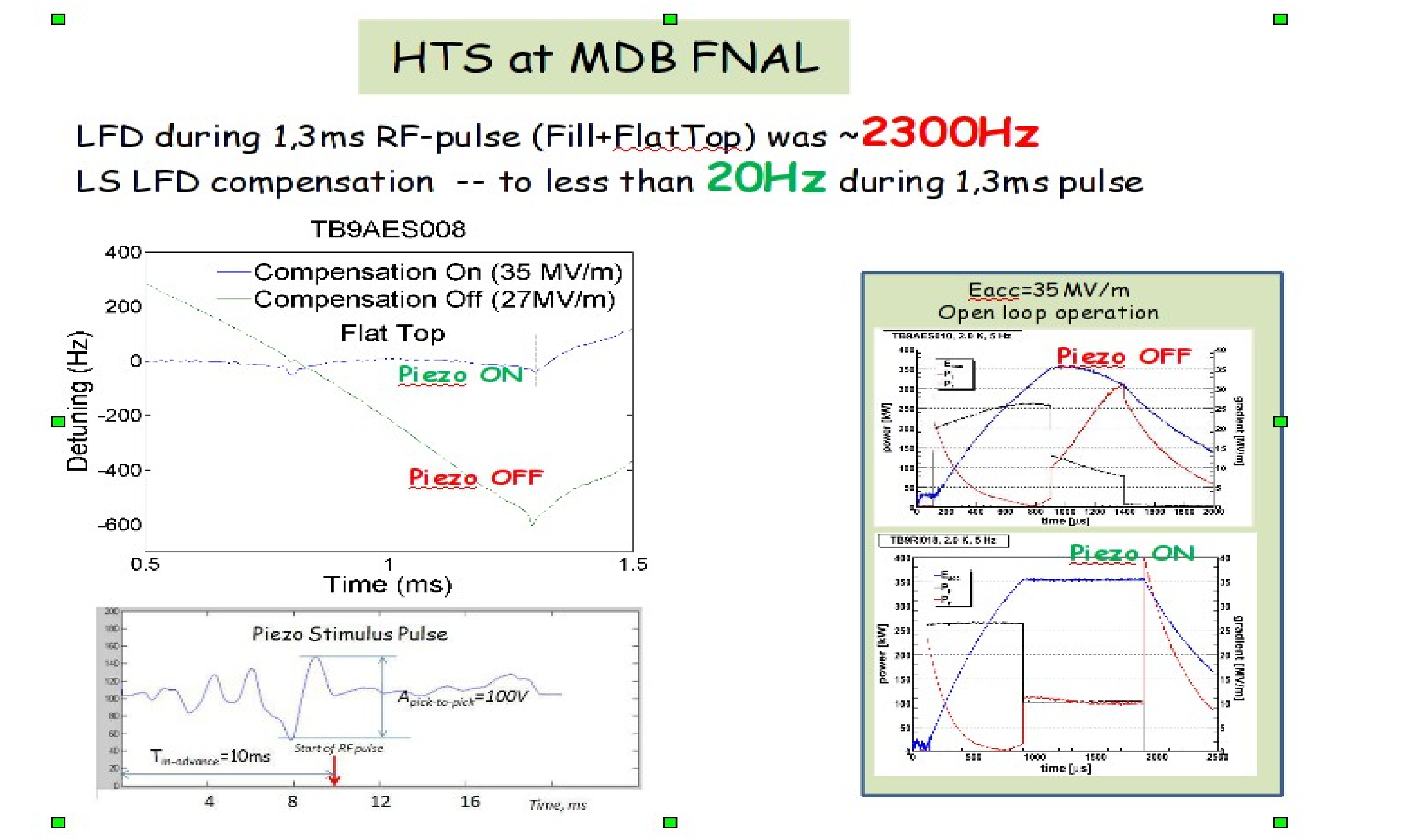
The response of the cavity frequency to the piezo impulse (TF) can be easily measured when cavity operated in CW-mode.
Since it is often not convenient to connect a pulsed cavity to CW source we developed alternative technique to measure this response (TF) when cavity operated in RF-pulse mode.

Piezo/cavity excited be sequence of small (several volts) narrow (1-2ms) pulses at various delay.
The forward, probe and reflected RF waveform recorded at each delay and used to calculate detuning.
[Response Matrix]



Details of Adaptive LS LFD Algorithm at :
"W. Schappert, Y.Pischalnikov, "Adaptive Lorentz Force Detuning Compensation".
Fermilab Preprint -TM-2476-TD.

LFD Compensation Test



Final Remarks

- 3-8 Pulsed linac RF control is challenging given the long pulse length and low beam loading.
- Effective LFD compensation is essential
- RF Power distribution scheme needs to be optimized, taking into account the need to operate with cavity (10-20% ?) gradient spread. (cavities/klystron ?)
- Optics design is relatively straightforward at high energy and appears under control although many details still need to be finalized.