Developing Common Metrics and Models for RF Overhead Calculations

Brian Chase FNAL
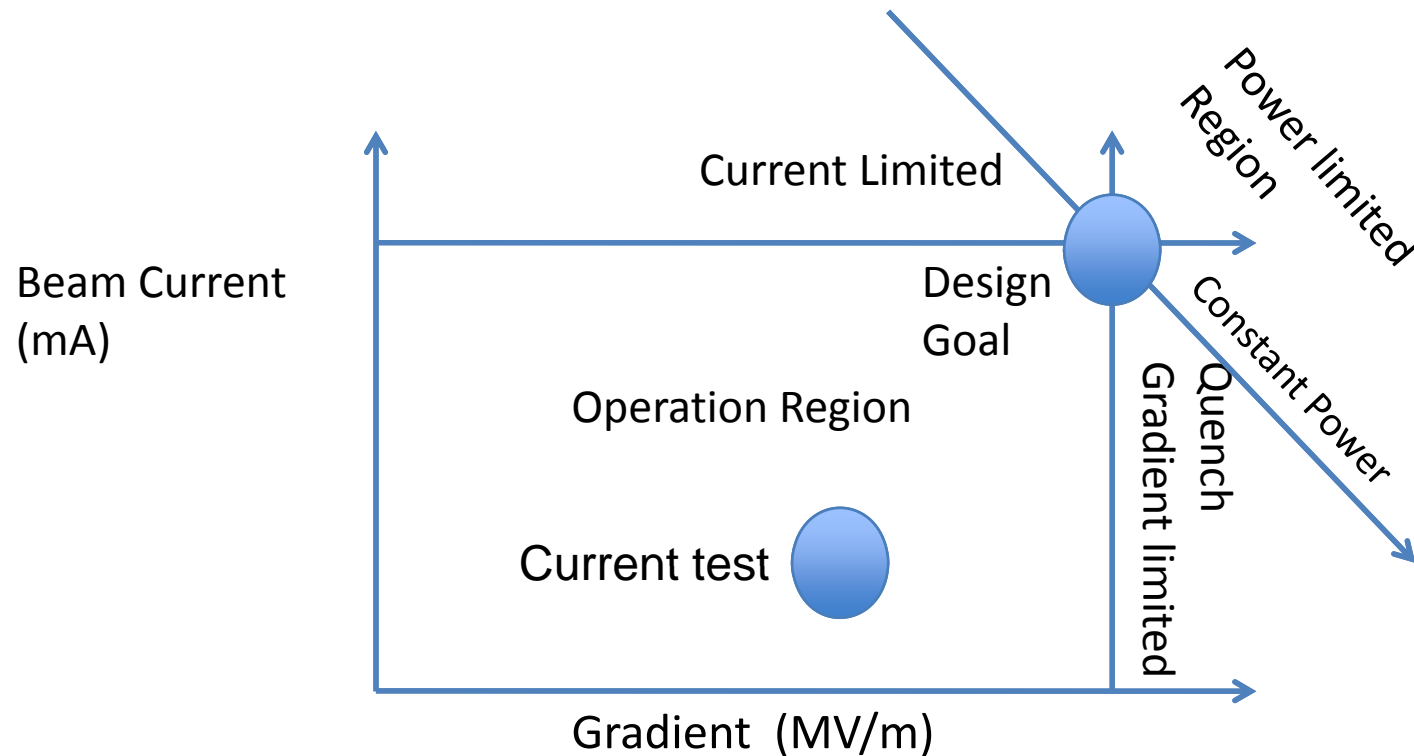Presenter for ILC LLRF Team

Overview

- Issues surrounding power overhead
  - Value engineering (performance vs. capital expense)
  - Optimize design
- Power budget
  - Understanding losses and disturbances
- Models
  - Global and local RF station
  - Simulations
- Metrics – how to make meaningful measurements
  - 9mA tests and other system tests
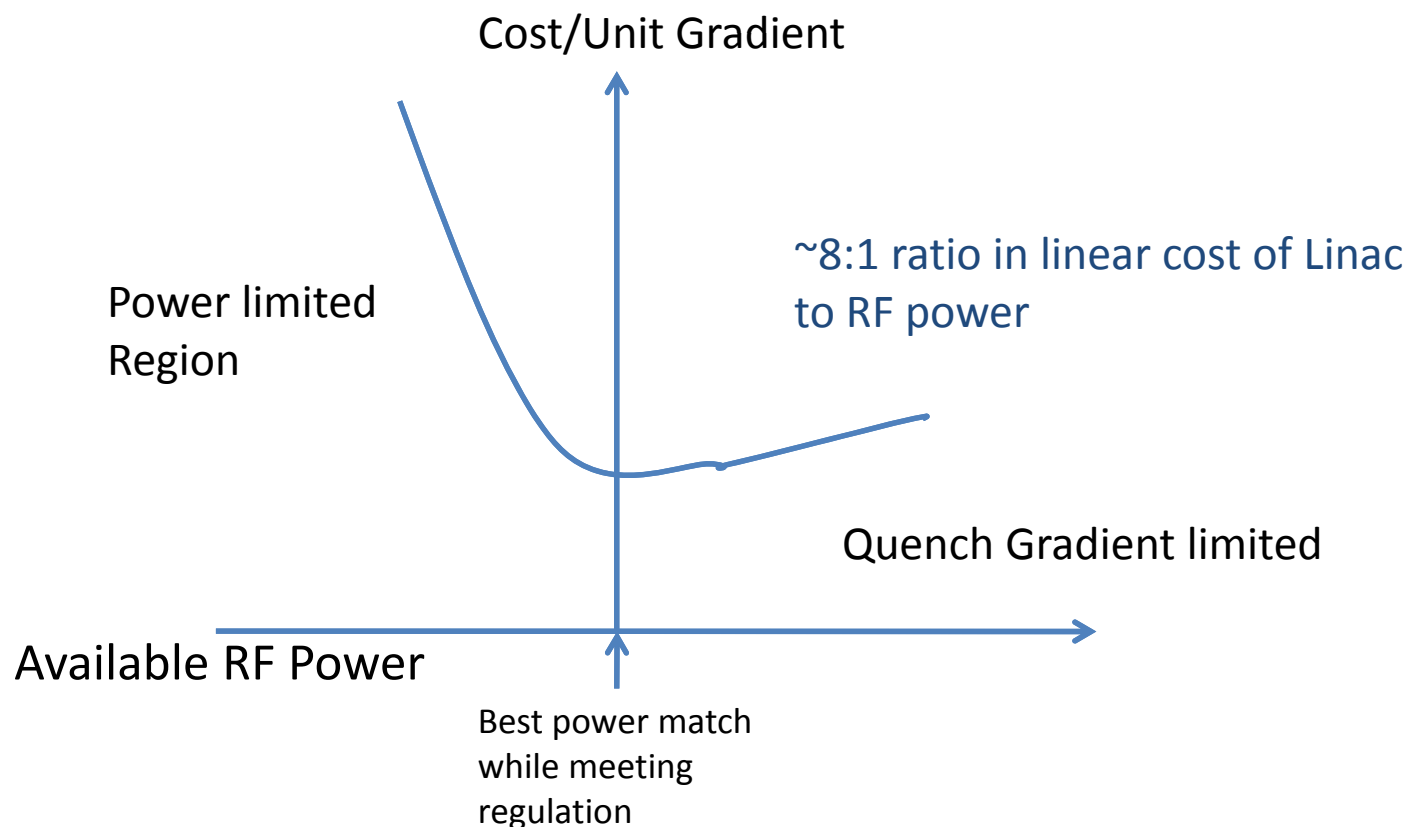 - Extrapolate to ILC
- Plans going forward

Power Requirements Based on Maximum Gradient and Maximum Beam Current

Beam Current (mA)

Current Limited

Power limited Region

Design Goal

Constant Power

Operation Region

Quench Gradient limited

Current test

Gradient (MV/m)

- Peak power is only required at peak gradient and beam current
- Goal: Meet design requirements with minimal power overhead (cost)
- Could operation ever go outside of the design operation region?

Accelerator Section Cost/Gradient vs. Klystron max Power

Cost/Unit Gradient

~8:1 ratio in linear cost of Linac to RF power

Power limited Region

Quench Gradient limited

Available RF Power

Best power match while meeting regulation

Example: If the last half of cryomodule production increased gradient to 33MV/m and we increased available power to match – save $## in capital expense

Sources of Perturbations

o <u>Beam loading</u>
  - **Beam current fluctuations**
  - **Pulsed beam transients**
  - Multipacting and field emission
  - Excitation of HOMs
  - **Excitation of other passband modes**
  - Wake fields

o <u>Cavity drive signal</u>
  - HV- Pulse flatness
  - HV PS ripple
  - Phase noise from master oscillator
  - Timing signal jitter
  - Mismatch in power distribution

o <u>Cavity dynamics</u>
  - cavity filling
  - settling time of field

o <u>Cavity resonance frequency change</u>
  - thermal effects (power dependent)
  - **Microphonics**
  - **Lorentz force detuning**

o <u>Other</u>
  - Response of feedback system
  - Interlock trips
  - Thermal drifts (electronics, power amplifiers, cables, power transmission system)

Static Losses

Distribution Loss	Mostly the same for all Stations
Cavity Gradient Variation	Dependent on Cavity quench limit
Parameter Variation	Dependent on Ql match
Peak Power Headroom	Same for all klystrons
Slow Thermal Drifts	Generate Vector Sum errors

There are few statistics available on these losses

Disturbance Categories

Narrowband or static errors	Broadband (noise)
Lorentz Force and microphonic detuning	System, Receiver and ADC noise * gain
Parameter variation	Transmitter and Drive amplifier
Waveguide loss	Klystron modulator ripple
Beam current fluctuations	Spurious noise sources

Static or phase modulating disturbances subtract in linear power

Amplitude modulating noise sources subtract in linear voltage

Non linear system responses cause AM - PM conversion and coupling in feedback loops

RF Station Power Budget
(Straw-man Proposal)

	Voltage loss	Power loss	Available Power (MW)
High Level RF Loss Factors			
Maximum Klystron Output Power		0.0%	10.00
De-rating of klystron for end of life time		0.0%	10.00
Modulator Ripple Spec = 1% (Often worse)	0%	0.0%	10.00
Waveguide and circulator losses		8.0%	9.20
Power loss due to cavity gradient variation		0.0%	9.20
Parameter variation	0.5%	1.0%	9.11
Low Level RF Loss Factors			
Peak power headroom	2.0%	4.0%	8.75
Dynamic Headroom	1.0%	2.0%	8.57
Beam current fluctuations of 1%pk		1.0%	8.49
Detuning errors of 30 Hz	1.0%	2.0%	8.32
Klystron drive noise sidebands	1.0%	2.0%	8.15
Beam Power Requirments for 26 cavities			
Power Required for 9.0ma @ 31.5 MV/m			7.651098
Excess Power Headroom			0.50

Note: Lower power per cavity -> higher QI and longer fill and decay times
This requires a longer modulator pulse and higher cryo loading
30 Hz detuning errors are the sum of microphonics and Lorentz force detuning. (Even if microphonics=0, we

Model for Overhead Power

- We develop a model that we use to estimate the required RF overhead given:
  - Performance requirements
    - Regulation of beam energy and jitter
    - Reliability and exception rate
  - Measured or calculated losses
  - Measured noise spectrum (rms, spectrum, peak, etc)
  - ...
- We use measurements at FLASH etc to help develop and validate the model and power budget
- Output would be a series of graphs, eg
  - Overhead requirements vs. noise power
  - Overhead vs. percentage of time within spec
  - ...

System response to noise + ramp into a compression stage
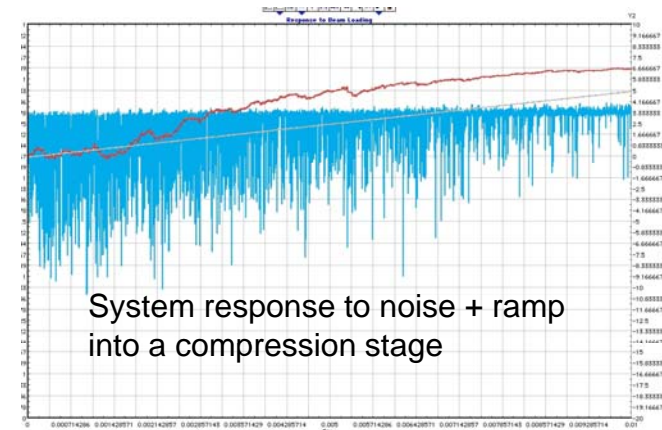
Models and Simulators

- Accepted model for the cavities (Tesla)
  - Dependent on dressed cavity design
- Model for HLRF is dependent on:
  - Drive amplifier
  - Modulator type and specification
  - klystron (3 types)
  - Distribution scheme
- Model for LLRF is dependent on
  - Design variations
  - Distribution scheme
- Present simulator features:
  - Cavity, klystron response, Ql, Pk
  - Drive amp response, receiver noise
- Goal: A common Matlab simulator for general use
  - We are fairly close

3 adjustment parameters :

1- LLRF (drive signal amplitude and phase)

2- cavity power coupler, Q_L
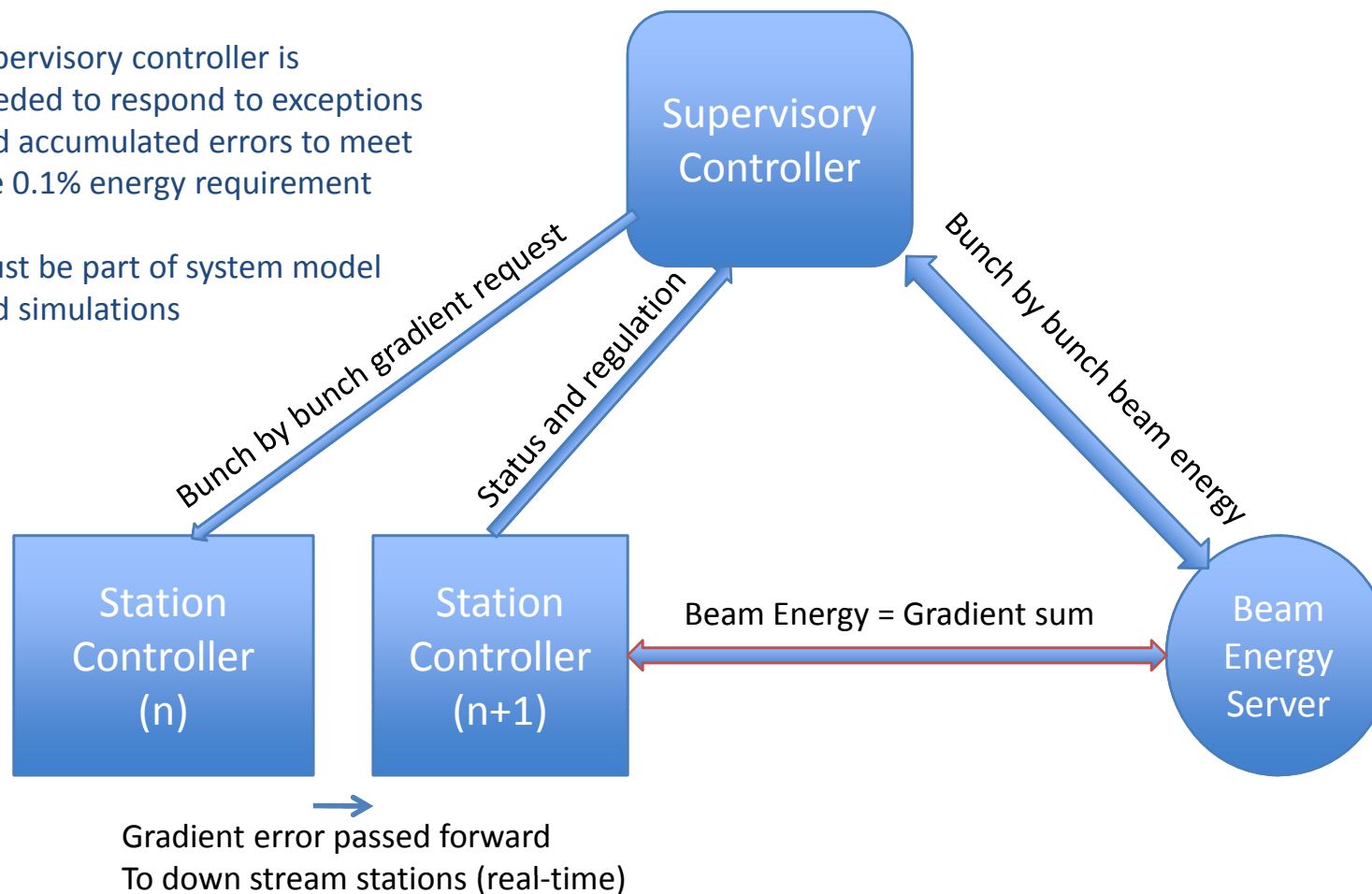
3- waveguide power coupler, P_k
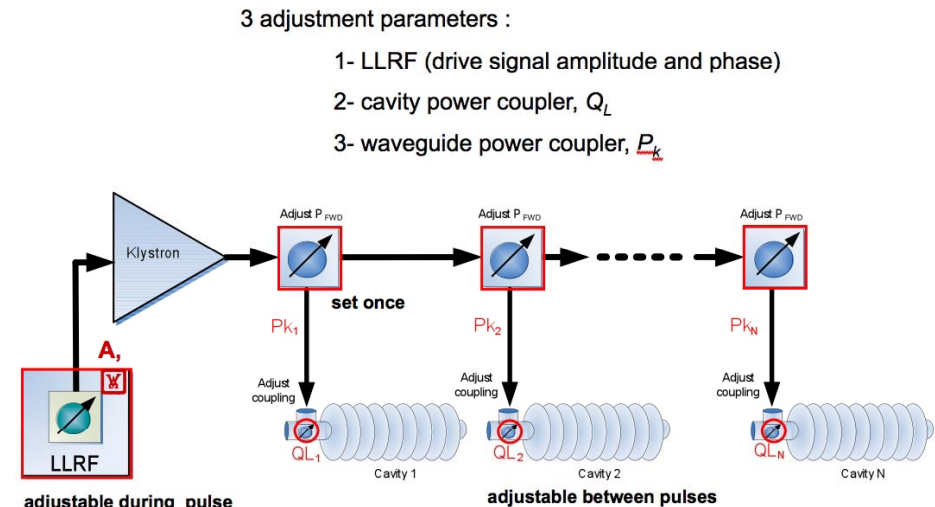
Supervisory Control of Energy Regulation

Supervisory controller is needed to respond to exceptions and accumulated errors to meet the 0.1% energy requirement

Must be part of system model and simulations

Supervisory Controller

Station Controller (n)

Station Controller (n+1)

Beam Energy Server

Bunch by bunch gradient request

Status and regulation

Bunch by bunch beam energy

Beam Energy = Gradient sum

Gradient error passed forward
To down stream stations (real-time)

Measurements at FLASH

- **Maximum Klystron Output Power**
  - We have no way to measure absolute value to better than 5% but we can make relative calibrations of forward power pickups
- **Modulator Ripple**
  - Will probably only measure modulator voltage and current, not RF AM and PM ripple
- **Waveguide and circulator losses**
  - Must rely on measurements made at installation
- **Cavity gradient variation**
  - While we can ignore for ILC calculations, how do we separate them out from FLASH measurements?
- **Parameter variation**
  - We could measure but how does this relate to the ILC? FLASH is hand tuned, ILC power ratios will be set with wrenches
- **Peak power headroom**
  - This is maybe our biggest concern. Will we be able to operate the klystron for cryo-modules 4,5,6 near saturation with 9mA?
- **Dynamic Headroom**
  - This is very dependent on feedback gain and measurement bandwidth
- **Beam current fluctuations**
  - Torroid data, extrapolate to ILC specification is direct
- **Cavity detuning**
  - LFD, microphonics, mistuning – can only be measured accurately at RF turnoff
- **Klystron drive noise sidebands**
  - Will need vector demodulation of power signals to measure complex spectrum

De-convolving the Measurements

- 3mA test – beam energy data
- 9 minutes of operation
  - 1.5% Pk to Pk spread, not 0.1% RMS

Beam Energy at the dump, 2713 pulses, Nominal Number of Bunches = 550
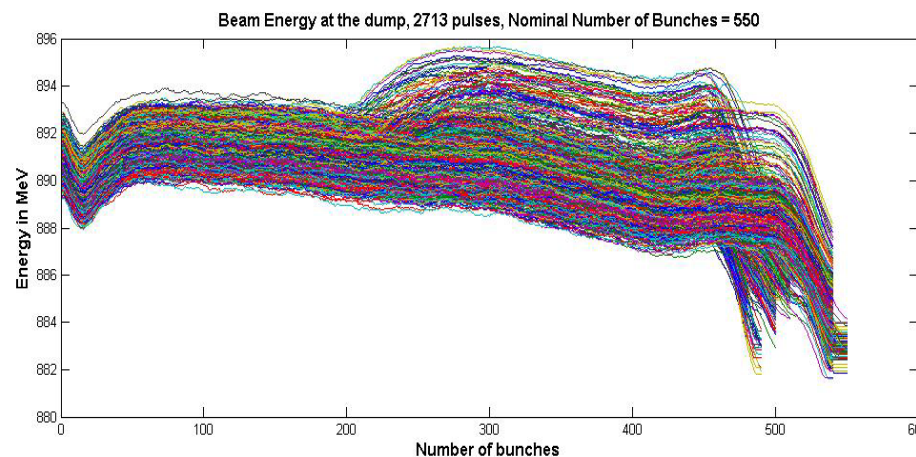
- Data sets are complex sums of many effects
- Many aspects of the cavity and RF systems are non-linear so disturbances inter-modulate
- Operating point is at only a fraction of 10MW
- Will take some work to fully analyze

What are the weaknesses to this approach?

- Models be themselves are often too simplistic
  - Need to study the real machines
- The 9mA tests are and will be very informative - but limited
  - Only one RF station close to ILC design
  - Operation at a fraction of design gradient
  - Power limited by circulators
  - Different distribution scheme
  - Studies are very time limited
- What do we need from 9mA tests to help?
  - Calibrated vector signals for forward and reflected power
  - Ql and Pk setup as per ILC design
  - Operation off crest with ACC1 (phase jitter)
- Studies at KEK and Fnal may fill in the gaps

Summary

- Work continues to validate the RDR RF power design

- Modeling, power budget, simulations, system tests, design improvements in a spiral design cycle
  - Simulations will be used to explore statistical beam energy and jitter regulation as a function of power overhead
  - High level simulations will include a supervisory controller
  - Machine studies will continue to provide insight