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Energy Efficiency and Availability Improvement in Control and Operation of Superconducting Cavities

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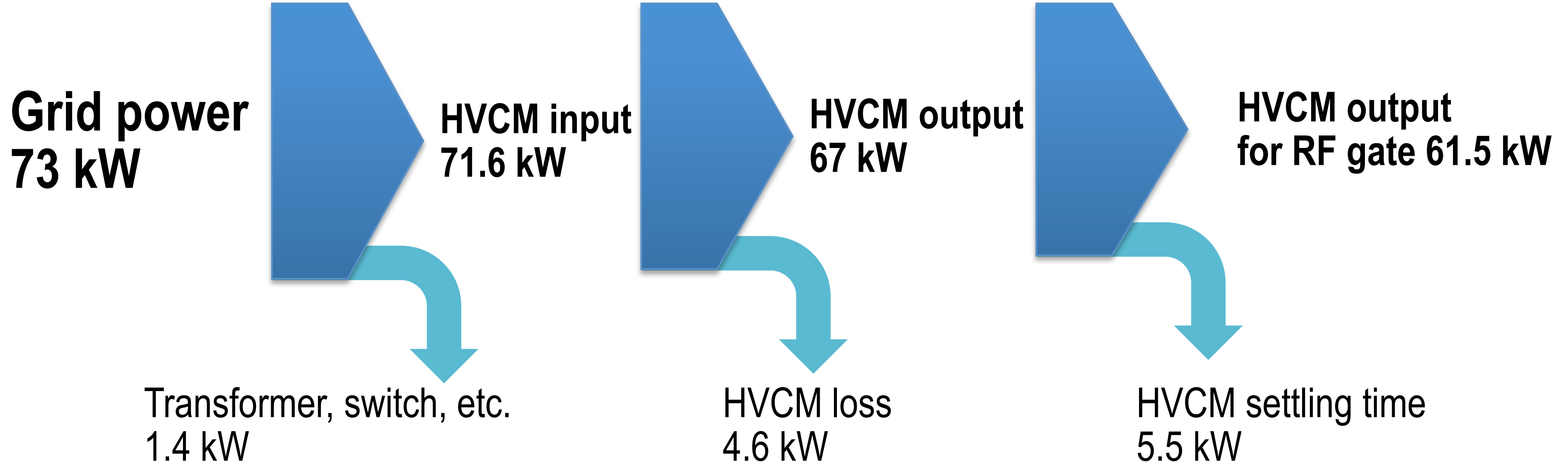
Outline

- Energy Efficiency and Availability in Accelerator
- Challenges to Achieve Higher Efficiency and Availability
- Advanced Technologies makes it possible
- Some consideration/progress at ESS

Efficiency
SRF Cavity at SNS(Sang-ho Kim)



Grid power
73 kW

HVCM input
71.6 kW

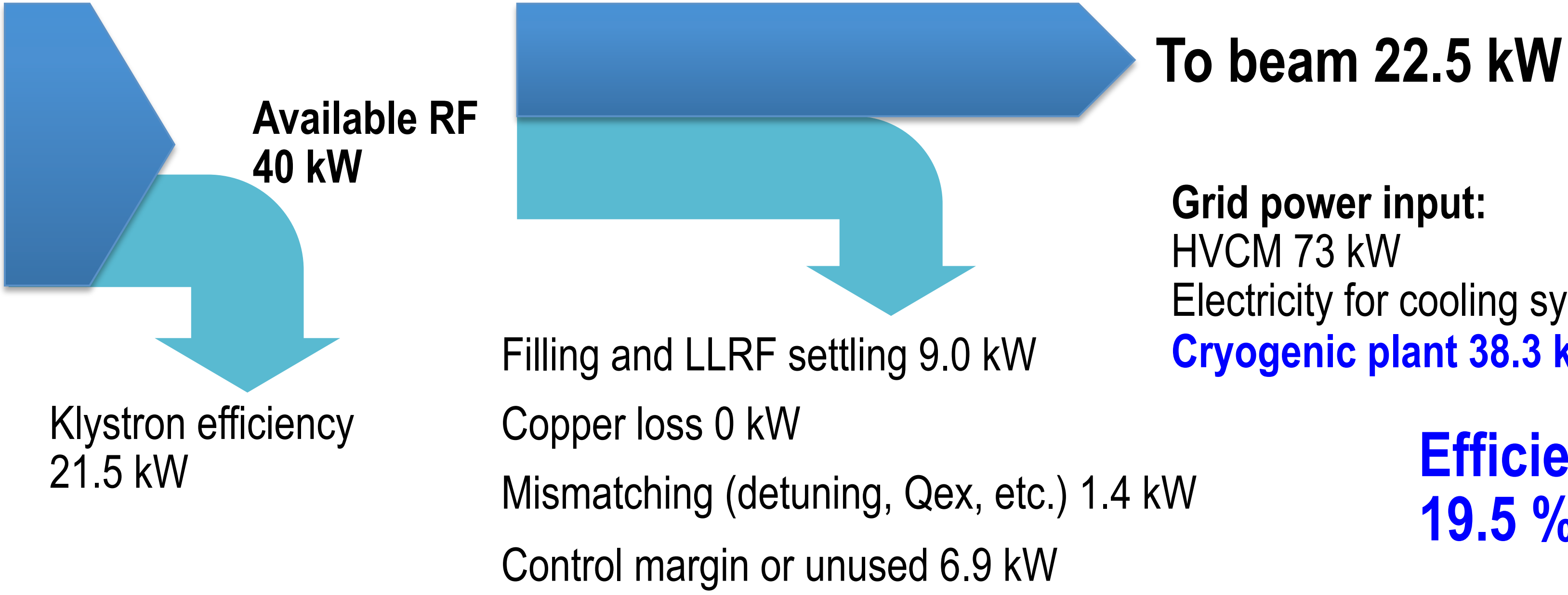
HVCM output
67 kW

HVCM output
for RF gate 61.5 kW

Transformer, switch, etc.
1.4 kW

HVCM loss
4.6 kW

HVCM settling time
5.5 kW



Available RF
40 kW

To beam 22.5 kW

Klystron efficiency
21.5 kW

Filling and LLRF settling 9.0 kW

Copper loss 0 kW

Mismatching (detuning, Qex, etc.) 1.4 kW

Control margin or unused 6.9 kW

Grid power input:
HVCM 73 kW
Electricity for cooling system 5 kW
Cryogenic plant 38.3 kW

Efficiency
19.5 %

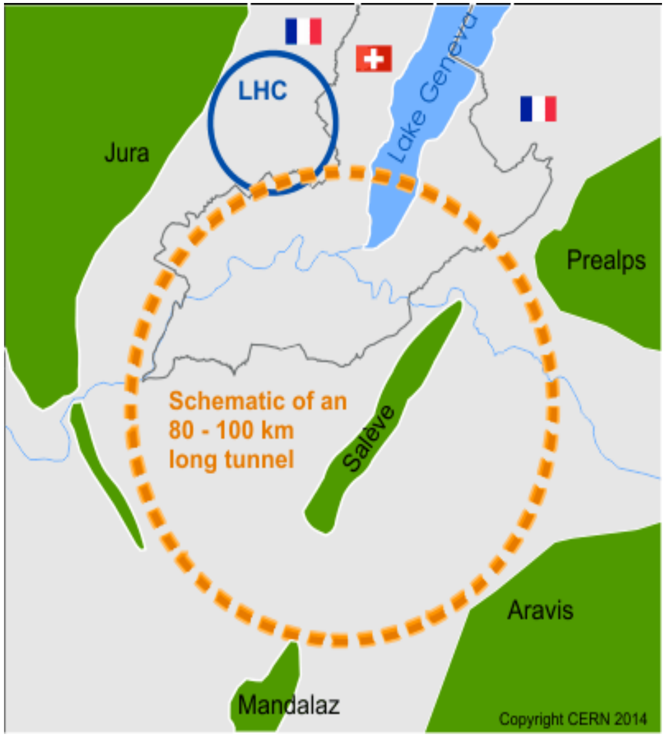
Availability

Distinguish in two aspects:

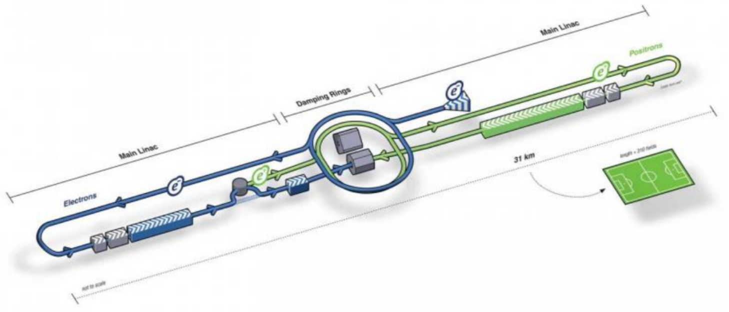
- **Enhance reliability in design and development stage(careful design, redundancy, high reliable key components, flexibility)**
- **Fault tolerance in operation stage: a mitigation strategy to the failures**

Future Large Scale Accelerators

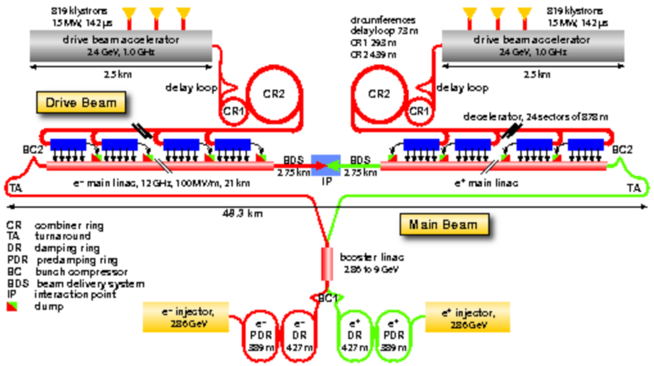
(Erk Jensen, CWRF2016)



FCC ^{ee}: CW, 0.8 GHz, P_{RF} total= 110 MW



ILC $^{e+e-}$: Pulsed, 1.3 GHz, P_{RF} total= 88 MW



CLIC $^{e+e-}$: Pulsed, 1.0 GHz, P_{RF} total= 180 MW

To Achieve Higher Efficiency and Availability

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Break through operation limitations:

- **to work at nonlinearities**
- **to work close to limitation**
- **to change operation point quickly and correctly.**

The Challenges

- **System is usually optimized at designed operating point, while**
- **RF dynamics and cavity dynamics were/are often black box**
  - Cavity pass band modes
  - Lorentz force detuning at different cavity field levels
  - Lorentz force to cavity tuning transfer function
  - Piezo tuner to cavity tuning transfer function (time domain, or frequency domain)
  - Moto tuner to cavity tuning transfer function
  - Microphonics spectrum
  - System open loop matrix
  - System closed loop matrix
  - Cavity field behaviour close to and at quench
  - Multipacting in cavity and power coupler
  - Fast fault detection and fault recovery
  - Power amplifier input-output characteristics (power and phase) at different modulator voltage
  - Modulator ripple frequency and amplitude
  - Circulator characteristics (return loss, frequency) under different power consumption, different reflection power, and working temperature
  - Power amplifier bandwidth variation at different output power level
  - Driver amplifier and power amplifier delay, rise time and falling time under different power level
  - Phase drift in cables due to temperature or humidity changes

Insight into RF & Cavity Dynamics

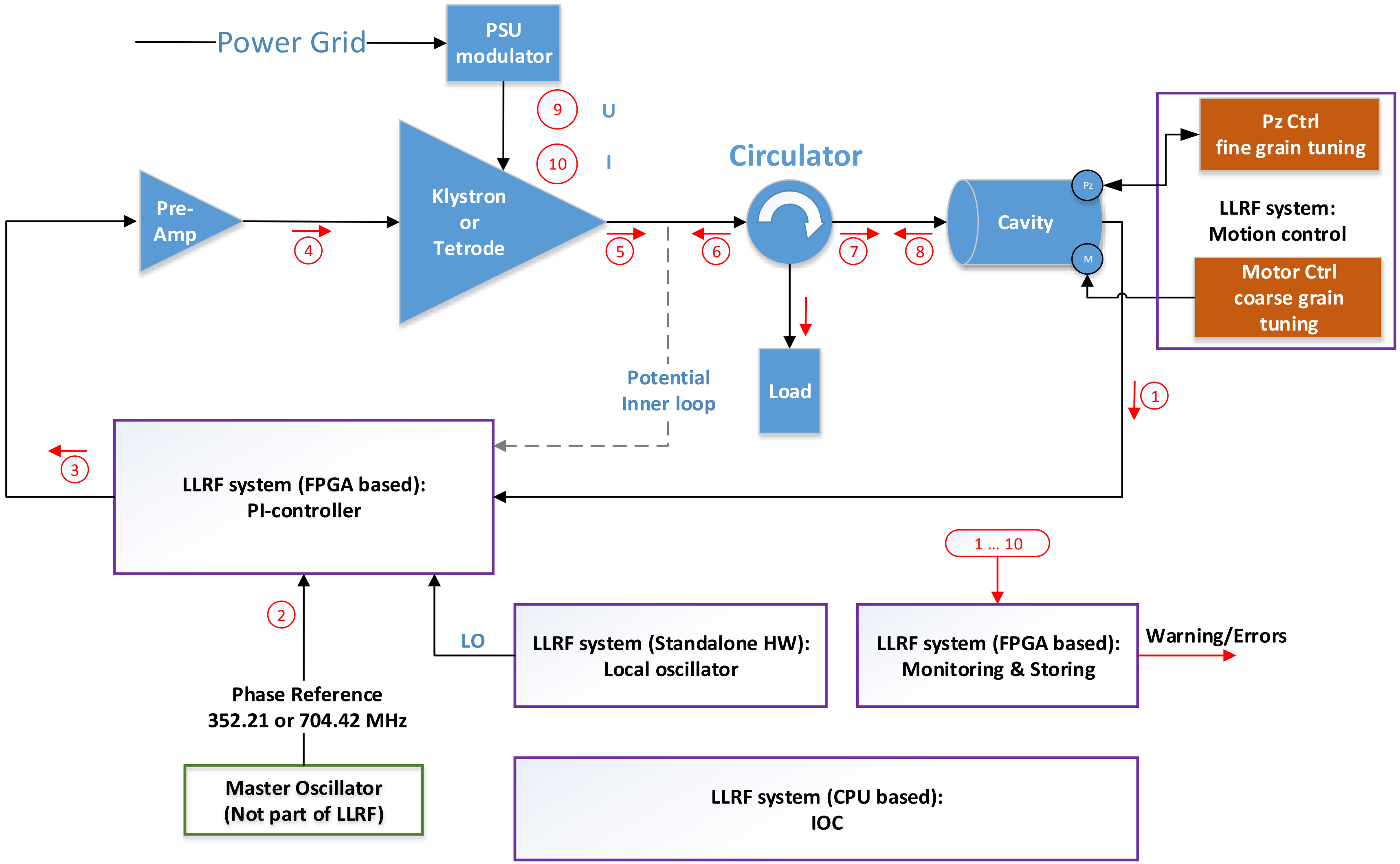
- **Rely heavily on high precision and online diagnostic of basic cavity parameters:**
  - Cavity voltage
  - Synchronous phase
  - Ql
  - Detuning
  - R/Q

$$\dot{\mathbf{V}}(t) = \left(-\omega_{1/2} + i\Delta\omega(t)\right)\mathbf{V}(t) + \kappa_g \mathbf{I_g}(t) + \kappa_b \mathbf{I_b}(t)$$

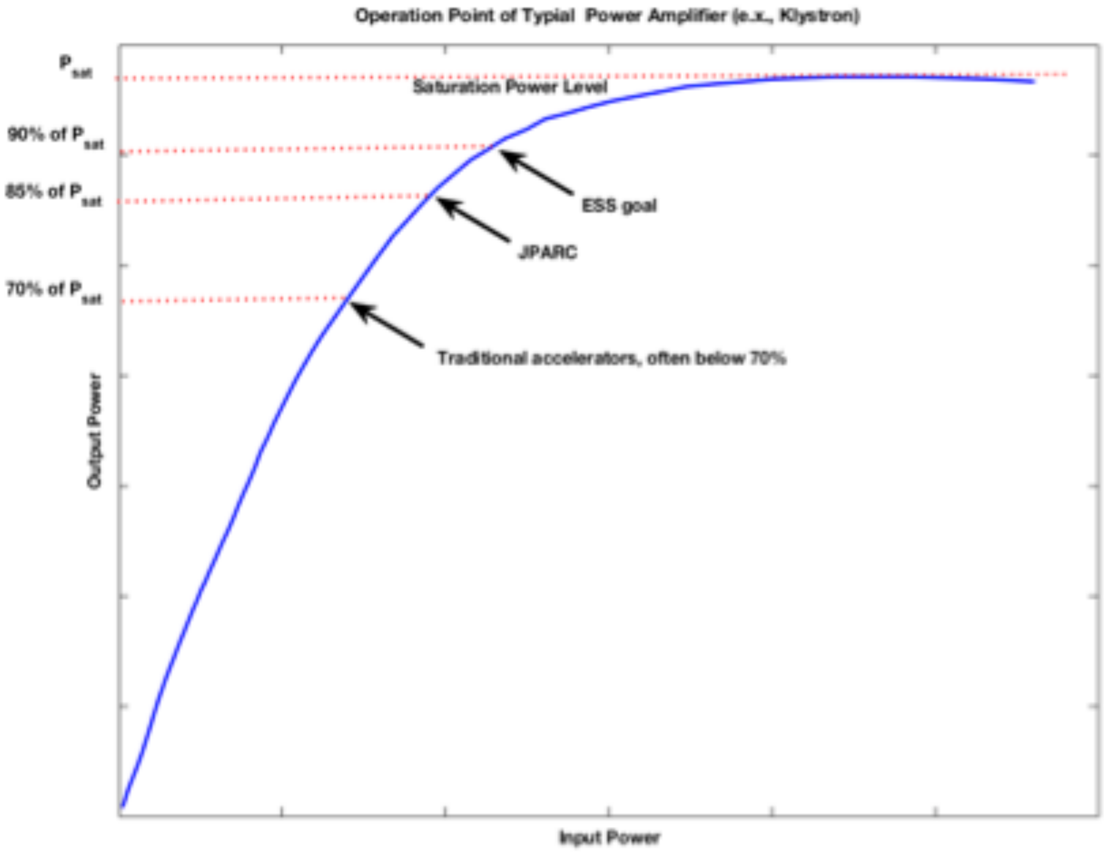
- **Rely heavily on high precision and online diagnostic of critical parameters in RF power chain**

Advanced Technologies Makes It Possible

(Anders Johansson)



The Goal at ESS

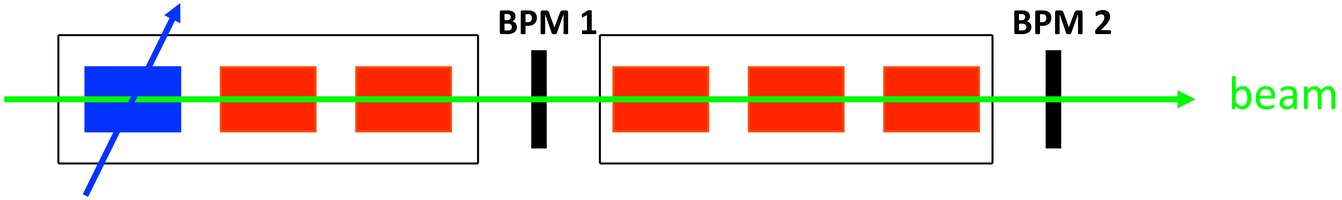


The Last Thing to Overcome

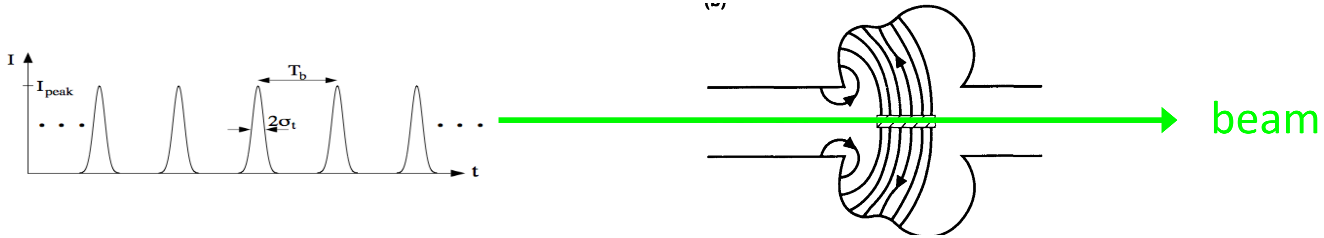
Online beam phase measurement

Phase Scan vs. Transient Beam Loading

- **Phase Scan**

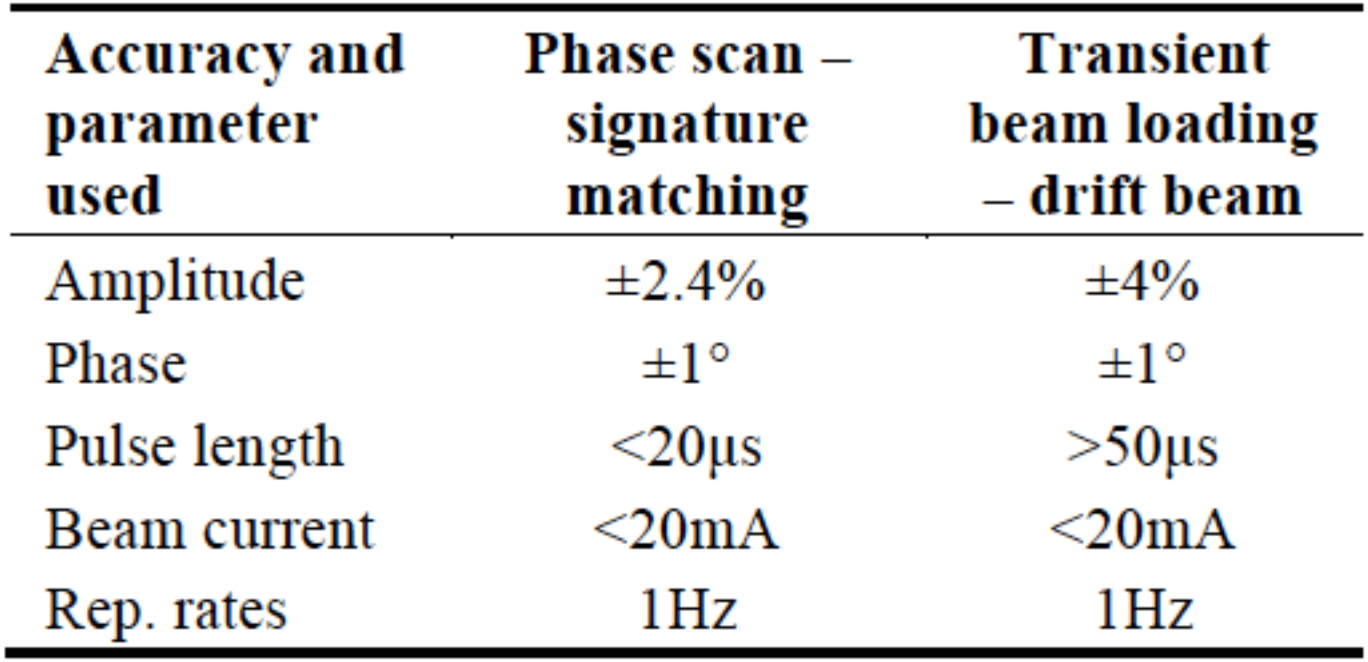


- **Transient Beam Loading**



$$V_b\left(t\right)=-\left(\frac{1}{2}V_{b0}e^{-(t-nT_b)/\tau}+V_{b0}e^{-(t-(n-1)T_b)/\tau}+V_{b0}e^{-(t-(n-2)T_b)/\tau}+\cdots+V_{b0}e^{-(t-T_b)/\tau}+V_{b0}e^{-t/\tau}\right)$$

Phase Scan vs. Transient Beam Loading



Accuracy and parameter used	Phase scan – signature matching	Transient beam loading – drift beam
Amplitude	±2.4%	±4%
Phase	±1°	±1°
Pulse length	<20μs	>50μs
Beam current	<20mA	<20mA
Rep. rates	1Hz	1Hz

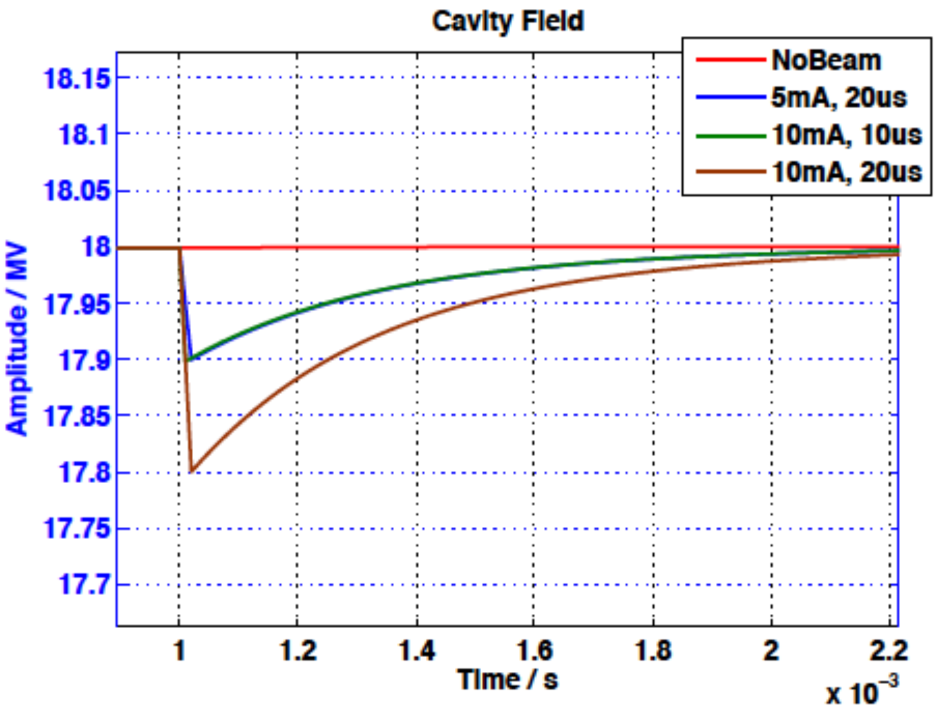
Improved Transient Beam Loading Method at DESY

- **Rather than suffering from poor signal to noise ratio (SNR in some case <10dB), strong signal and clear information is observed**

Build constant cavity field without beam:
$V_{cav,1} = V_g$

Pulse beam comes:
$V_{cav,2} = V_g + V_b$

$V_b = V_{b,r} + jV_{b,i}$

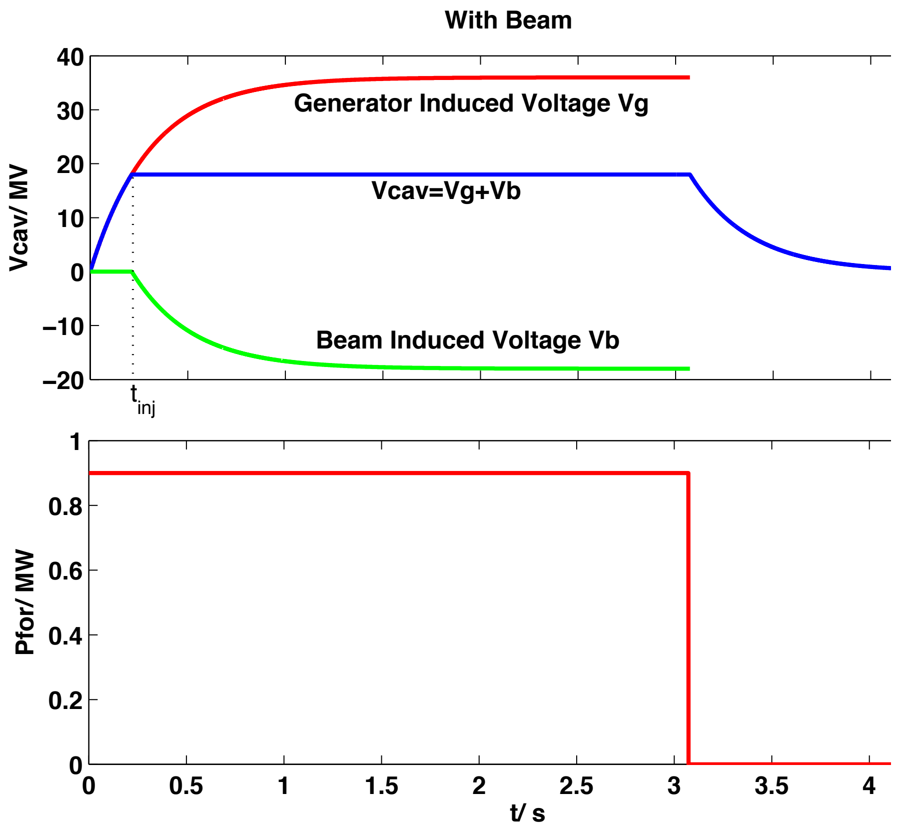


Online Beam Phase Measurement

At filling time(no beam):
Vcav,1= Vg

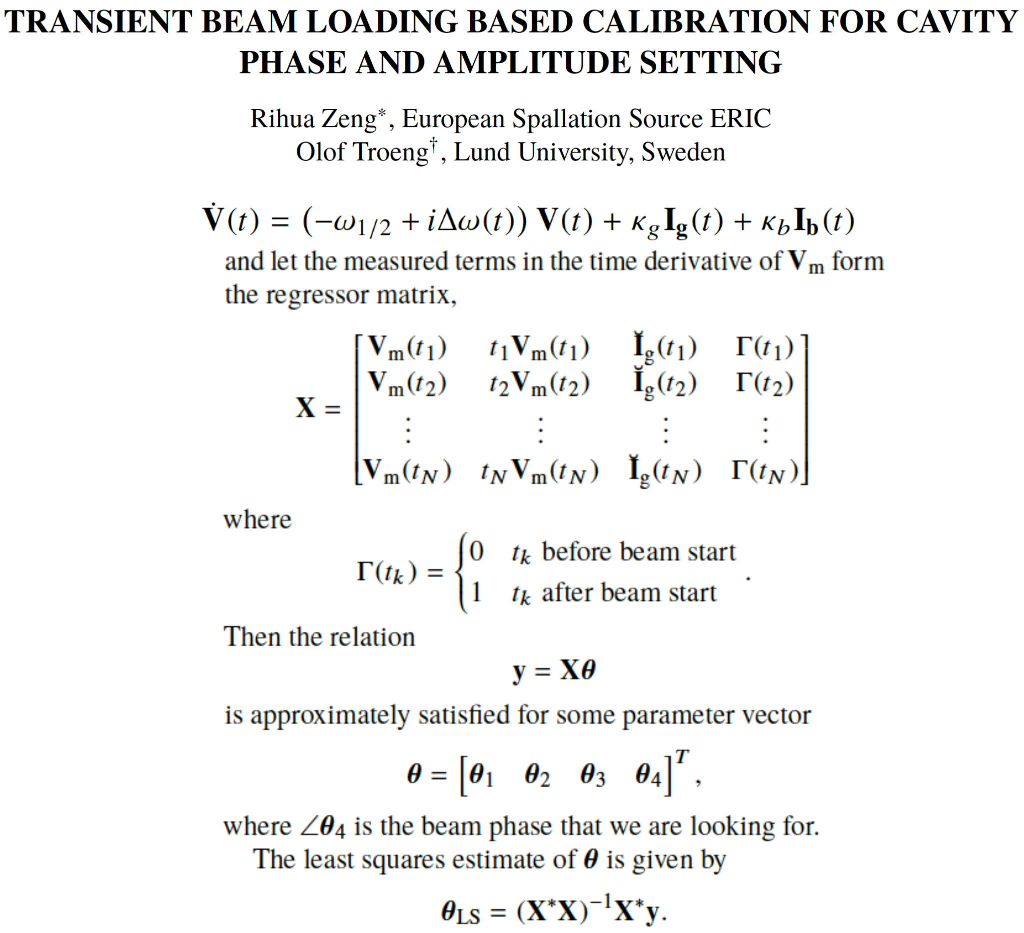
During beam pulse:
Vcav,2=Vg+Vb

Vb = Vb,r + jVb,i



Online Beam Phase Measurement

MOPL025



TRANSIENT BEAM LOADING BASED CALIBRATION FOR CAVITY PHASE AND AMPLITUDE SETTING

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Olof Troeng†, Lund University, Sweden

$$\dot{\mathbf{V}}(t) = (-\omega_{1/2} + i\Delta\omega(t))\,\mathbf{V}(t) + \kappa_g \mathbf{I_g}(t) + \kappa_b \mathbf{I_b}(t)$$

and let the measured terms in the time derivative of $\mathbf{V}_\mathrm{m}$ form the regressor matrix,

$$\mathbf{X} = \begin{bmatrix} \mathbf{V}_\mathrm{m}(t_1) & t_1\mathbf{V}_\mathrm{m}(t_1) & \check{\mathbf{I}}_\mathrm{g}(t_1) & \Gamma(t_1) \\ \mathbf{V}_\mathrm{m}(t_2) & t_2\mathbf{V}_\mathrm{m}(t_2) & \check{\mathbf{I}}_\mathrm{g}(t_2) & \Gamma(t_2) \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{V}_\mathrm{m}(t_N) & t_N\mathbf{V}_\mathrm{m}(t_N) & \check{\mathbf{I}}_\mathrm{g}(t_N) & \Gamma(t_N) \end{bmatrix}$$

where

$$\Gamma(t_k) = \begin{cases} 0 & t_k \text{ before beam start} \\ 1 & t_k \text{ after beam start} \end{cases}.$$

Then the relation

$$\mathbf{y} = \mathbf{X}\boldsymbol{\theta}$$

is approximately satisfied for some parameter vector

$$\boldsymbol{\theta} = \begin{bmatrix} \boldsymbol{\theta}_1 & \boldsymbol{\theta}_2 & \boldsymbol{\theta}_3 & \boldsymbol{\theta}_4 \end{bmatrix}^T,$$

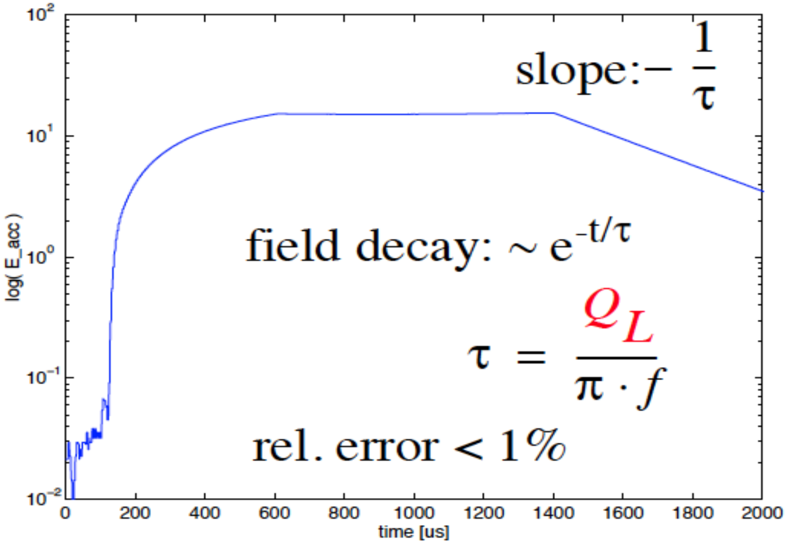
where $\angle\boldsymbol{\theta}_4$ is the beam phase that we are looking for.

The least squares estimate of $\boldsymbol{\theta}$ is given by

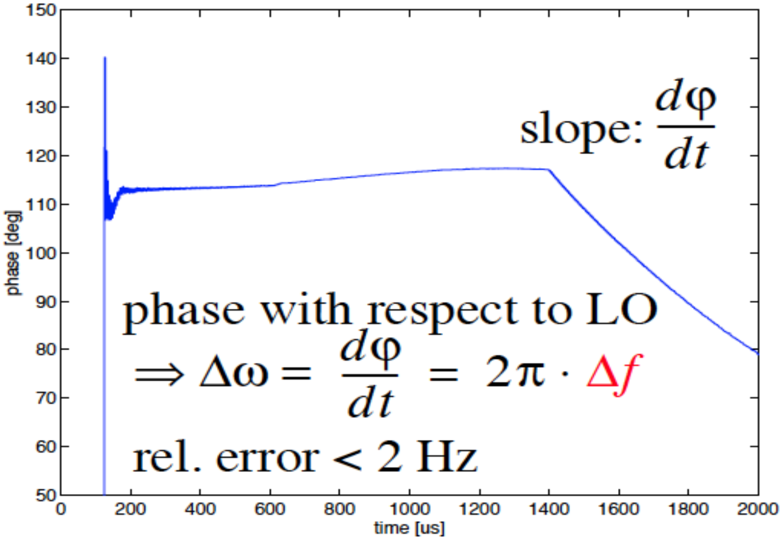
$$\boldsymbol{\theta}_\mathrm{LS} = (\mathbf{X}^*\mathbf{X})^{-1}\mathbf{X}^*\mathbf{y}.$$

Opportunities and Challenges

- **Build upon Existing High precision and online RF measurement: Ql, detuning, klystron, circulator characteristics, etc..**



Loaded Q

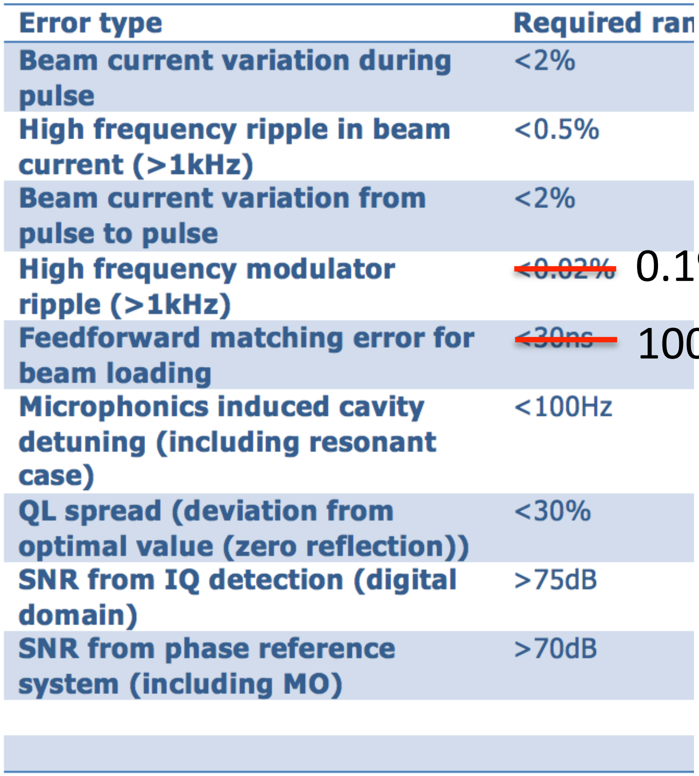


Detuning

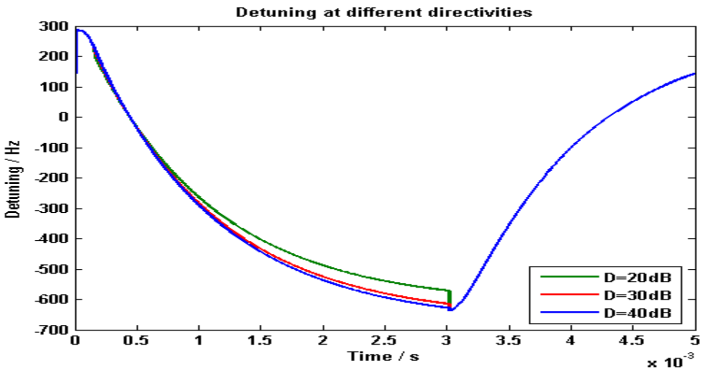
S. Simrock

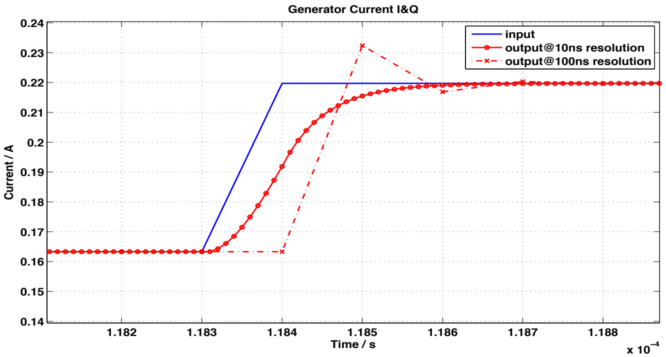
Opportunities and Challenges

- **Build upon Advanced Hardware:**



Error type	Required ran
Beam current variation during pulse	<2%
High frequency ripple in beam current (>1kHz)	<0.5%
Beam current variation from pulse to pulse	<2%
High frequency modulator ripple (>1kHz)	~~<0.02%~~ 0.1%
Feedforward matching error for beam loading	~~<30ns~~ 100ns
Microphonics induced cavity detuning (including resonant case)	<100Hz
QL spread (deviation from optimal value (zero reflection))	<30%
SNR from IQ detection (digital domain)	>75dB
SNR from phase reference system (including MO)	>70dB





Opportunities and Challenges

- **It is promising**
- **Uncertainties in reality.**
- **Interactive learn from practice(data, experiment)**
- **Guided by modeling (expressing uncertainty in a precise, quantitative and controlled way)**

Learning from Practice:
Integrate Data, Modeling and Tests

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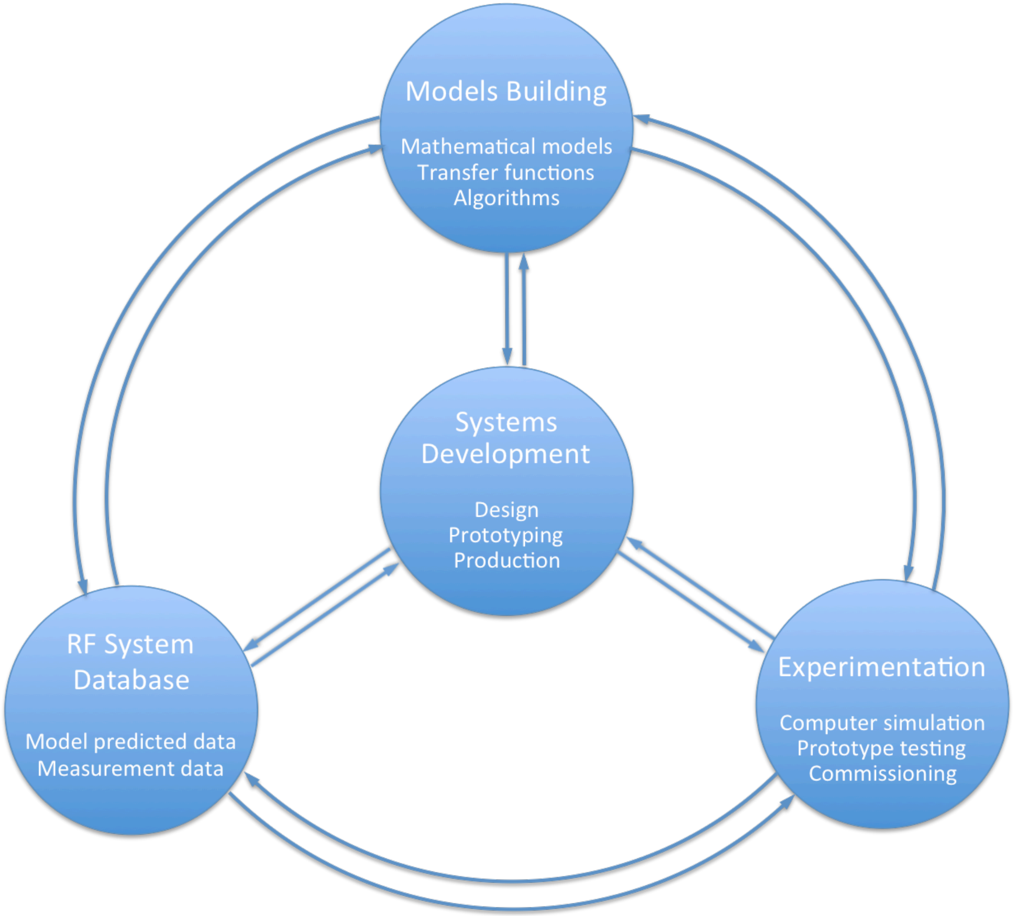
- **A methodology to integrate RF measurement, modeling and data/database, to really identify detailed dynamics**



Models Building

Mathematical models
Transfer functions
Algorithms

Systems Development

Design
Prototyping
Production

RF System Database

Model predicted data
Measurement data

Experimentation

Computer simulation
Prototype testing
Commissioning

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Thanks!