Precision Control of SRF Cavities

At FLASH & the European XFEL

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for the MSK-LLRF team

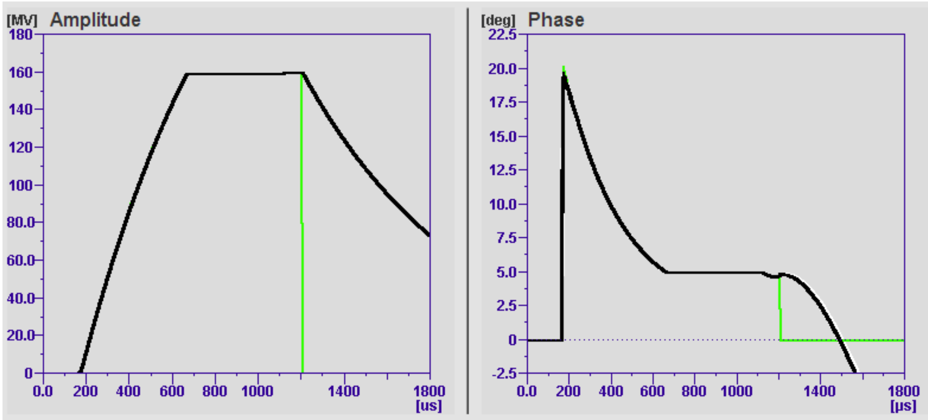
DESY-TEMF-Meeting
Hamburg, 15.11.2018

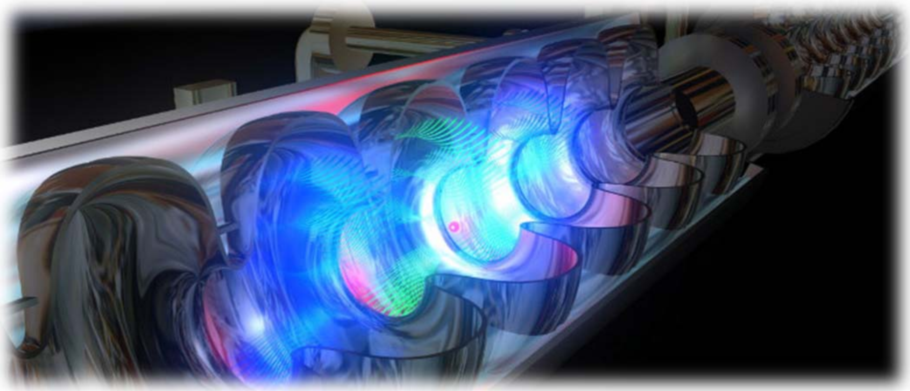
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

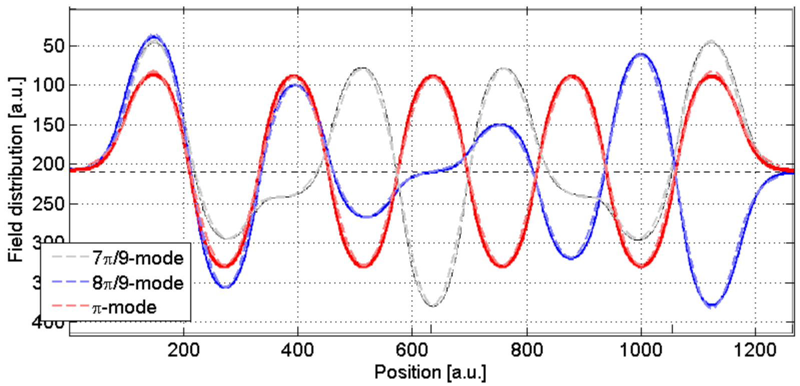
DESY.

Outline

1. Current feedback scheme at FLASH
   - RF regulation at FLASH/XFEL
   - RF stability
2. Beam loading
   - Our biggest disturbance…
   - Multi-bunch simulation
   - Energy contribution of cavity modes
3. Summary & Questions



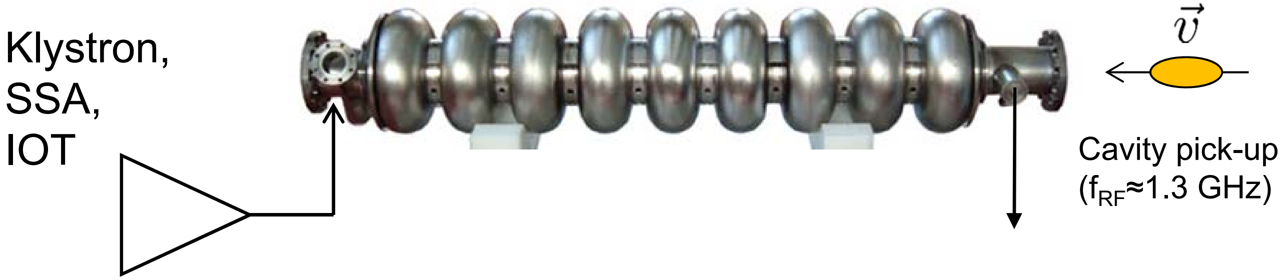




SRF cavity regulation

SRF cavity regulation

Digital LLRF regulation system



TESLA type cavity

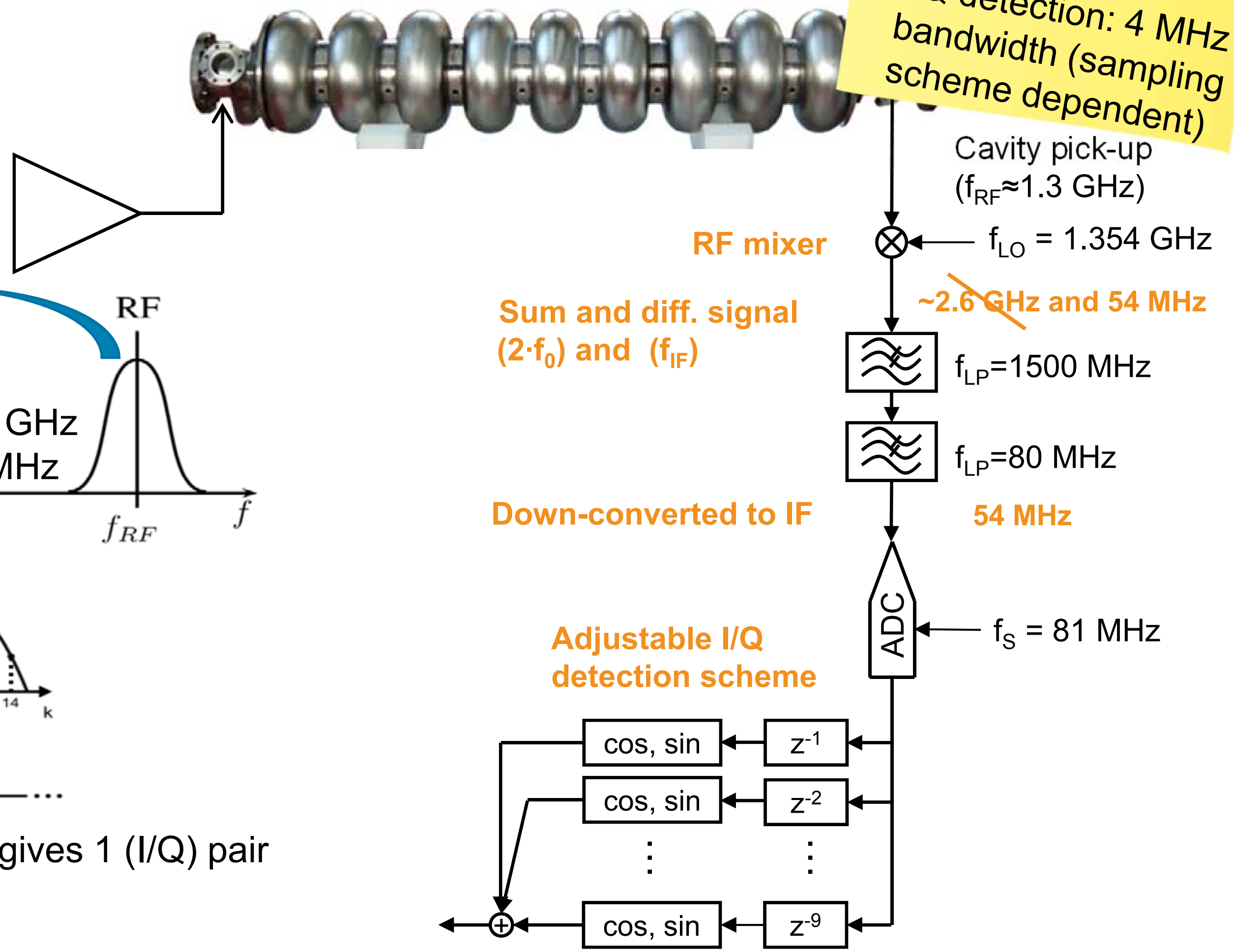
- f_0 = 1.3 GHz, l = 1.036 m, $Q_0 \approx 10^{10}$, standing wave
- HOMs – 2 for damping → previous talks
- RF field pick-up for signal detection and regulation
- Input port with adjustable coupling
    - $Q_L = [3 \cdot 10^6 \ldots 4.6 \cdot 10^6]$; (CW: $> 10^7$)

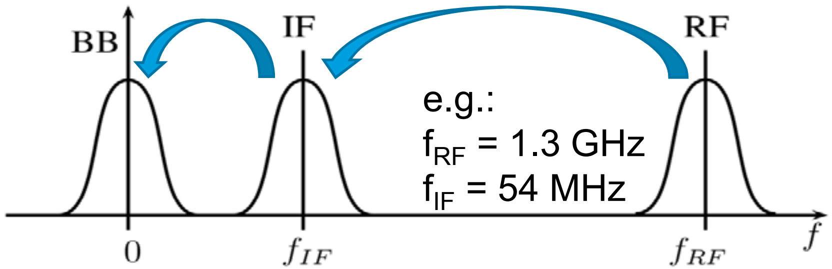
- Electron bunch(es) of variable charge/ repetition rate (0.5, 1, 1.5 nC @ 0.5 1, 4.5 MHz)

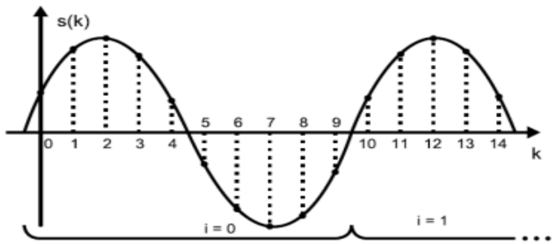
SRF cavity regulation

Digital LLRF regulation system - signal detection

- ADC: 26 MHz analog bandwidth (asymmetric)
- I/Q detection: 4 MHz bandwidth (sampling scheme dependent)







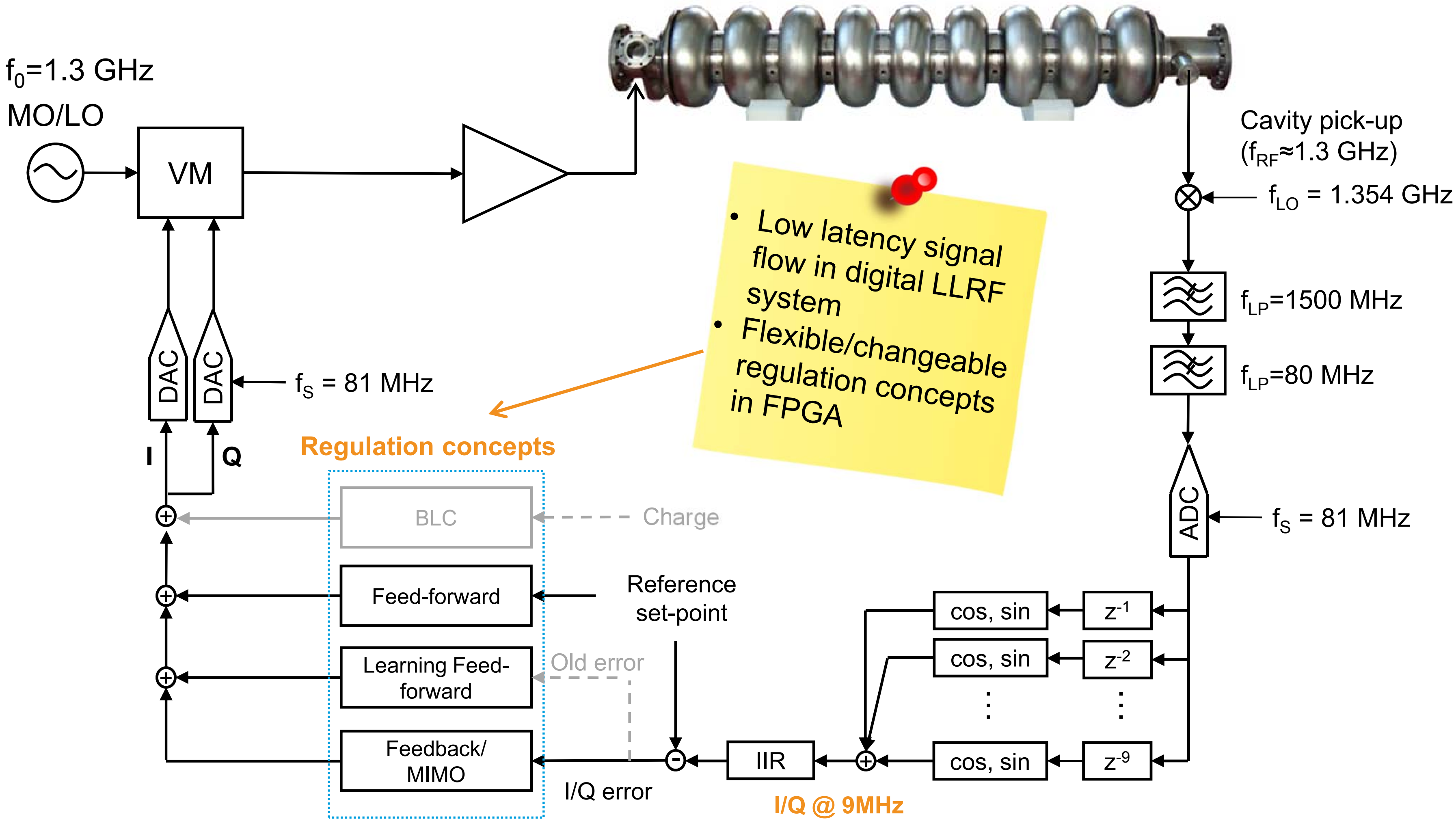
Average 9 samples at 81 MHz gives 1 (I/Q) pair each 9 MHz with step window

In-phase **Quadrature**

$$I = \frac{2}{P \cdot S} \sum_{k=0}^{(P \cdot S)-1} y_{mix}(k) \cdot \cos\left(k \cdot \frac{2\pi}{S}\right) \text{ and } Q = \frac{2}{P \cdot S} \sum_{k=0}^{(P \cdot S)-1} y_{mix}(k) \cdot \sin\left(k \cdot \frac{2\pi}{S}\right)$$

SRF cavity regulation

Digital LLRF regulation system



SRF cavity regulation

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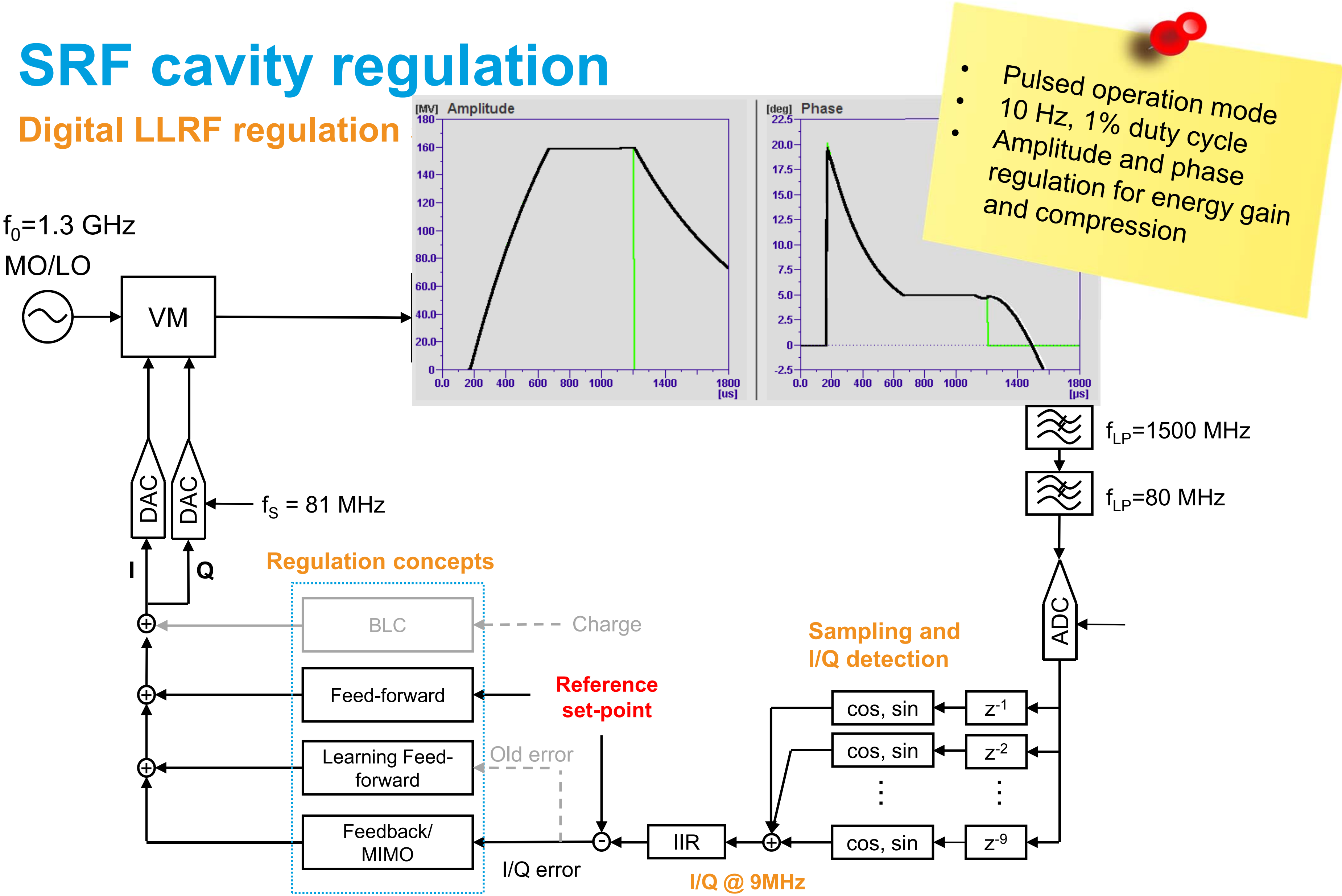
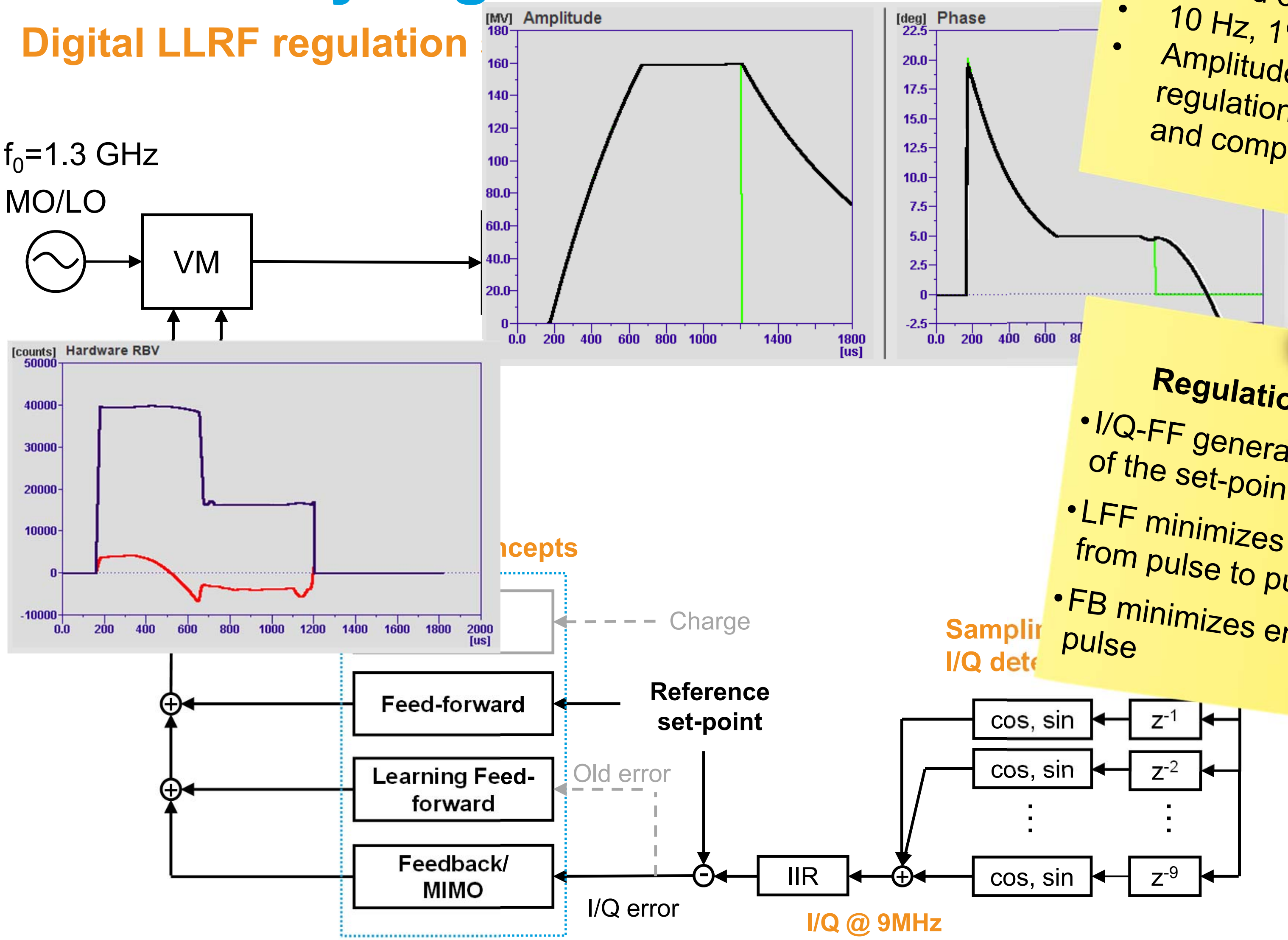


SRF cavity regulation

Digital LLRF regulation



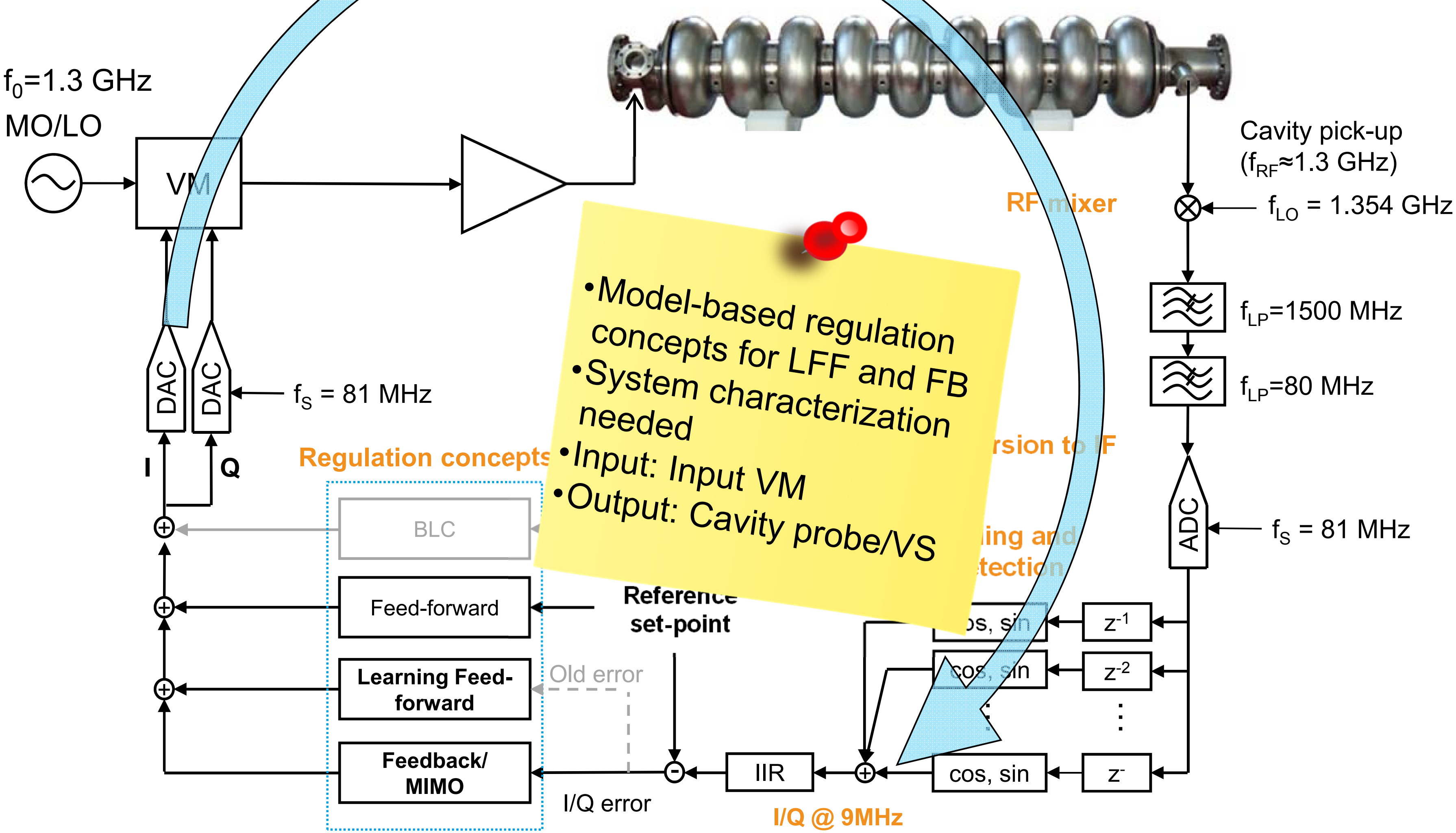
- Pulsed operation mode
- 10 Hz, 1% duty cycle
- Amplitude and phase regulation for energy gain and compression

Regulation concepts

- I/Q-FF generation as function of the set-point in A/ϕ
- LFF minimizes rep. errors from pulse to pulse
- FB minimizes errors within the pulse

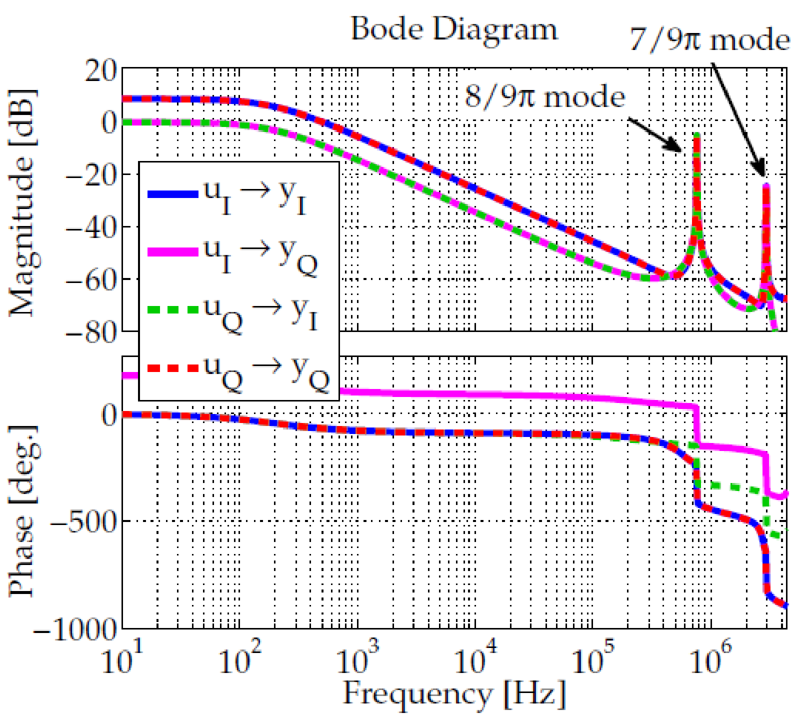
SRF cavity regulation

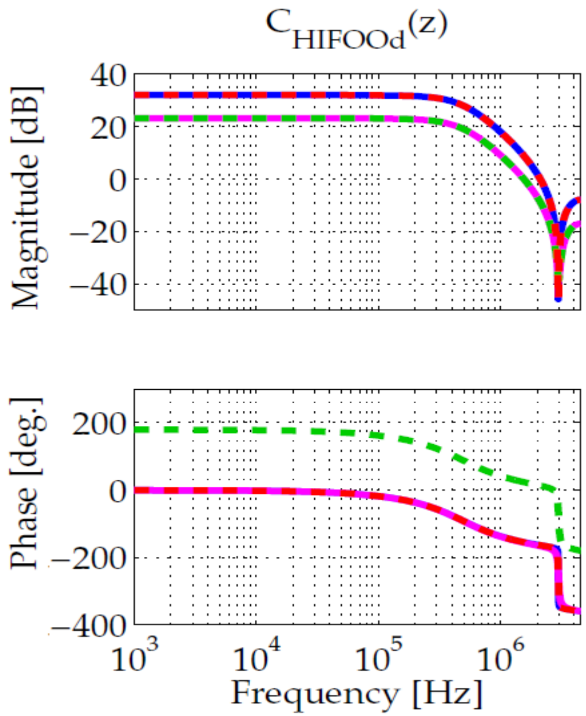
Digital LLRF regulation system



System Identification & FB Controller Design

… as example





- f = 0 Hz (π mode - accelerating mode)
- f ≈ 800 kHz (8π/9 – mode) ⟶ Notch of cavity probe (IIR-FPGA)
- f ≈ 3 MHz (7π/9 – mode) ⟶ Notch in FB controller

Grey-box system characterization by exploiting the known system characteristics.
RF field controller design based on system characterization.

SRF stability measurements

LLRF regulation

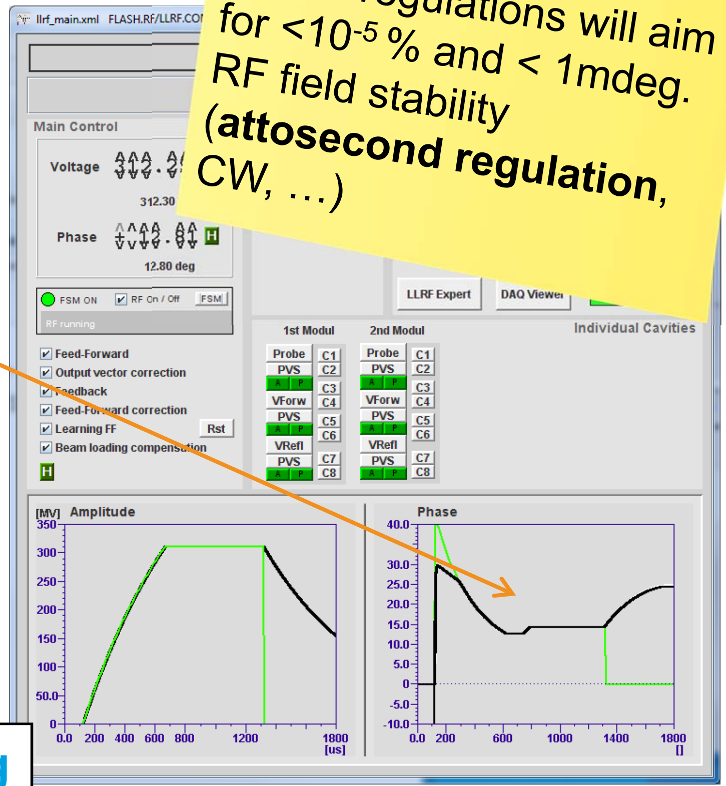
Objective: Keep RF field amplitude and phase within specification

- Feedforward
- **Feedback (MIMO)**
- **Learning Feedforward**
- Beam Loading Compensation

Optimization using model-based approach

Future regulations will aim for <10^{-5} % and < 1mdeg. RF field stability (**attosecond regulation**, CW, …)

Multi-beamline support



Regulation Goal: dA/A < 0.01%, dφ < 0.01deg

RF stability (rms)	ACC1*	ACC39*	ACC23*	ACC45*	ACC67*
Ampl. Intra pulse [%]	0.0057	**0.011**	0.0053	**0.0052**	0.0069
Ampl. pulse to pulse [%]	0.0013	0.0025	0.0024	0.0007	0.0039
Phase Intra pulse [deg]	0.0065	**0.0087**	**0.00484**	0.005	0.0076
Phase pulse to pulse [deg]	0.003	0.002	0.002	0.0022	0.004

Table: In-loop regulation for 600 consecutive RF pulses

* at 9 MHz

Study: Receiver with attosecond-resolution

In cooperation with TU Hamburg-Harburg (PhD student@DESY)

TUHH Technische Universität Hamburg

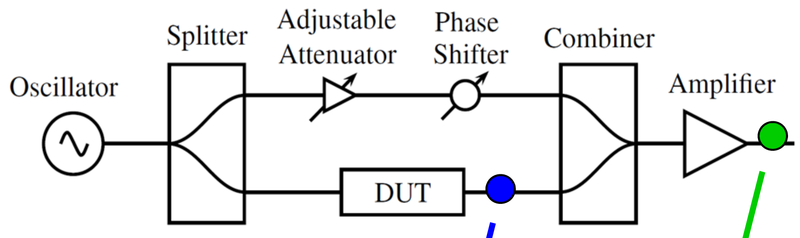
Device Under Test (DUT) is voltage controlled phase shifter

- Cavity probe signal in application

Interferometer based method to suppress the carrier

Outlook: Technical realization (2018-20??):

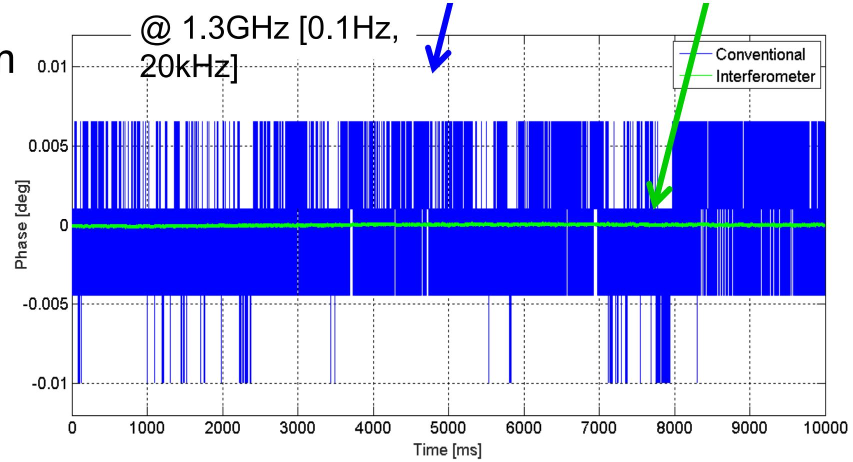
- Many challenges to be addressed → long-term development
- Pulsed mode vs. continuous mode operation
- Carrier tracking algorithm, ...
- Development of ultra low noise attenuator and phase shifter
- …



Reduction factor >50:

2.6mdeg (rms), ≈5.5fs

0.045mdeg (rms), ≈96as



Blue: signal in front of the interferometer (non-suppressed carrier)
Green: signal behind the interferometer (suppressed carrier)

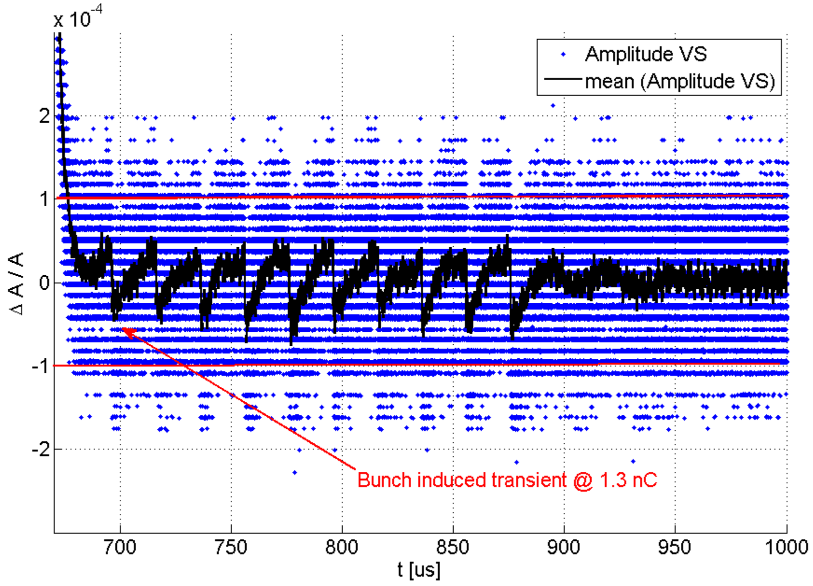
CarrierSupp_noMod_M10_524k_20171129T1352.mat; SIS8300V2, DWC8VM1, fs =81.25MHz, IF=54MHz, N=512K, D=1600

Beam Loading

Beam Loading

… our biggest disturbance acting to the RF field…

- Single beam transients are measurable by averaging
  - Limitation: ADC resolution (16 bit)
  - Field drop by 1 bunch: 4.25 keV/nC
  - Refilling/decay with cavity bandwidth
- LLRF controller (and beam loading compensation) tries to compensate for this
  - Remaining are fast drops which can not be compensated by FB/BLC (band-width limitation)



Beam loading simulation for an absolute cavity calibration at XFEL.

Beam Loading

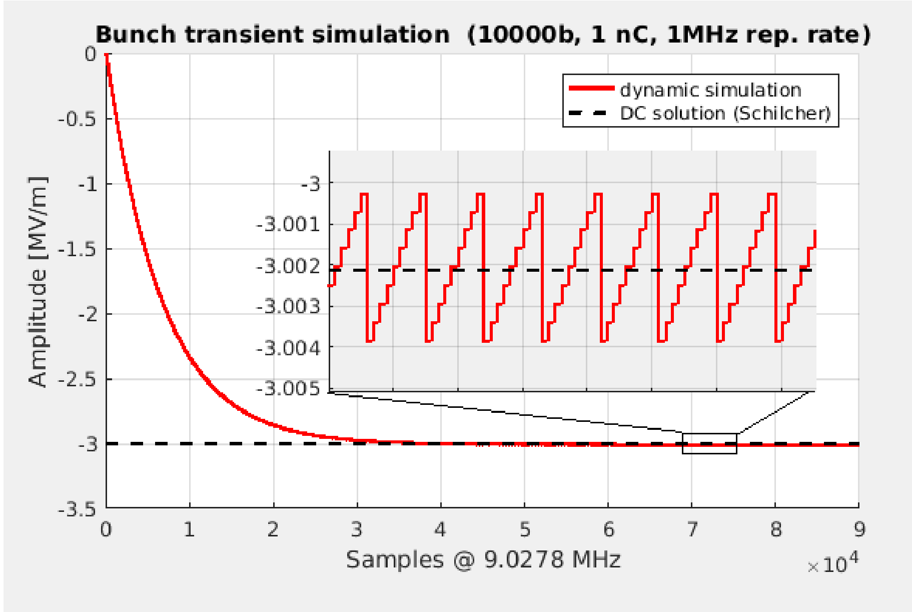
… our biggest disturbance acting to the RF field…

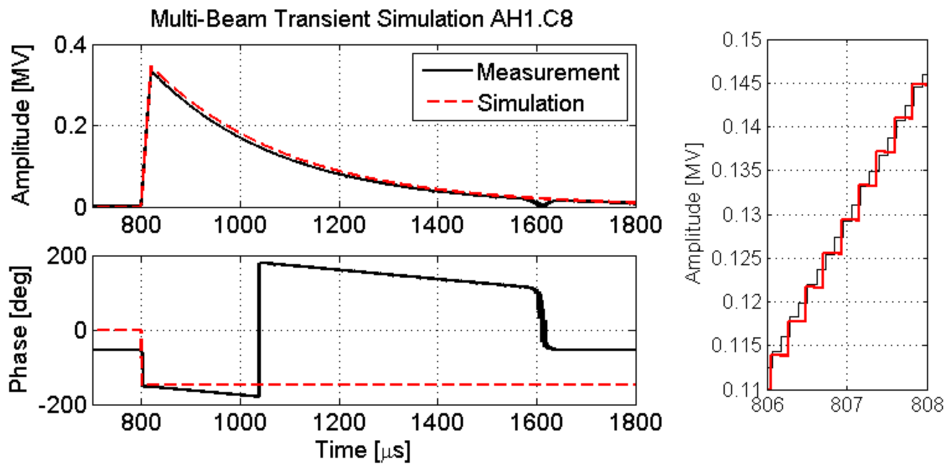
Beam loading using pillbox cavity

- $Q_L = 3 \cdot 10^6$
- $q_B = 1nC$
- $f_B = 1$ MHz

Beam loading for DC solution $(t \to \infty)$ and transient pillbox cavity approach (π-mode) is well understood.

Calibrated most of XFEL cavities using this approach.

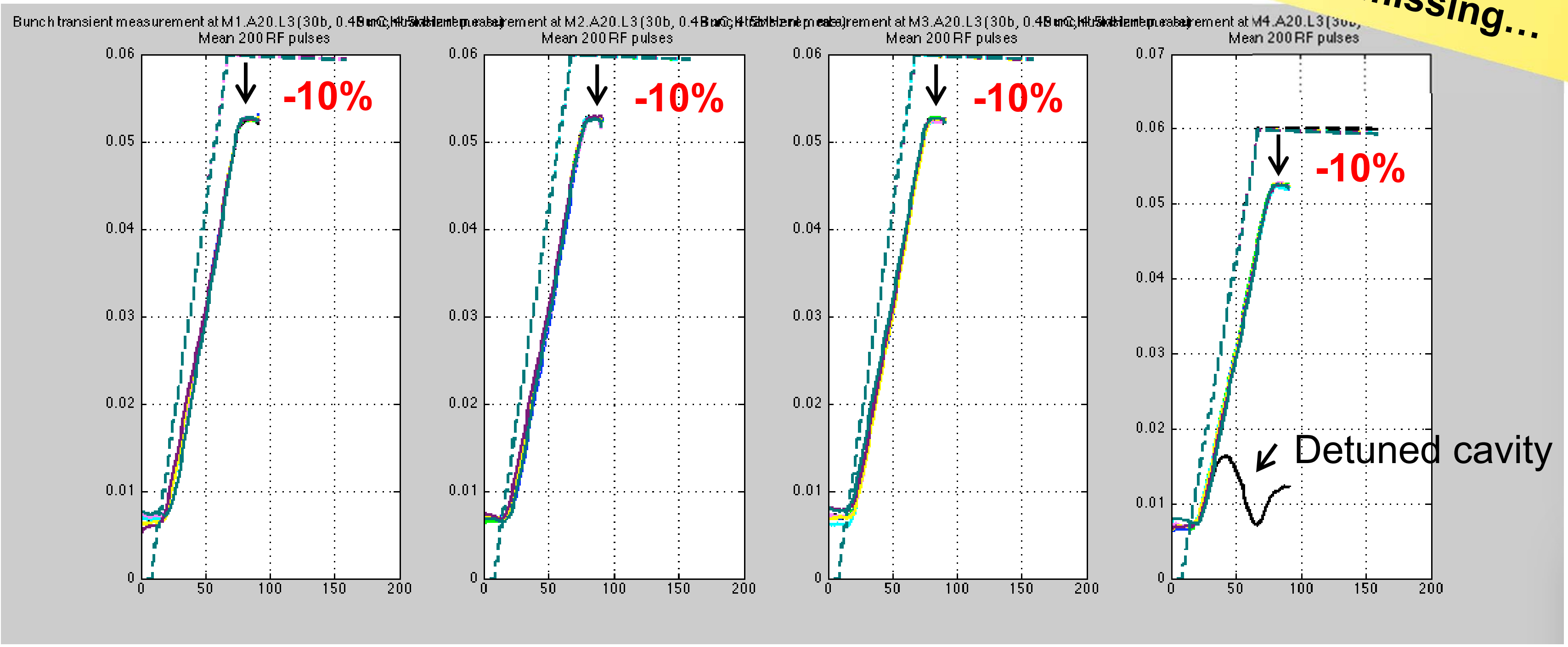




Beam Loading

Absolute cavity calibration in amplitude and phase at XFEL

Precise 9-cell model for beam loading is missing…



Cavities calibrated and validation using relative energy measurement in dispersive section. Found **systematic 10% error** at XFEL &FLASH; need to be understood!

10% of additional electrical field modes for 9-cell cavity, (r/Q) or q_B not correct, ADC bandwidth limitation due to cell to cell coupling and energy flow,…

One question to be answered.

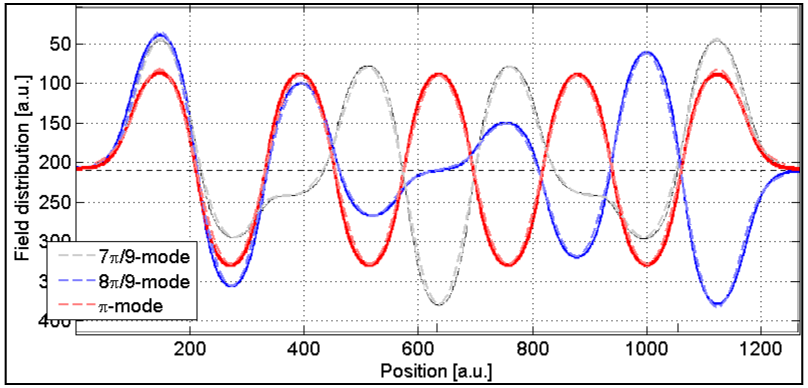
Cavity mode contribution to the beam

… started MATLAB simulation longer time ago

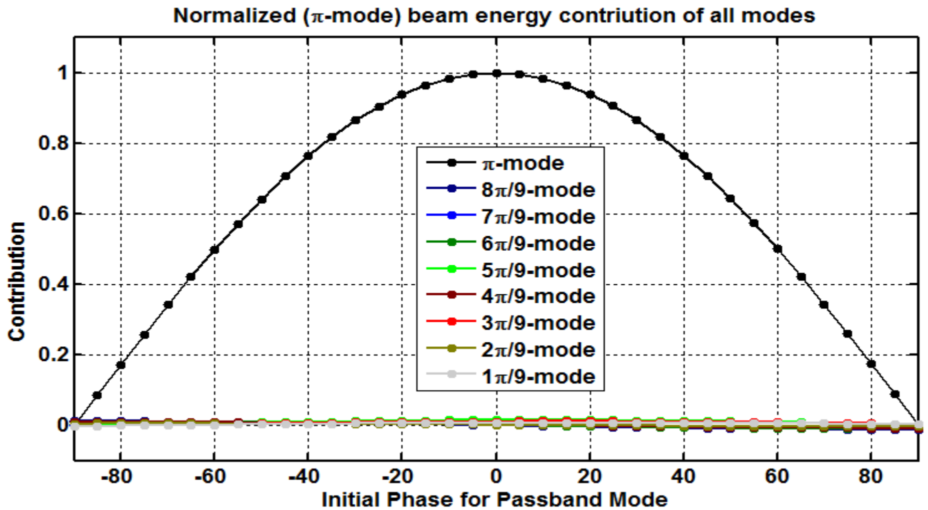
- Imported RF field characteristics for all RF modes from paper [J. Sekutovicz, 2007, "MULTI-CELL SUPERCONDUCTING STRUCTURES FOR HIGH ENERGY e+ e- COLLIDERS AND FREE ELECTRON LASER LINACS"]
- Symmetry check of field distribution
  - Line (odd mode) and point (even) symmetry
- Passband mode frequency taken from paper [E.Vogel, "High gain proportional rf control stability at TESLA cavities", 2007]

TABLE I. Frequencies of the FMs measured in the superconducting state at 116 cavities produced for the TESLA collaboration and succeeding projects [9]. The values are the mean eigenfrequency and the rms of the eigenfrequencies (not the mode bandwidths).

FM	Mean eigenfrequency of 116 cavities
π	$f_\pi = (1\,300\,444 \pm 303)$ kHz
$8/9\,\pi$	$f_\pi - (785 \pm 51)$ kHz
$7/9\,\pi$	$f_\pi - (3053 \pm 94)$ kHz
$6/9\,\pi$	$f_\pi - (6501 \pm 157)$ kHz
$5/9\,\pi$	$f_\pi - (10\,694 \pm 243)$ kHz
$4/9\,\pi$	$f_\pi - (15\,122 \pm 347)$ kHz
$3/9\,\pi$	$f_\pi - (19\,237 \pm 430)$ kHz
$2/9\,\pi$	$f_\pi - (22\,594 \pm 503)$ kHz
$1/9\,\pi$	$f_\pi - (24\,773 \pm 543)$ kHz



- Result: Normalized beam energy contribution of all field modes



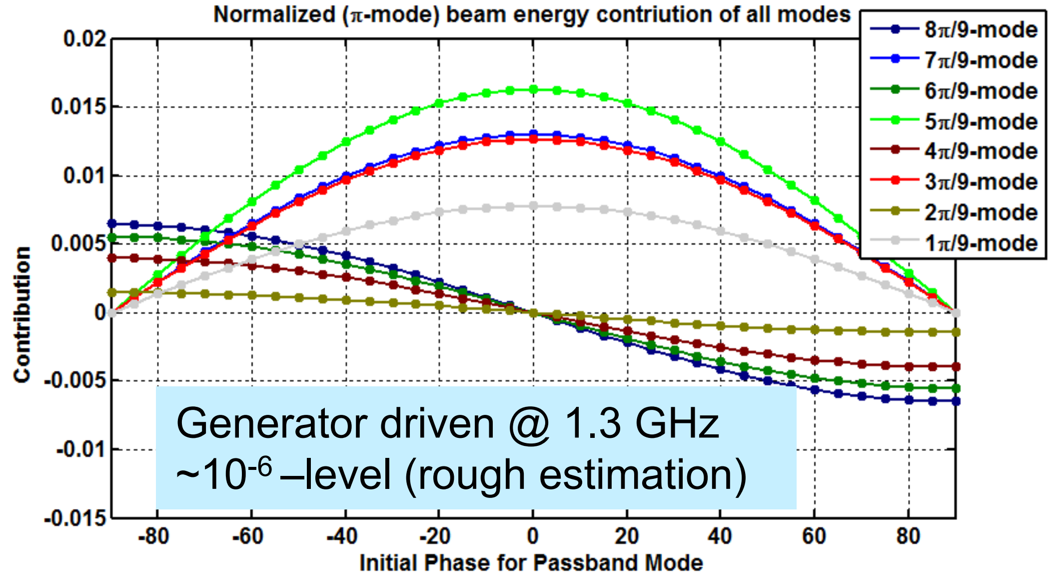
Cavity mode contribution to the beam

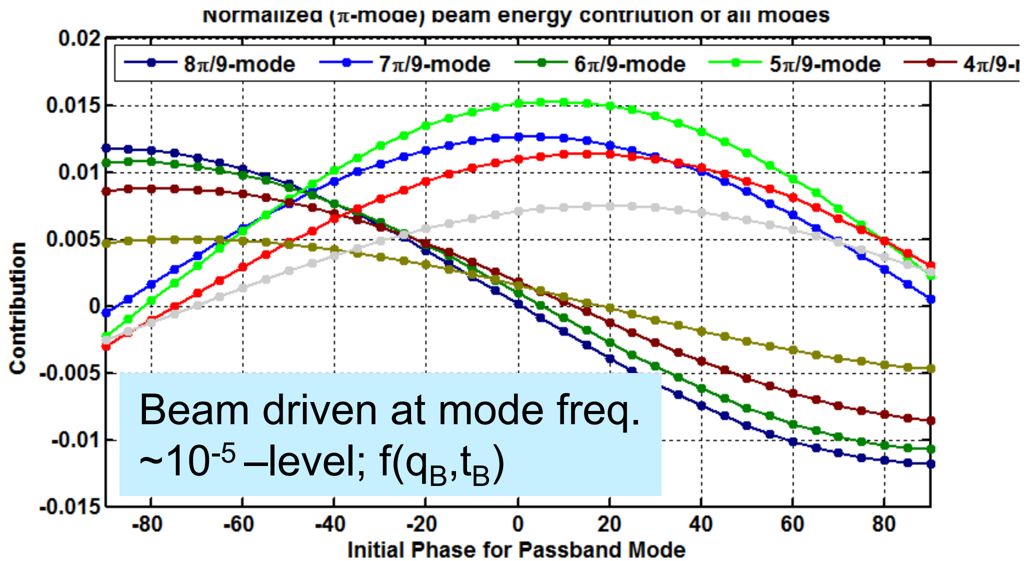
… started MATLAB simulation longer time ago

- Mode contributions are dependent of initial RF field phase seen by the beam
    - Important for multi bunch operation

1. Adding e.g. passband mode contributions driven by generator
    - Beam contribution if each mode is driven as the π-mode in amplitude
    - Modes phase w.r.t. π-mode unknown

2. Adding e.g. passband mode contributions from beam driven excitation at 0 deg. lead to 5 % energy change
    - For beam drive similar to RF drive
    - Modes are not phase stable and change over time





Summary & Questions

Questions to be answered by simulation experts

1. Field probe measurement errors during beam transition

Goal: Do we measure what we expect from physical model at the probe pick-up?

- Cell-to-cell coupling during refill process
  - Transient behavior of end-cell (pick-up) identical to the others?
  - Pickup measurement during refilling time?
  - Does this refilling process with given ADC bandwidth explain the 10 % discrepancy?
- Probe pick-up location correctly chosen?
- Is maybe a 2^{nd} probe required/helpful?

2. Additional beam loading effects

Goal: Get beam loading white-box model like the cavity equation for it's characterization.

- Assumption of on-axis and Gaussian beam properties (ideal cases)
- Beam loading to the π-mode?
- Beam loading to the remaining passband modes (8π/9 down to the 1π/9-mode)?
- Cell-to-cell effects while the beam is passing?

Summary & Questions

Questions to be answered by simulation experts

3. Exploit additional passband modes (8π/9 … 1π/9)

Goal: Extract additional information from the passband modes.

- Assumption of mode excitation by beam or drive if energy gain stays constant
- Can we get additional information's from the passband modes?
  - Resonance frequency of pi-mode?
  - Detuning?
  - Beam phase?

4. Mechanical cavity model

Goal: Find an appropriate mechanical cavity model including mechanical couplings.

- Piezo excitation/correction to detuning of π-mode?
- Cavity-to-cavity couplings (mechanical) in spatial distribution?

Thank you

Contact

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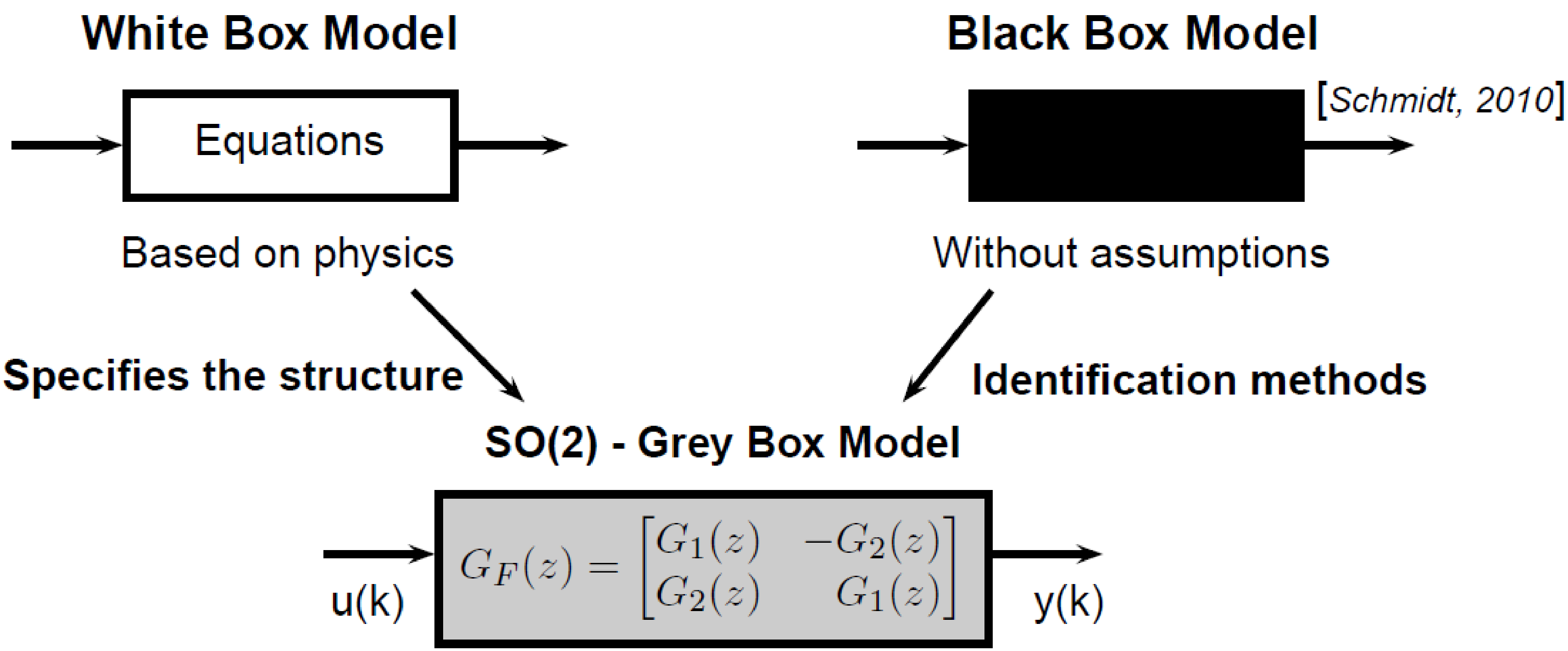
Backup Slides

System Identification

… using grey-box modelling



- Parameter identification within minutes
- Linear time-invariant (LTI) model:
  - Static gain, bandwidth, passband modes

SRF stability measurements

LLRF regulation

Objective: Keep RF field amplitude and phase within specification

- Feedforward
- **Feedback (MIMO)**
- **Learning Feedforward**
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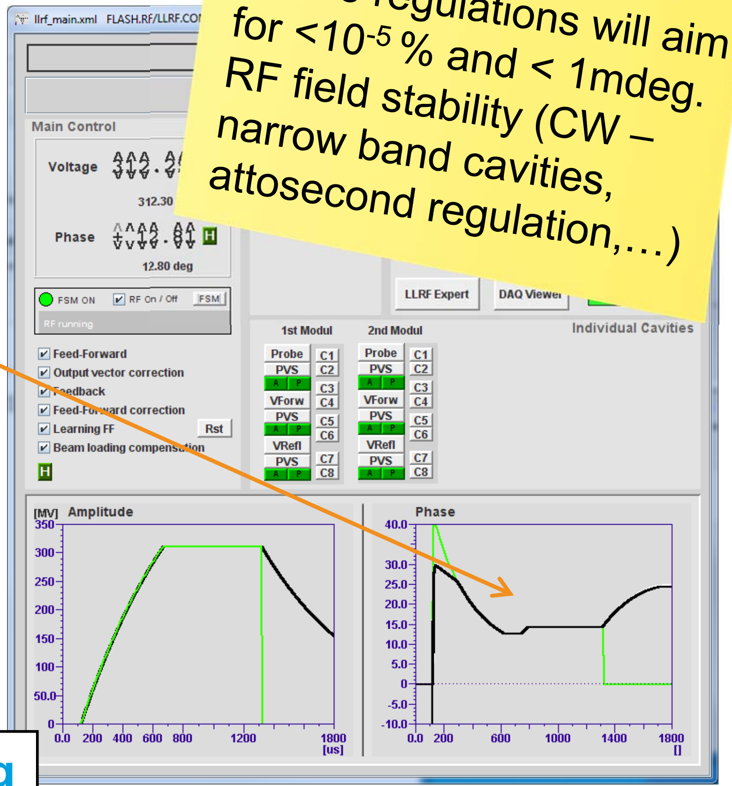
Multi-beamline support

Future regulations will aim for <10^{-5} % and < 1mdeg. RF field stability (CW – narrow band cavities, attosecond regulation,…)



Optimization using model-based approach
Precise 9-cell model for beam loading missing…

Regulation Goal: dA/A < 0.01%, dφ < 0.01deg

RF stability (rms)	RF-gun*	ACC1**	ACC39**	ACC23**	ACC45**	ACC67**
Ampl. Intra pulse [%]	0.0044	0.0057	**0.011**	0.0053	**0.0052**	0.0069
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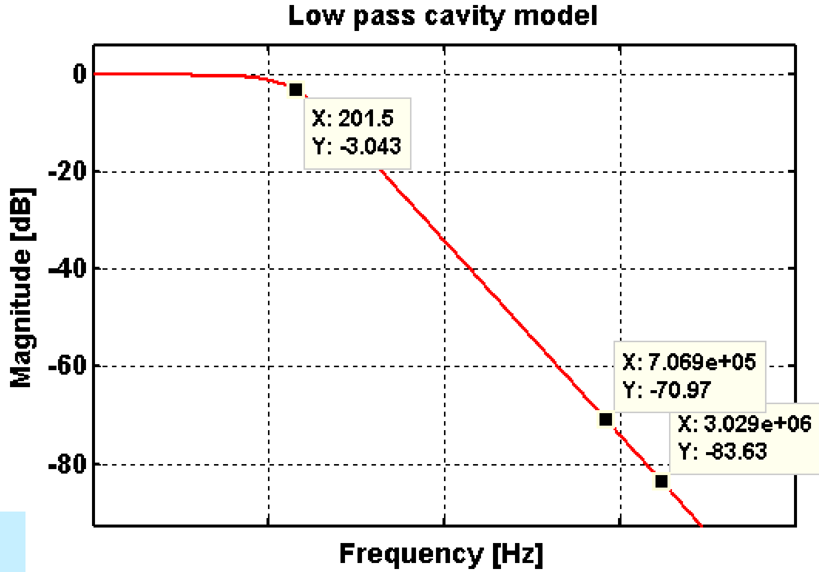
Table: In-loop regulation for 600 consecutive RF pulses

* at 100kHz BW (BW RF-gun ~ 53 kHz)
** at 9 MHz

Passband mode excitation

Maximum contribution to first two passband modes

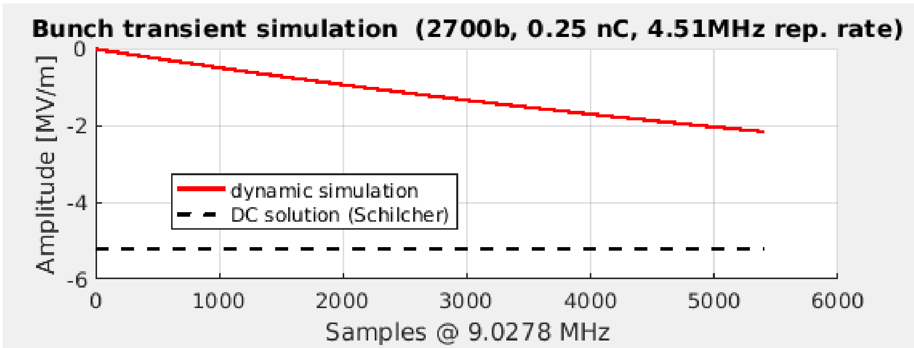
- 8pi/9-mode
  - -71dB * 0.007 = 2e-6 (generator)
  - -20dB * 0.011 = 1.1e-3 (beam)
- 7pi/9-mode
  - -83dB * 0.016 = 1e-6 (generator)
  - -40 dB * 0.015 = 1.5e-4 (beam)



Beam driven; XFEL: 4.6e6, 0.25nC, 4.5 MHz, ~4% RF drive by beam

M. Ferrario, 1996, “Field propagation effects and related multibunch instability in multicell capture cavities”

…with a relativistic beam, the average accelerating field vanishes for all modes, except of course for the π-mode. … The induced bunch-by-bunch energy spread is with max. $3 \cdot 10^{-6}$ very small…



Cavity mode contribution to the beam

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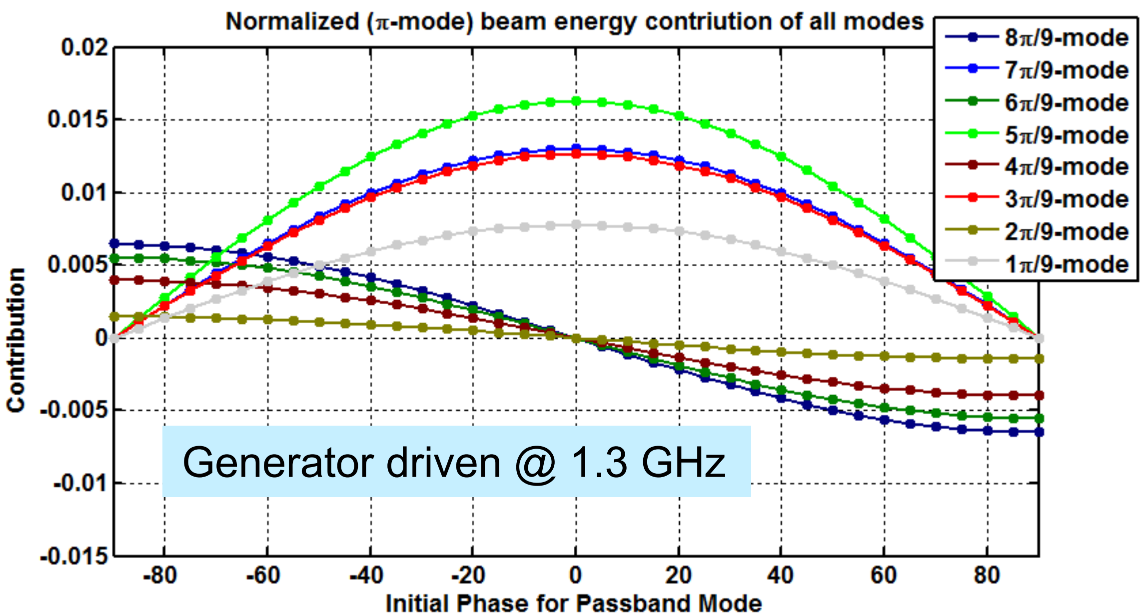

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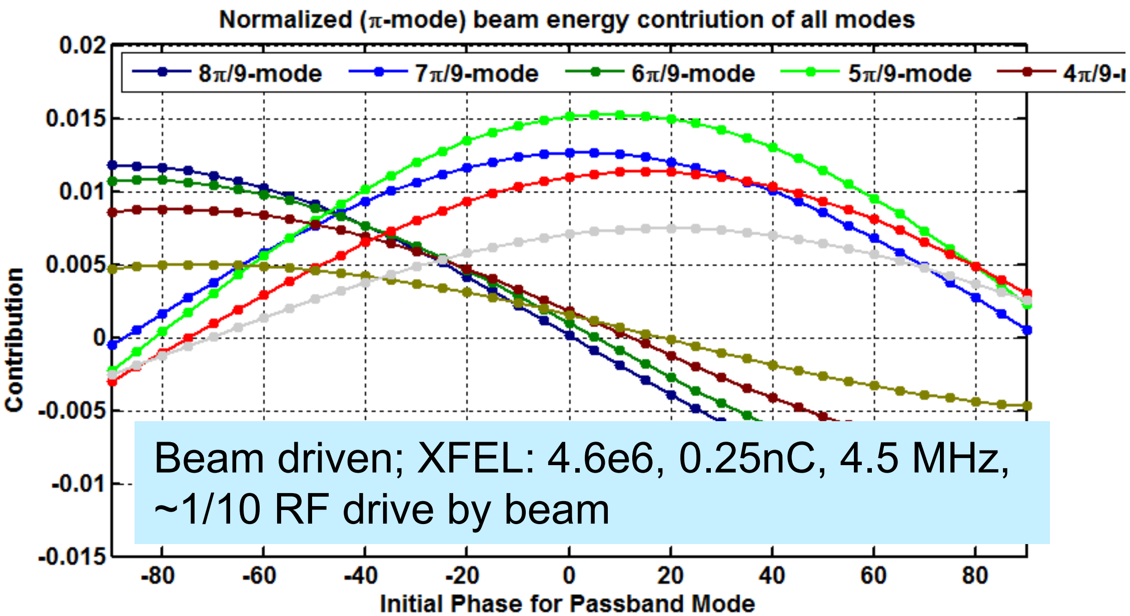
  - Modes are not phase stable and change over time
  - beam drive similar to generator drive…



Beam driven; XFEL: 4.6e6, 0.25nC, 4.5 MHz, ~1/10 RF drive by beam

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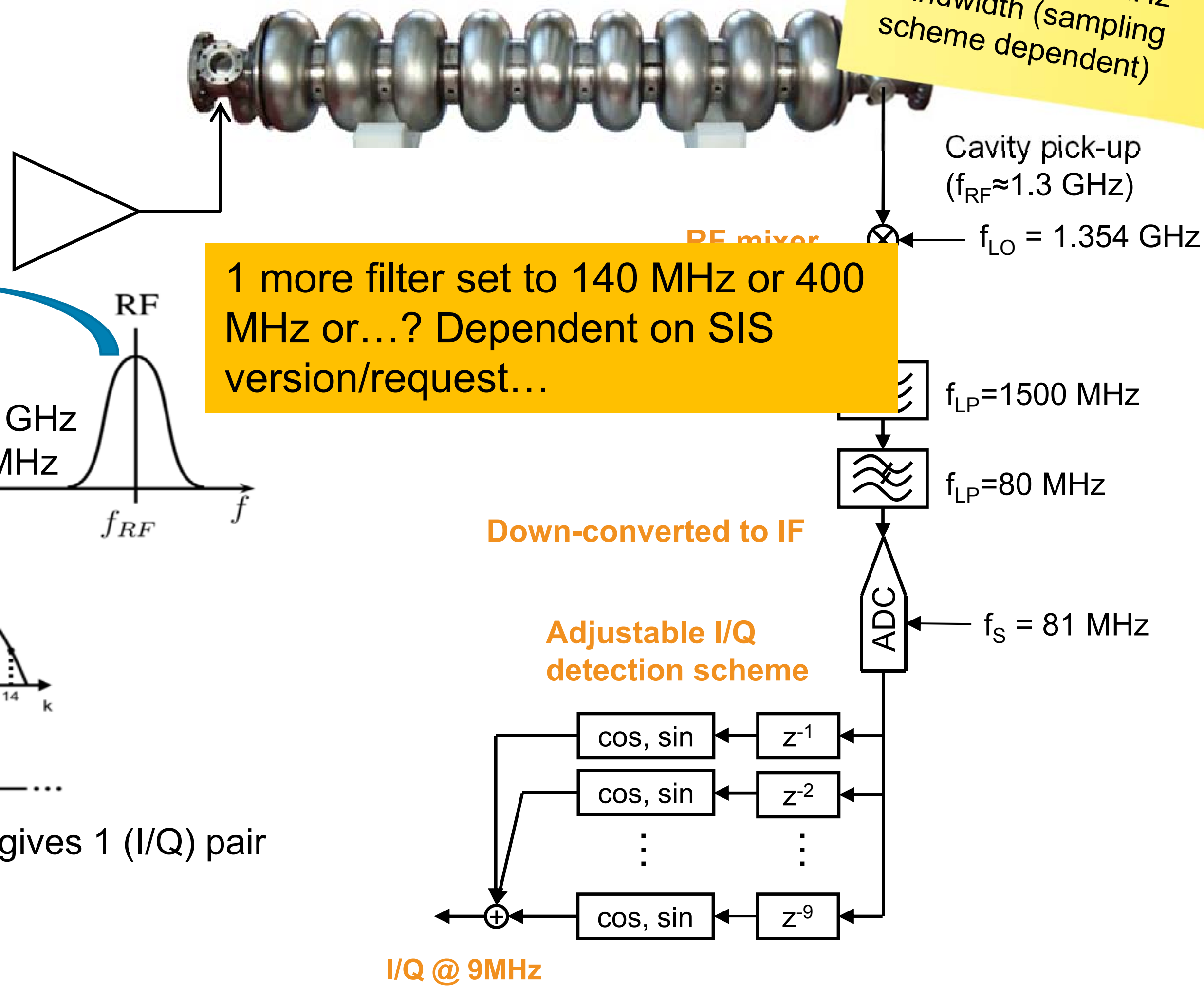
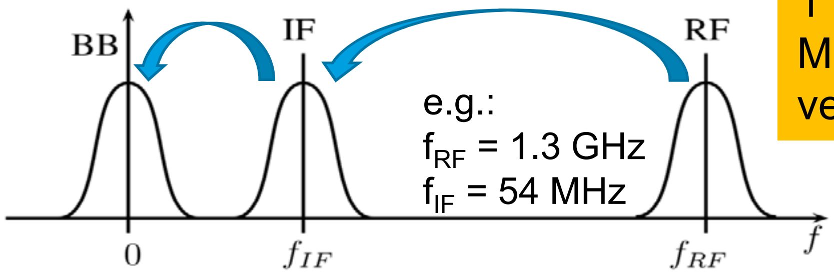
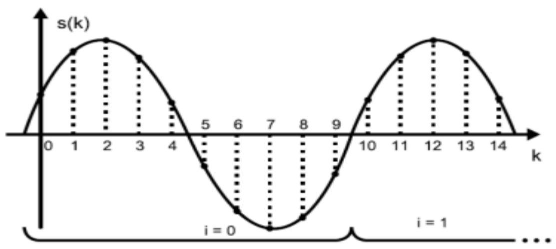


1 more filter set to 140 MHz or 400 MHz or…? Dependent on SIS version/request…





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