Regulation Requirements for LLRF Control

MSK LLRF Seminar

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Contents

Requirements

- What is ment by this?

The XFEL

- ...from the RF point of view.

Functional Requirements

- Do we already know how the thing is going to behave?

Technical Requirements

- Performance
- Implementation
- Interfaces, Connectors, User-Interfaces

Specifications

- Subsystems working together.

Introduction

- Everything starts by thinking.
- Following Questions havt to be answered before starting to build anything.
- What do we want to achieve?
- What do we thing we need to build for this?
- How do we want to build it?
-
- **Requirements** and **Specifications**
- **Technical Requirements Functional Requirements**

Requirement

To acheive ...X... it is required, that ...Y...!

- **Example:** To achieve optimal bunch compression in BC1 it is required, that the bunch phase stability of the beam at the exit of ACC1 is better than 0.01°!
- **Example:** To achieve a bunch arrival time jitter of better than 20 fs at the end of XFEL it is required, that either th RF of each single RF station of the injector linac is controlled with $\Delta\phi < 0.01^\circ$ and $\frac{\Delta A}{A} \leq 10^{-4}$ or a beam based feedback needs to be build.

Hirarchy of Requirements

1. **Global** Requirements (of beam parameters) to acheive optimal SASE.
2. Requirements on the technical components (like the RF control and other diagnostics and feedback equipment) to fulfill the beam parameter requirements.
3. **Compatibility** Requirements on other technical equipment to be compatible with the specifications of the system in focus. (technical, functional, operational, etc ...)
4. Specifications on
   - what to be build and
   - what is already there.

Compatibility Requirements

For a particular subsystem.

Technical Requirements

- Technical Performance (To acheive compatibility with ...xyz... it is required, that this system needs ...abc...)
- Hardware Implementation
- Software Implementation
- **Extra:** Interfaces, Connectors, User-Interfaces
- **Extra:** Electronic design and standards
- **Extra:** Racks, Crates and Modules
- **Extra:** EMC and EMI
- Spare parts availability

Compatibility Requirements

Functional Requirements

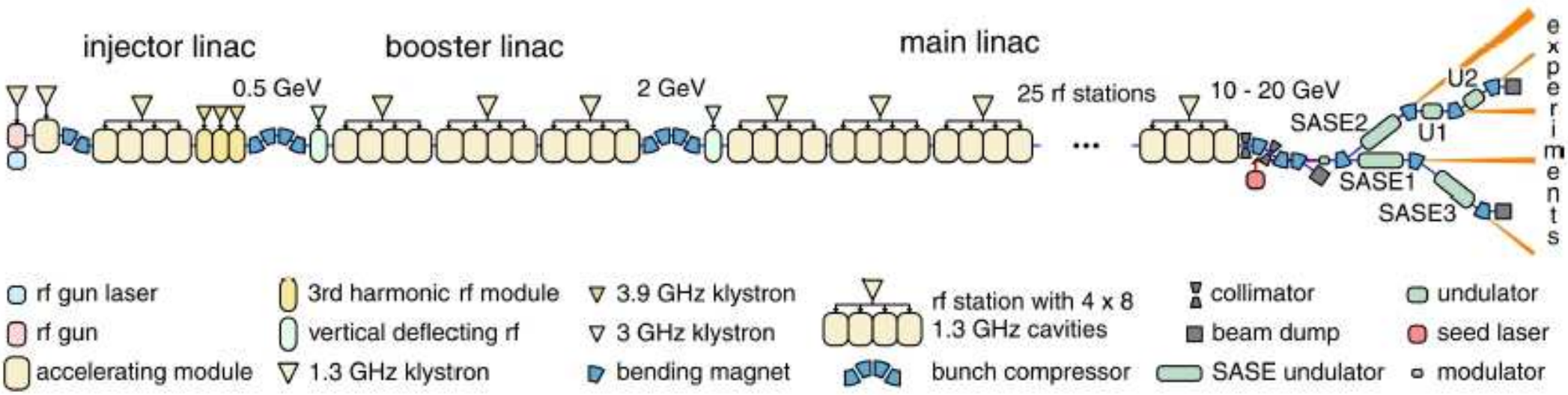
- Functionability
- Reliability (It is required to aceive an uptime of ...x... to not conflict with ...y...)
- Maintainability, Availability
- Radiation Immunity

Specifications

A specification is a **description** of the capabilities of a specific subsystem. These capapilities need not be really required.

- Garantees for lifeetime, uptime, MTBF
- Performance: Under which conditions are the Requirements not fullfilled anymore.
- Impelmentation: What has been built and how.

The XFEL



Electron beam parameters:

Electron energy	17.5-20 GeV
Bunch charge	1 nC
Bunch length	20 μm, 25 μm (rms) $\longrightarrow 7 \cdot 10^{-14}$s $= 70$fs
Emittance at undulator	1.4 mm mrad (slice)
Energy spread	1 MeV (slice), 1.5 MeV (rms) $\longrightarrow 5 \cdot 10^{-5}$
Peak Current	10 kA

Global Requirements

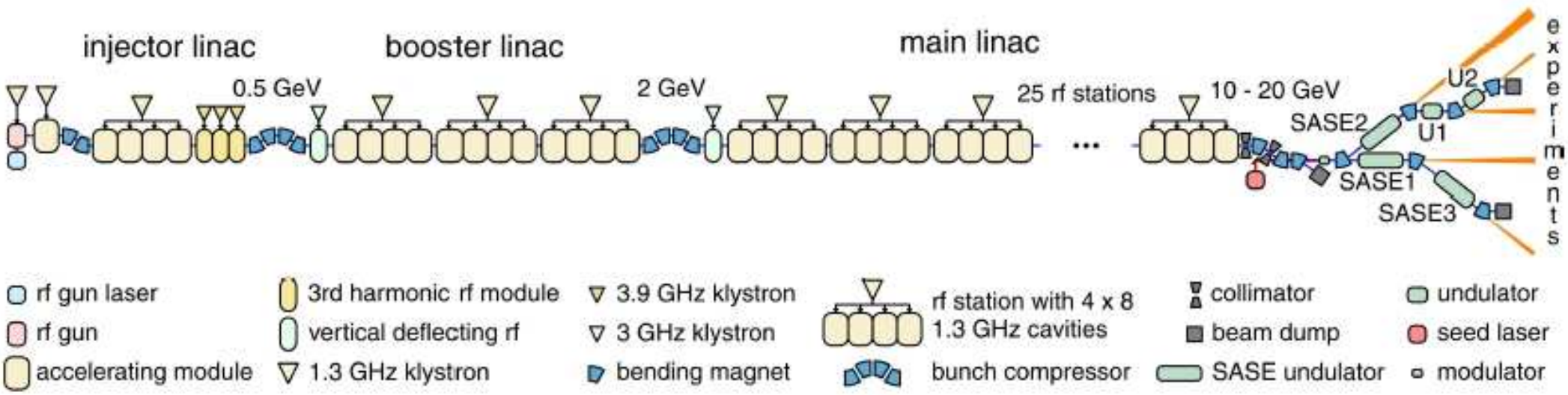
given from physics, from SASE, from the users

1. Final **energy spread** $\frac{\Delta E}{E} \leq 5 \cdot 10^{-5}$
2. Final bunch **peak current** $I_{\text{peak}} \geq 5$ kA (1nC)
3. **current variation** $\frac{\Delta I}{I} < 10\%$ (because of SASE)
4. Final **arrival time** jitter $\Delta t < 30$ fs.

- 1 and 4 are directly influenced by the **phase (and amplitude) stability** of all RF components
- 2 and 3 influenced by Electron Gun and Photocathode Laser and **bunch compressors**.
- bunch compressor operation required highly stable beam parameters **before** passing the BC. Therefore stability at low energy is more critical.

Now lets look at the consequences...

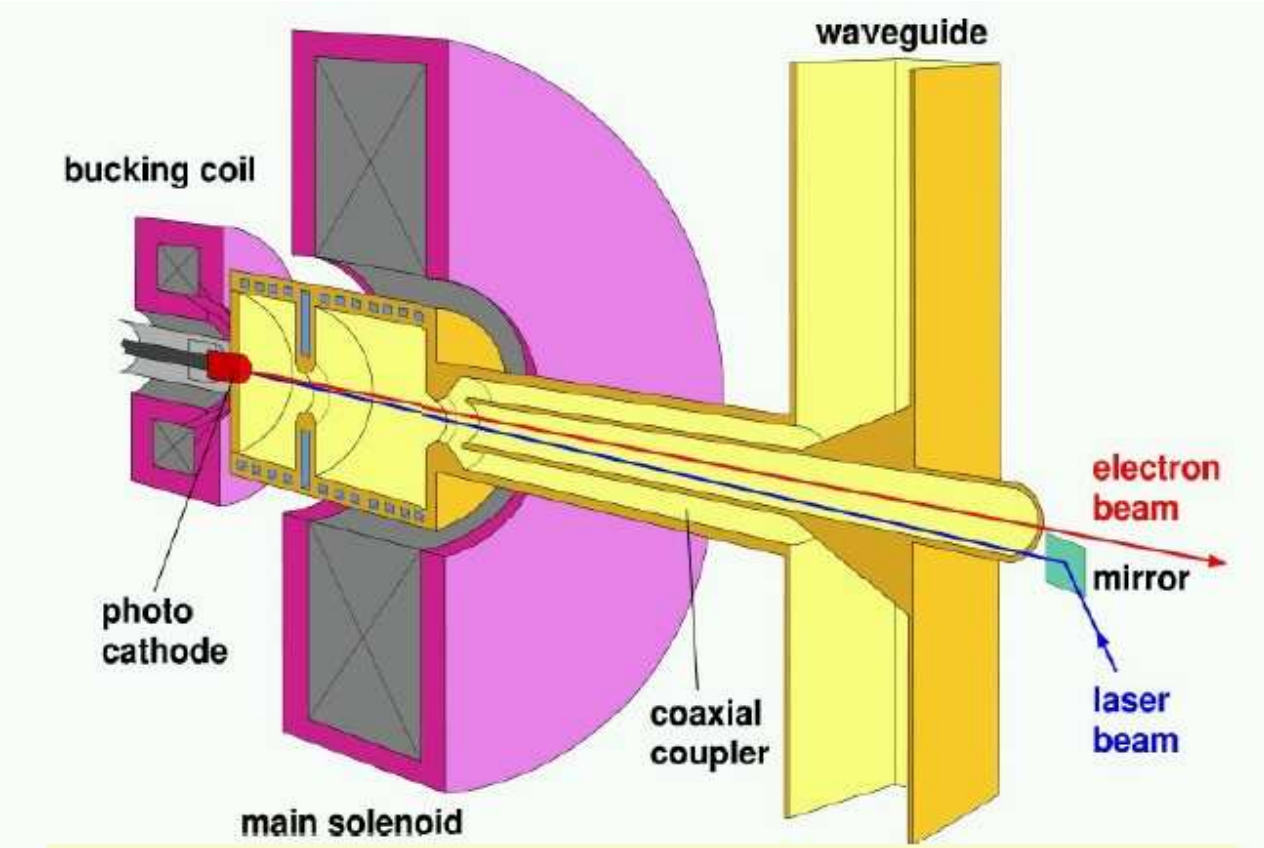
RF Stations

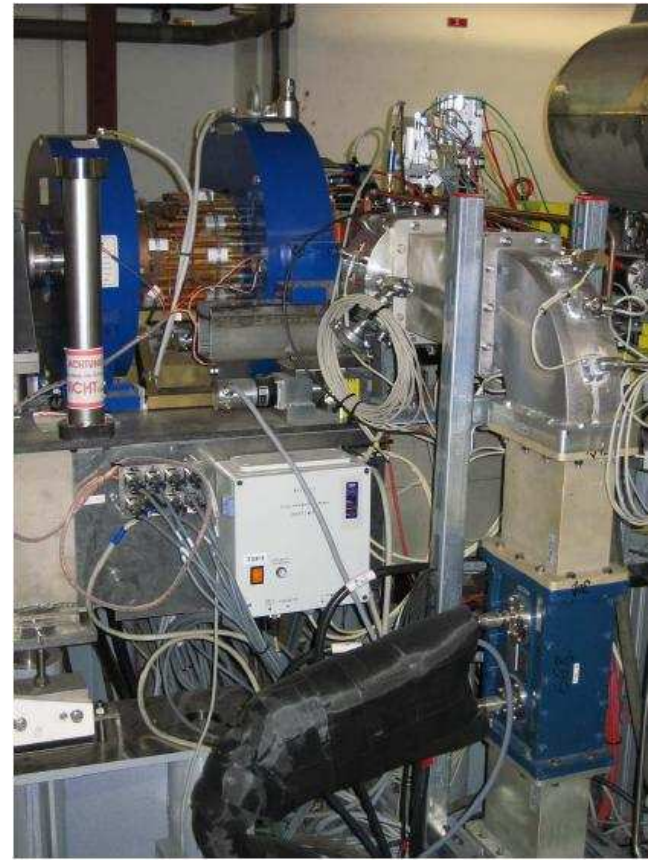


There are 34 individual RF stations of the Accelerator Complex:

- 1 RF station of the **RF Gun**
- 1 RF stations for the **Pre Accelerator** (accelerator module ACC1)
- 1 RF station of the **Injector Linac**
- 4 RF stations of the **3rd. Harmonic System**
- 3 RF stations for the **Booster Linac**
- 24 RF stations for the **Main Linac**

RF Gun

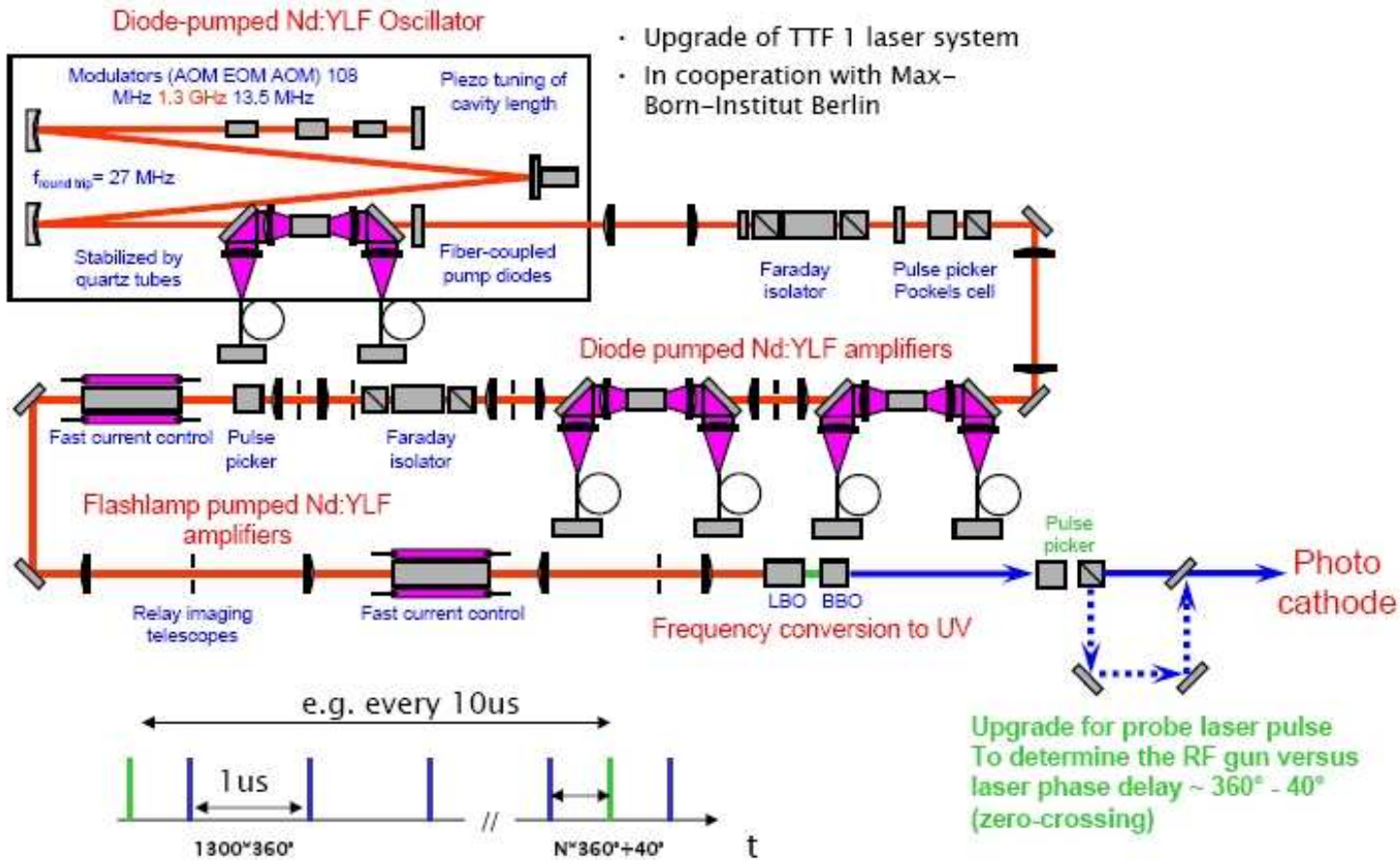




- (1.3 GHz) RF gun sync. LASER
- filling time: typical 30 μs
- flat top time: up to 800 μs
- pulse repetition: up to 5 (10) Hz
- high RF field: 40 MV/m

- FEL operation is sensitive to RF gun phase
- ... not so sensitive to RF amplitude.
- ... very sensitive to LASER intensity

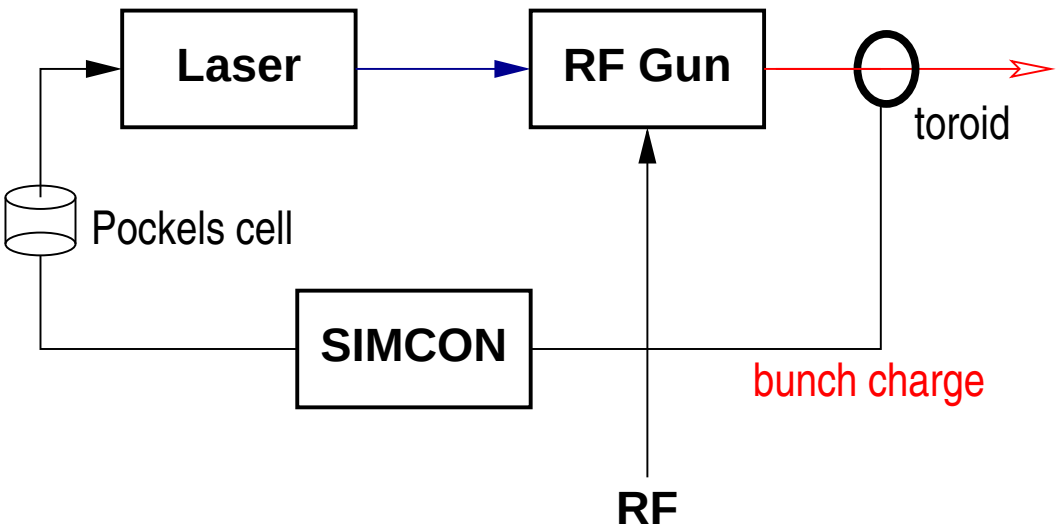
Gun LASER



- Cs_2Te Bi alkali photocathode
- Bunch charge: 1nC
- Wavelength $\lambda = 262$ nm (UV)
- Pulse length 20 ps at 5 MHz rep. freq.
- Bandwidth $\Delta\lambda = 1$ nm
- Phase stability ≈ 10 fs (rms)$\ll 200$ fs
- Reference is Master Oscillator

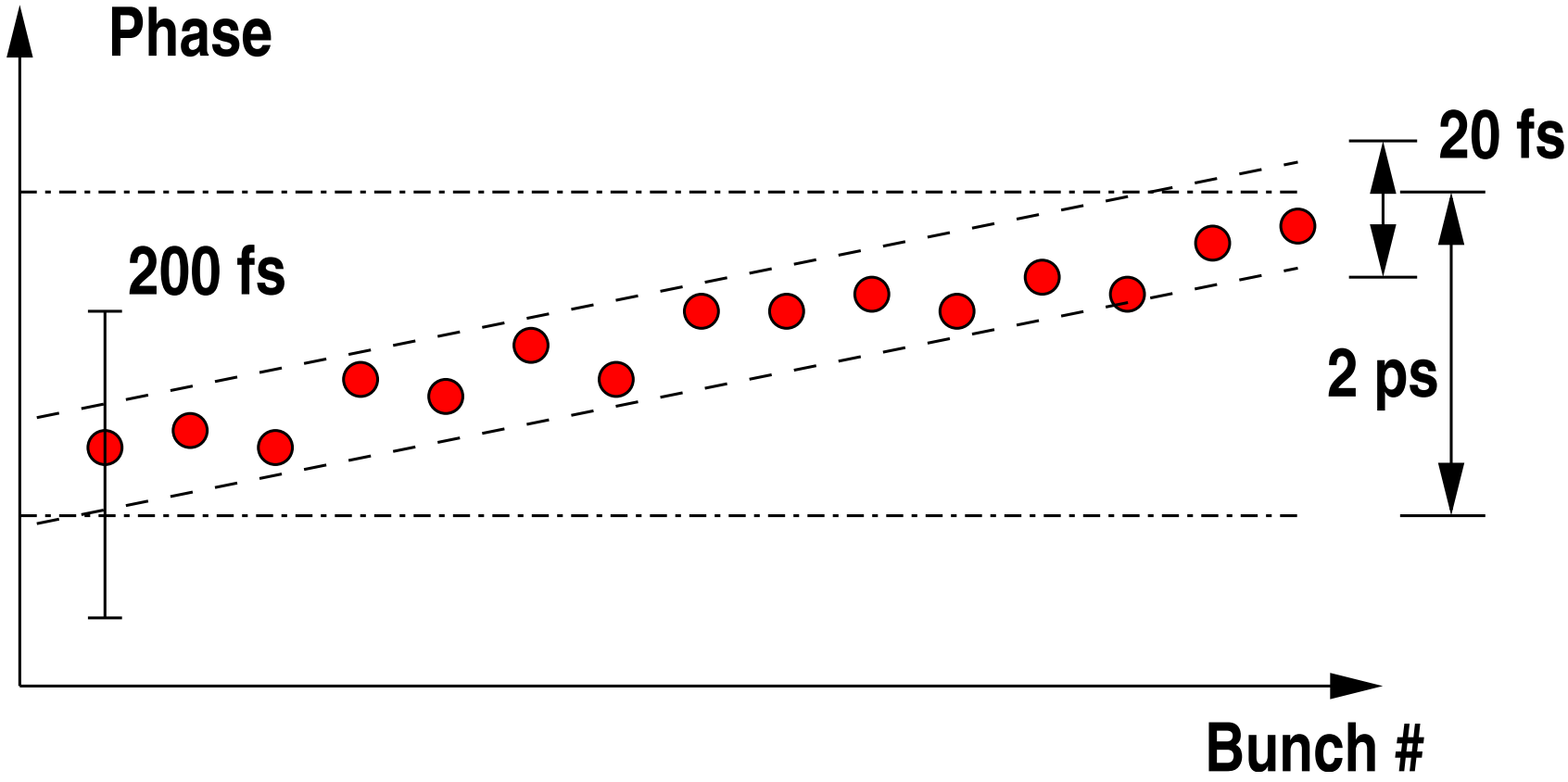
Requirements on RF Gun and LASER

- Arrival time jitter $\Delta t|_{20\mathrm{GeV}} = \frac{1}{100}\Delta t|_{0\mathrm{GeV}} \longrightarrow \Delta t|_{0\mathrm{GeV}} < 3ps$ but
- Phase jitter shall be $\frac{1}{1000}$ of the bunch length, so $\Delta t \approx 10$ fs.
- ΔE is not important here, because it is still low energy.
- Bunch charge: A feedback from toroid measurement to Photocathode laser is necessary:



- RF amplitude stability $5 \cdot 10^{-4}$ required
- RF phase stability is more critical. it transforms 2:1 (0.5) to the beam. $\Delta\phi \approx 0.01^\circ$ (20 fs)

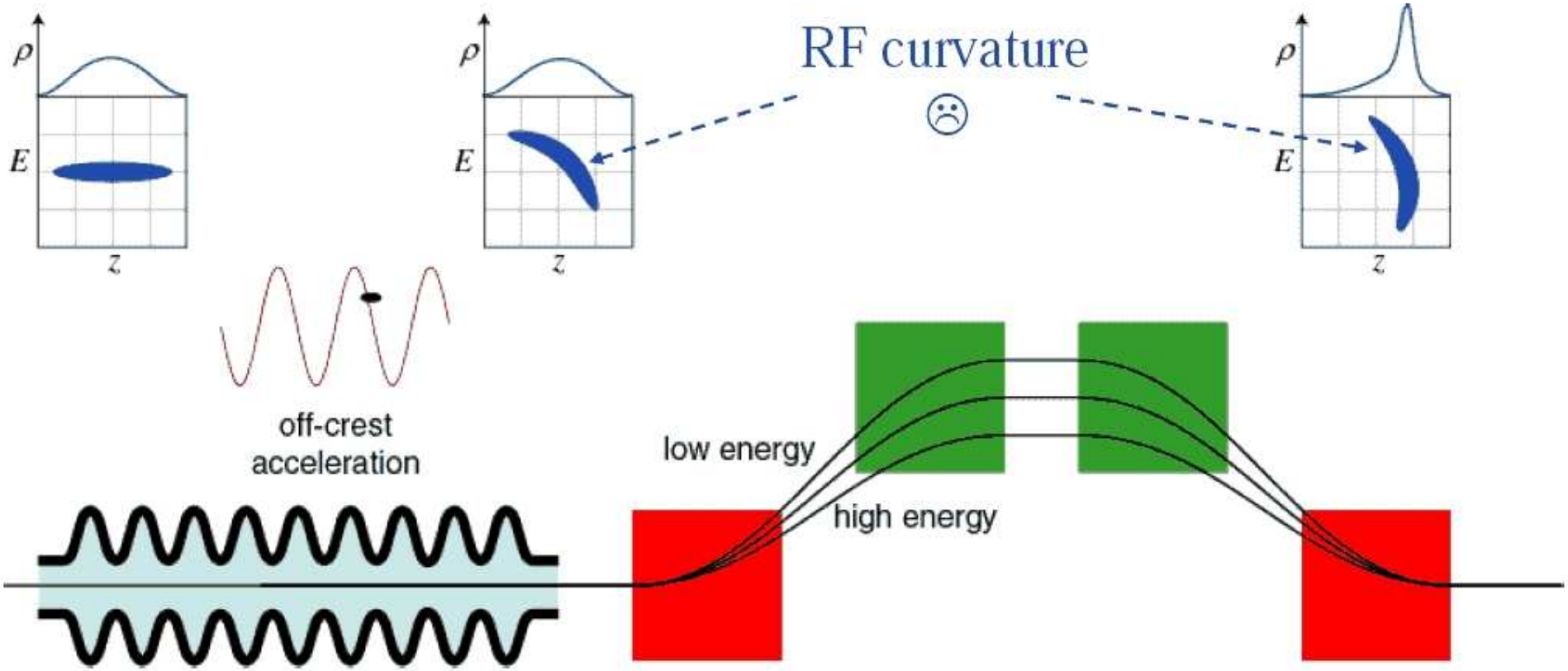
Different Numbers



- Bunch to bunch: 20 fs (0.01°) (0.02° already acheived at FLASH!)
- Intra-Bunch-Train: 2 ps (1°) (drift-like)
- From RF pulse to RF pulse: 200 fs (0.1°)
- With a beam based **beam phase** feedback (to the Laser) everything could be 20 fs.

Bunch Compressor

How to produce high **peak currents** and short bunches.



- Apply energy differences of particles in front and in the tail of the bunch.
  $\longrightarrow$ Off-crest acceleration in one cavity.
- No difference in velocity (almost c anyway) but different path length in magnetic chicane.

Requirements on RF control of ACC1

From Bunch-Compression:

$$\Delta z = R_{56}\frac{\Delta p}{p}$$

$R_{56} = 100$ mm: momentum compaction
Required:

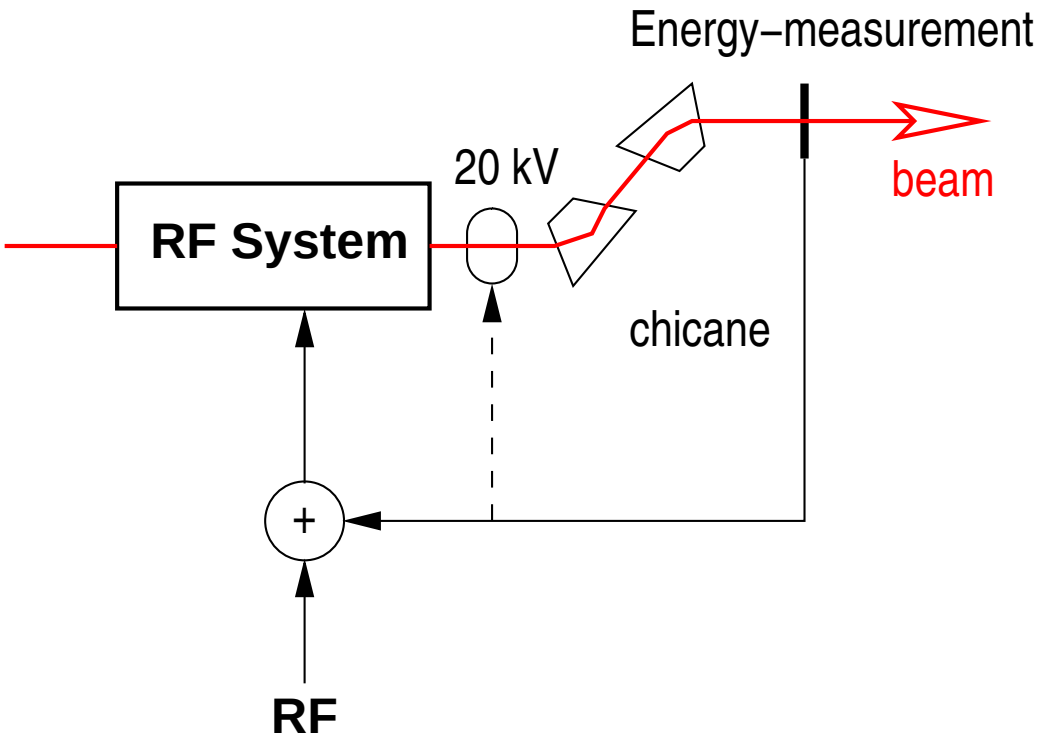
$$\Delta z < \sigma_z \approx 20\mu\mathrm{m}$$

- $\longrightarrow \frac{\Delta p}{p} < 2 \cdot 10^{-4}$ at exit of ACC1 (67 MeV).
- energy spread: $\frac{\Delta E}{E} = \frac{\Delta p}{p} < 2 \cdot 10^{-4}$
- time jitter: $\Delta t = 70$fs (20μs from Δz)
- Energy-drift compensation with Feedback on Energy-Measurement at BC1 possible.
- RF amplitude stability $2 \cdot 10^{-4}$ required
- RF phase stability $\Delta\phi = 0.03°$.

Req. on Injector Linac and 3rd Harmonic Sys

Stabilities are strongly dependant of the operational setpoints of these systems. This is non-trivial! Critical for optimal bunch compression!

- RF amplitude stability: $\frac{\Delta A}{A} = 10^{-4}$
- RF phase stability: $\Delta\phi = 0.03^{\circ}$
- the phase translates 1:1 to final arrival time jitter.



Although there are particular setpoints where the RF stability is not critical, a **beam based feedback** looks necessary in any case, not to be limited.

Requirements on Booster and Main Linac

Booster Linac ($\longrightarrow$2 GeV)

the requirements are relaxed by a factor 2 to 3 ...

- correlated phase jitter $\Delta\phi_{\mathrm{RF}} = 0.1^\circ$
- $\frac{\Delta E}{E} < 10^{-4}$, so $\frac{\Delta A_{\mathrm{RF}}}{A_{\mathrm{RF}}} < 10^{-4}$ will do.

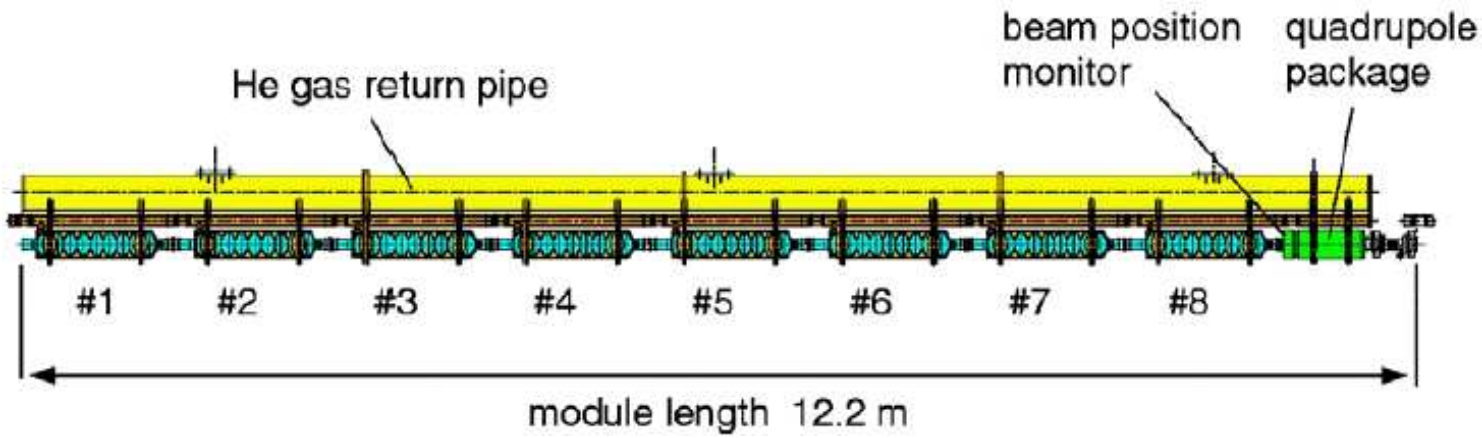
for each RF station. Otherwise a **beam based feedback** would be necessary.

Main Linac (2GeV$\longrightarrow$20 GeV)

- $\Delta\phi_{\mathrm{RF}} = 0.1^\circ - 0.2^\circ$ (0.5° might be tolerable)
- $\frac{\Delta A_{\mathrm{RF}}}{A_{\mathrm{RF}}} < 10^{-3}$

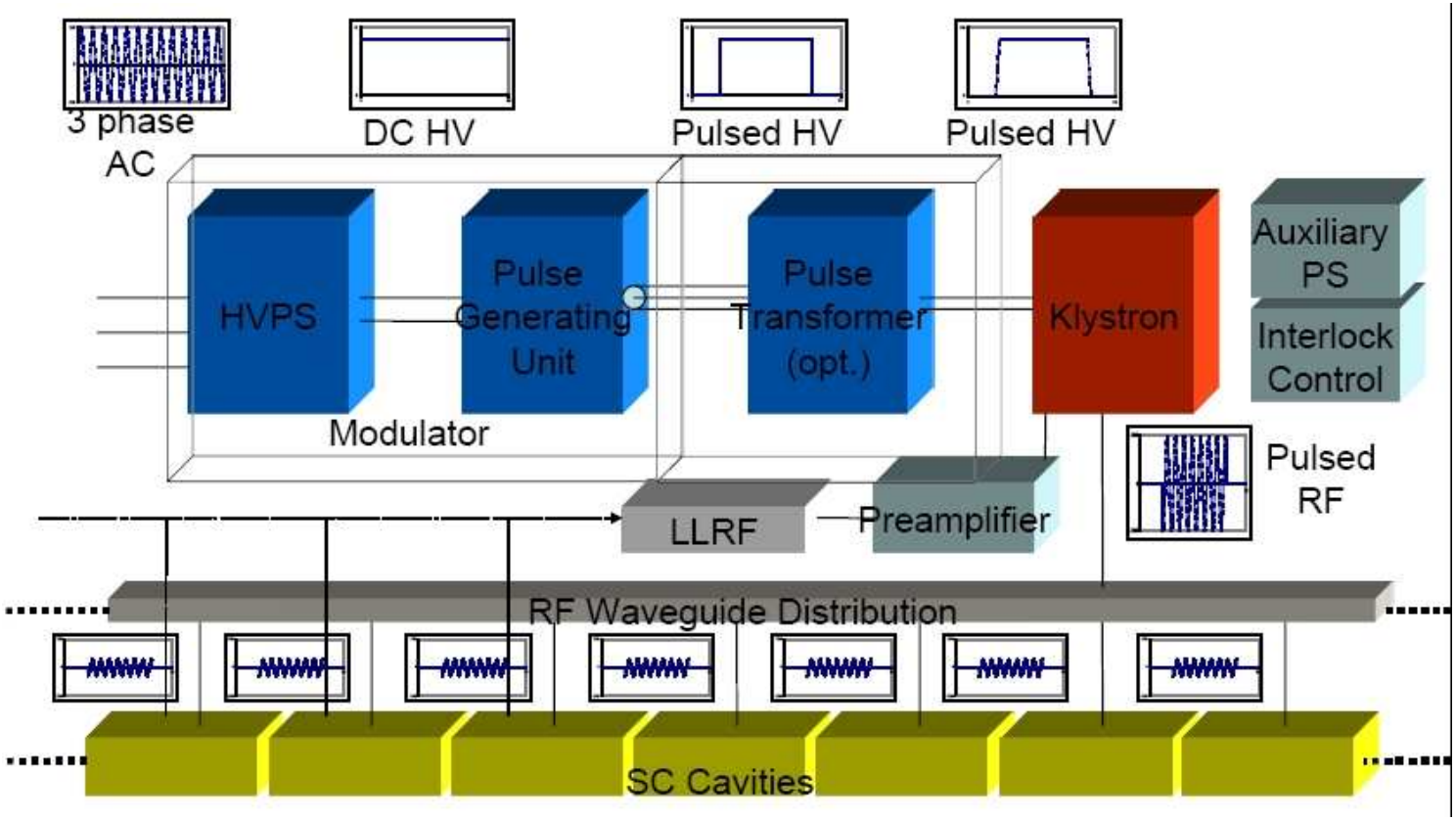
for each RF station. Otherwise a beam based feedback would be necessary.

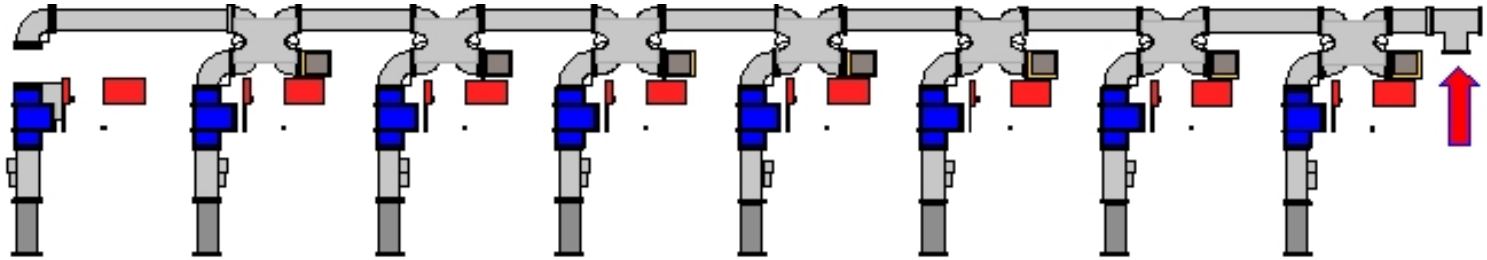
Cryomodule


He gas return pipe
beam position monitor
quadrupole package
#1
#2
#3
#4
#5
#6
#7
#8
module length 12.2 m


11698,86mm
11991,86mm

RF Station


3 phase
AC
DC HV
Pulsed HV
Pulsed HV
HVPS
Pulse
Generating
Unit
Pulse
Transformer
(opt.)
Klystron
Auxiliary
PS
Interlock
Control
Modulator
Pulsed
RF
LLRF
Preamplifier
RF Waveguide Distribution
SC Cavities



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