Beam Stability Challenges at the European XFEL

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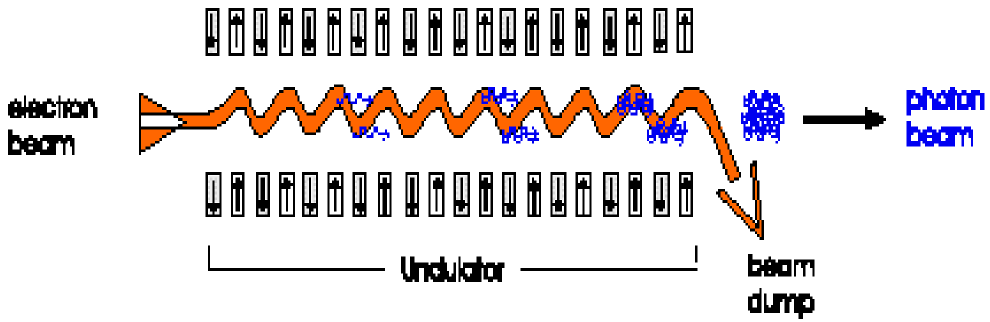
IWBS 2004

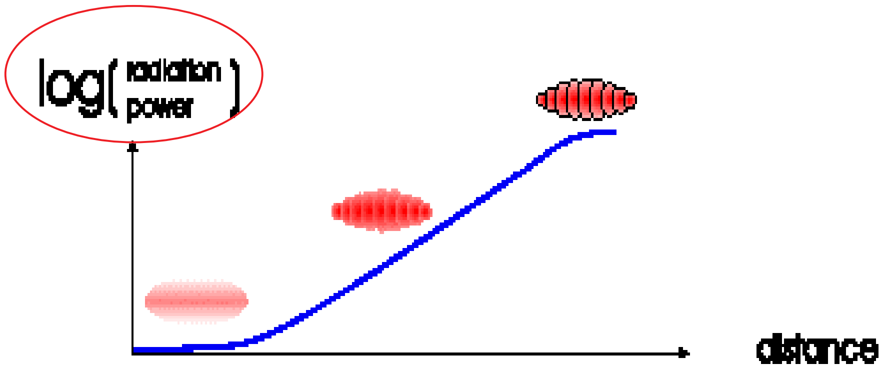
Outline

- Introducing the XFEL
- Beam Stability:
  - Slow
    - Undulator alignment
  - Medium
    - Element Jitter
  - Fast
    - Transients
    - Beam distribution
- Conclusions

XFEL Principle

Linear Accelerator based Self Amplification of Spontaneous Emission (SASE) Free Electron Lasers (FELs) in the X-Ray regime (~0.85 - 60 Å)





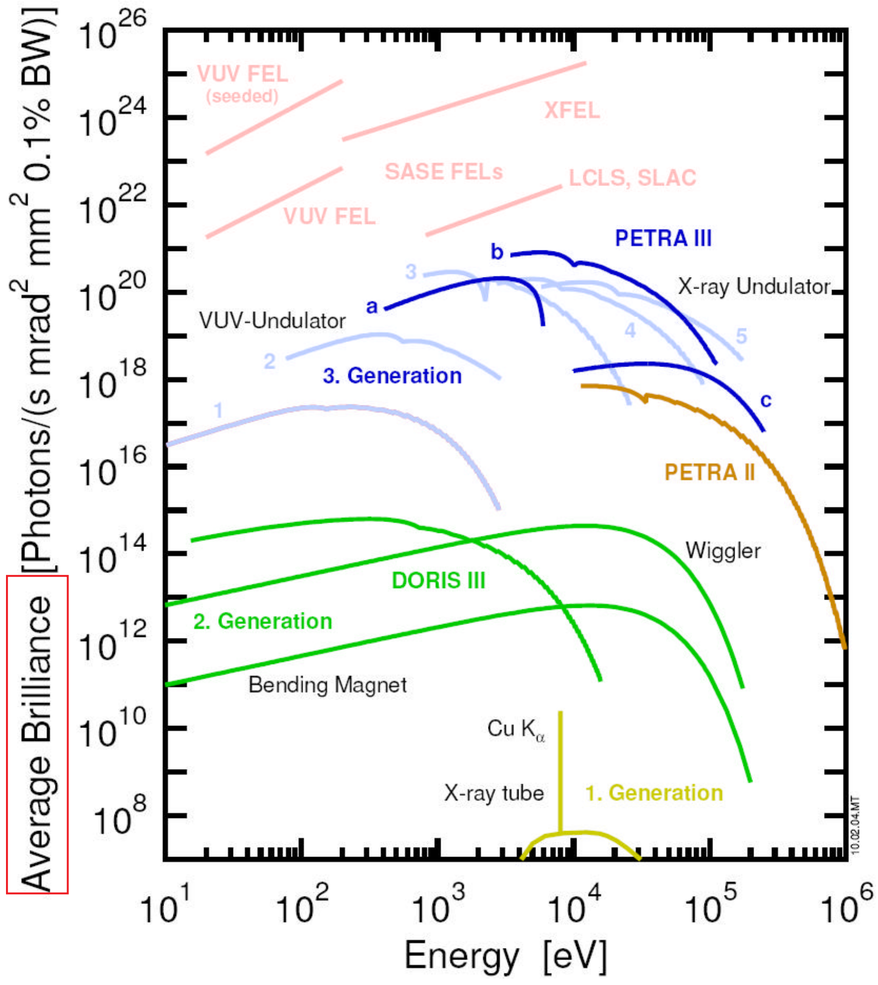
Electron bunch modulated with its own synchrotron radiation field
⇒ micro-bunching
⇒ more and more electrons radiate in phase until saturation is reached

Need excellent electron beam quality:

- low emittance
- low energy spread
- extremely high charge density

Need long undulator

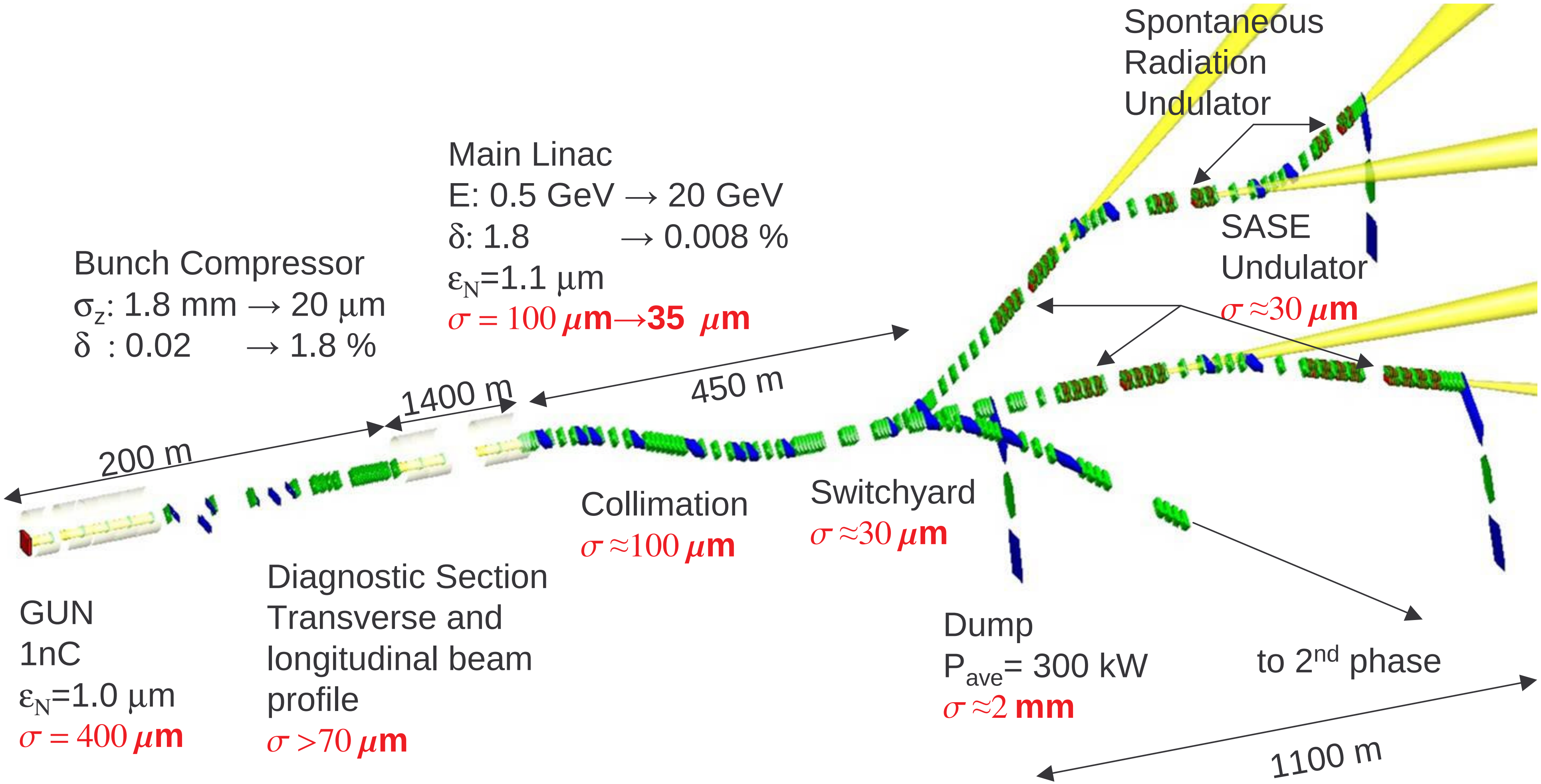
Spectral Characteristics of Radiation



Average brilliance : 1. BESSY II U125, 2. ALS U5, 3. DIAMOND U46, 4. ESRF ID16, 5. SPring-8 BL46; PETRA III: a. soft-X-ray undulator (4 m, high-), b. standard Kmax 2.2 undulator (5 m, high-), c. hard X-ray wiggler (Kmax 7, 5 m, high-).

- Radiation properties:
  - narrow bandwidth
  - fully polarized
  - transversely coherent
- Gain factors: (compared to 3rd generation sources)
  - peak brilliance
    - 10^9 SASE
    - 10^4 spontaneous
  - average brilliance
    - 10^4 SASE
  - coherence
    - 10^9 photons/mode SASE

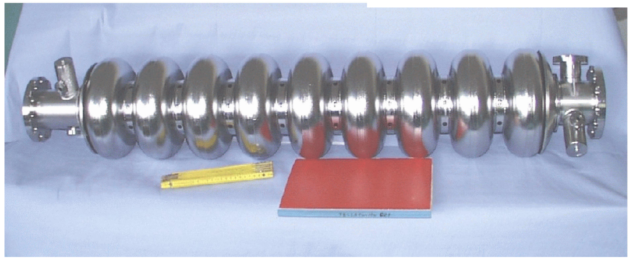
European XFEL

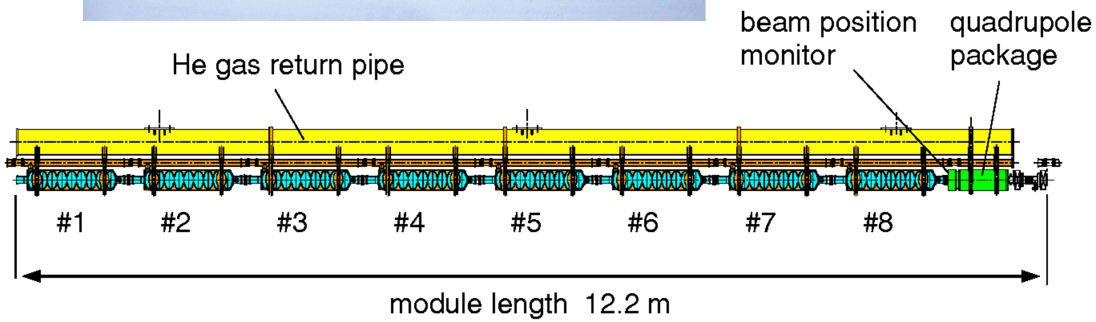


‘Bullet’ Beam: 20-30 μm transverse and longitudinal beam size
Sub-micron (or fs) stability in all 3 planes

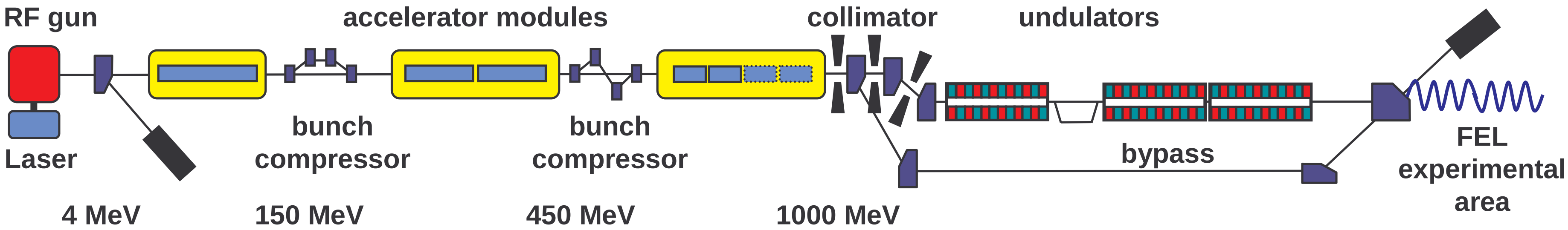
TESLA Technology / TTF

9 cell, 1.3 GHz Nb TESLA cavity





TTF module/SASE test facility => VUVFEL user facility



XFEL Time Structure

- Linac is pulsed with 10 Hz rep. rate
  (compromise between duty cycle and cryo load)
- Pulse length 650 μsec
- Minimum bunch distance in pulse 200 ns →
  ≈ 3200 bunches per pulse
- Pulse structure at experiment should be flexible

Beam Stability - Time Scales

Slow & medium

- Ground motion,settlement,drift
- Girder/Magnet excitation by cooling water, He-flow, …

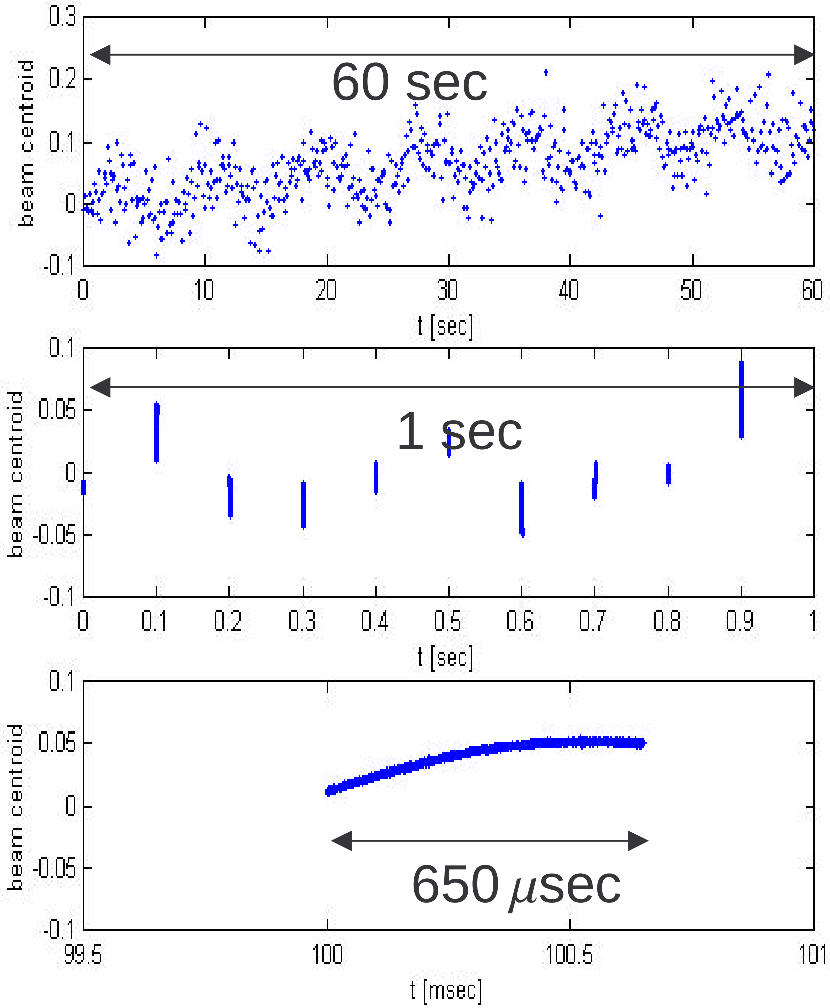
Fast

- Switching magnets
- RF transients
- Long range wakes
- RF jitter
- Photocathode laser jitter
- PS jitter > 1000 kHz

Leads to:

- beam centroid motion
- beam shape variations → effects on SASE power and gain length

Example: beam centroid motion (a.u.)



Tolerances

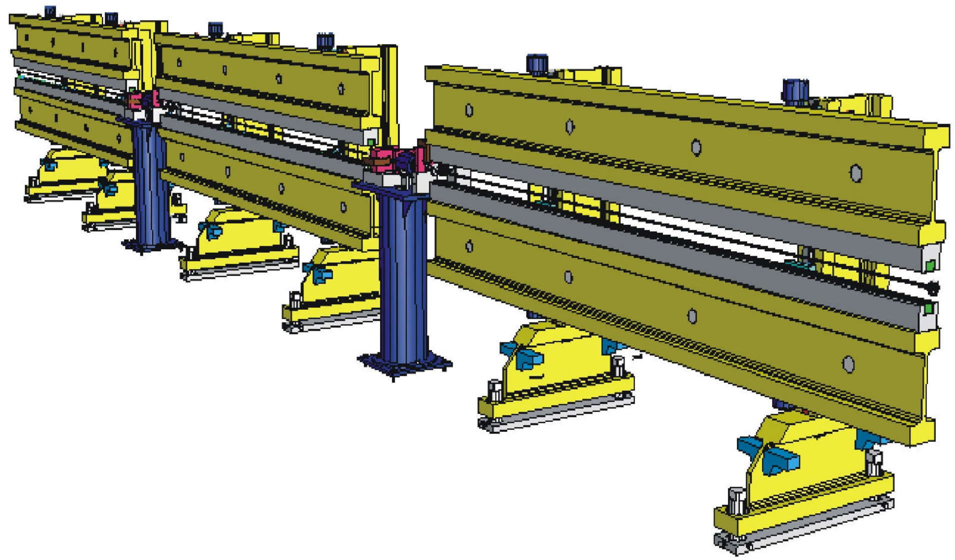
- Linac and Diagnostic
  - knowledge of bunch position at diagnostic to 0.1σ sufficient
- From SASE process:
  - 0.1σ (whole undulator, absolute alignment)
  - Particle density and bunch shape to be maintained
- User requirements
  - Depend strongly on beam line layout
  - 0.1σ (last part of undulator)
  - pointing stability (800 m long beamlines), opening angle of $\approx 1\ \mu$rad

Undulator Alignment

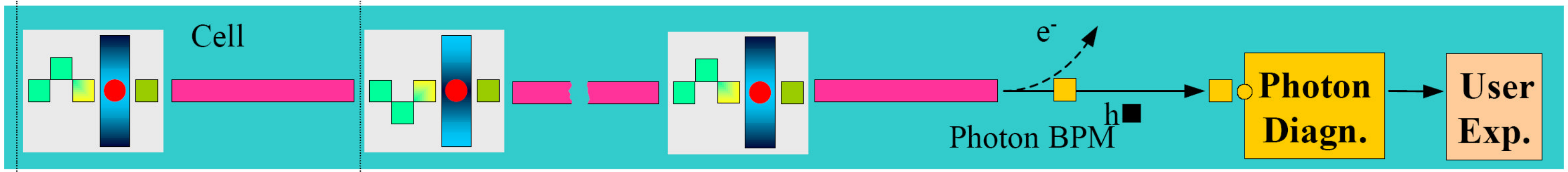
- Change of magnetic field and thus resonant wavelength due to
  - Temperature : < 0.08 K
  - Gap : < 1 μm
  - Alignment error : < 100 μm

Undulator:

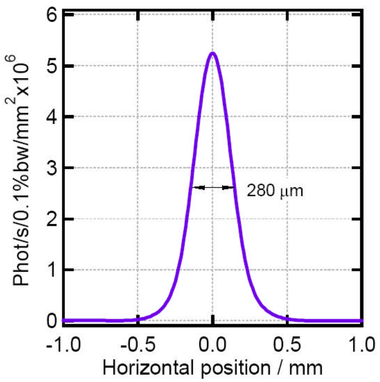
•Tunable Gap for e-energy independent wavelength selection
• λ ≈ 40- 80 mm
•B ≈ 0.5 – 1.3 T
•Gap > 10 mm
•5 m long segments embedded in 12.2 m long FODO cell
•Total length ≈ 700 m

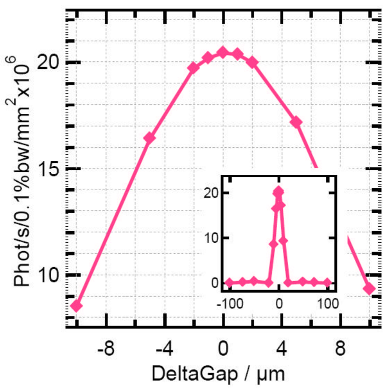


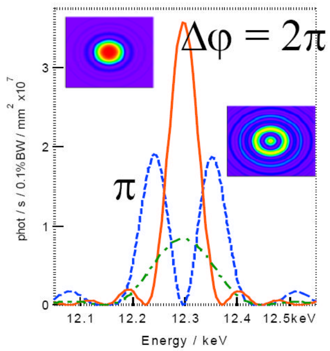
Photon Diagnostic based Undulator Alignment



Alignment of Trajectory, Gap, Phase







- precision ~0.2µrad
- 5^{th} harm. ~ 62 keV
- detuning above peak
  ⇒ narrowing of cone
- cms independent of detuning

  0.2µrad resolution

  ⇔ ~7% cms accuracy

- precision ~3µm
- fixed MC energy
- 5^{th} harm. ~ 62 keV

  (ref. gap = 23mm, open)

  3µm deviation

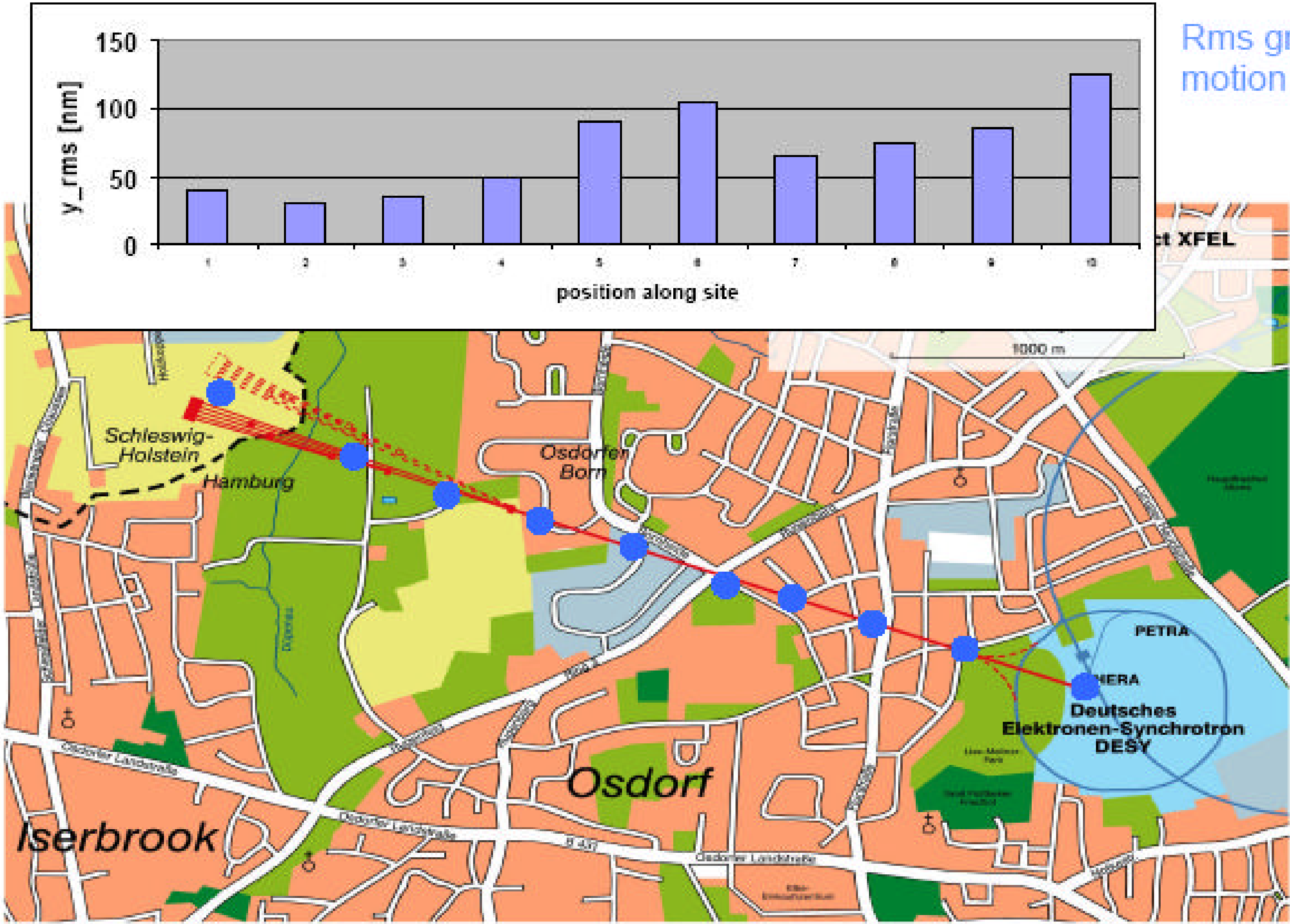
  ⇔ ~8% intensity drop

- Measurement at const. energy E_{fund}
- ⇒ flux variation ~400

  for φ advance π→2π

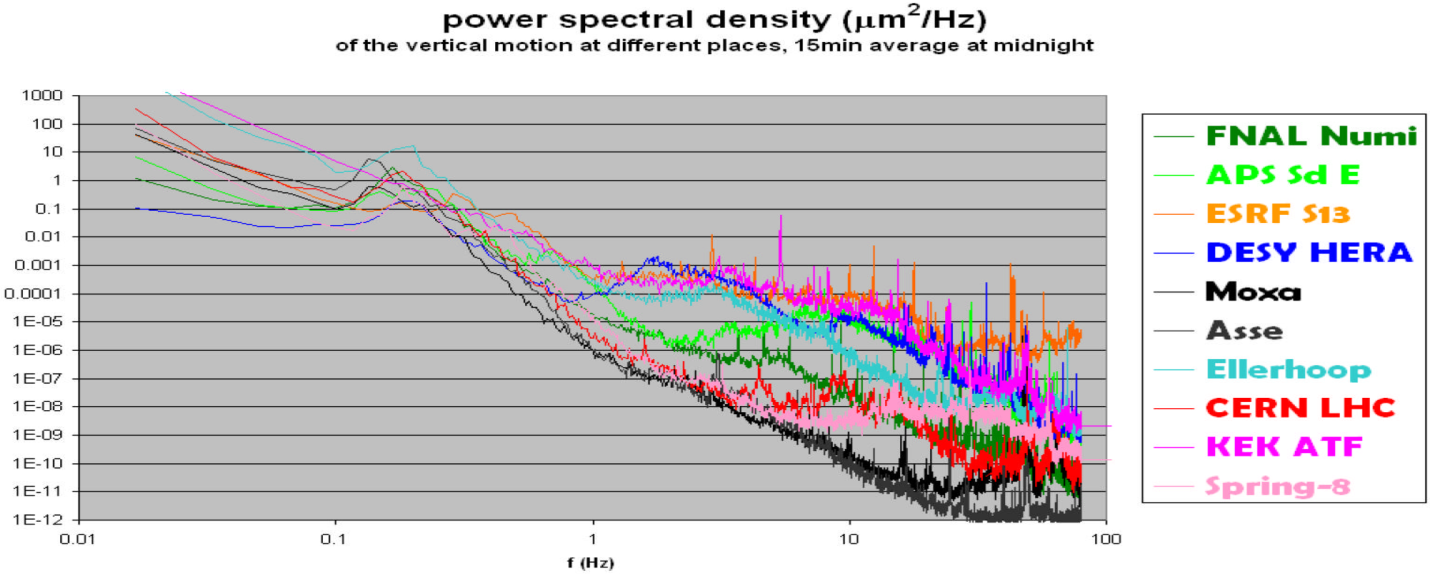
M. Tischer, P. Illinski, U. Hahn, J. Pflüger, H. Schulte-Schrepping, Nucl. Instr. & Meth A483 (2002) 418, TESLA-FEL 2000-13

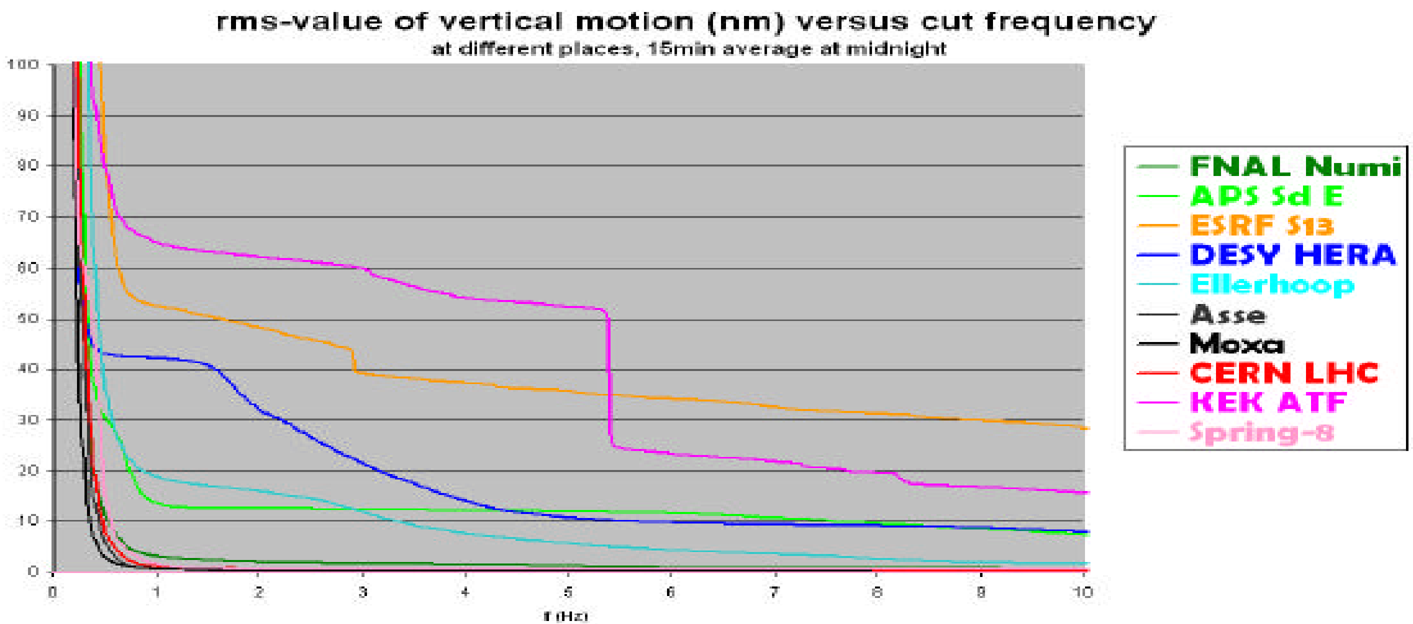
RMS Ground Motion along Site



Rms ground motion (>1Hz)

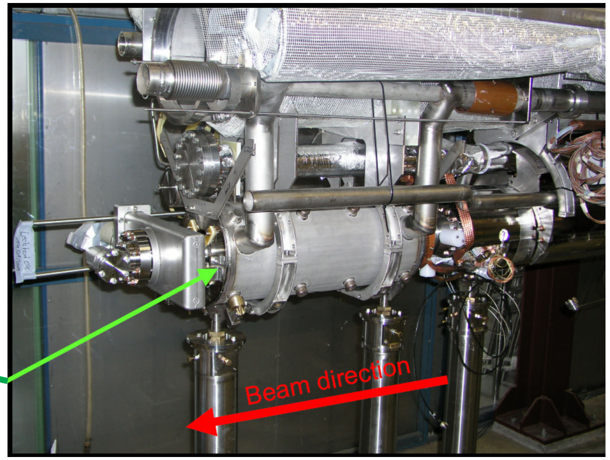
Ground Motion Spectra





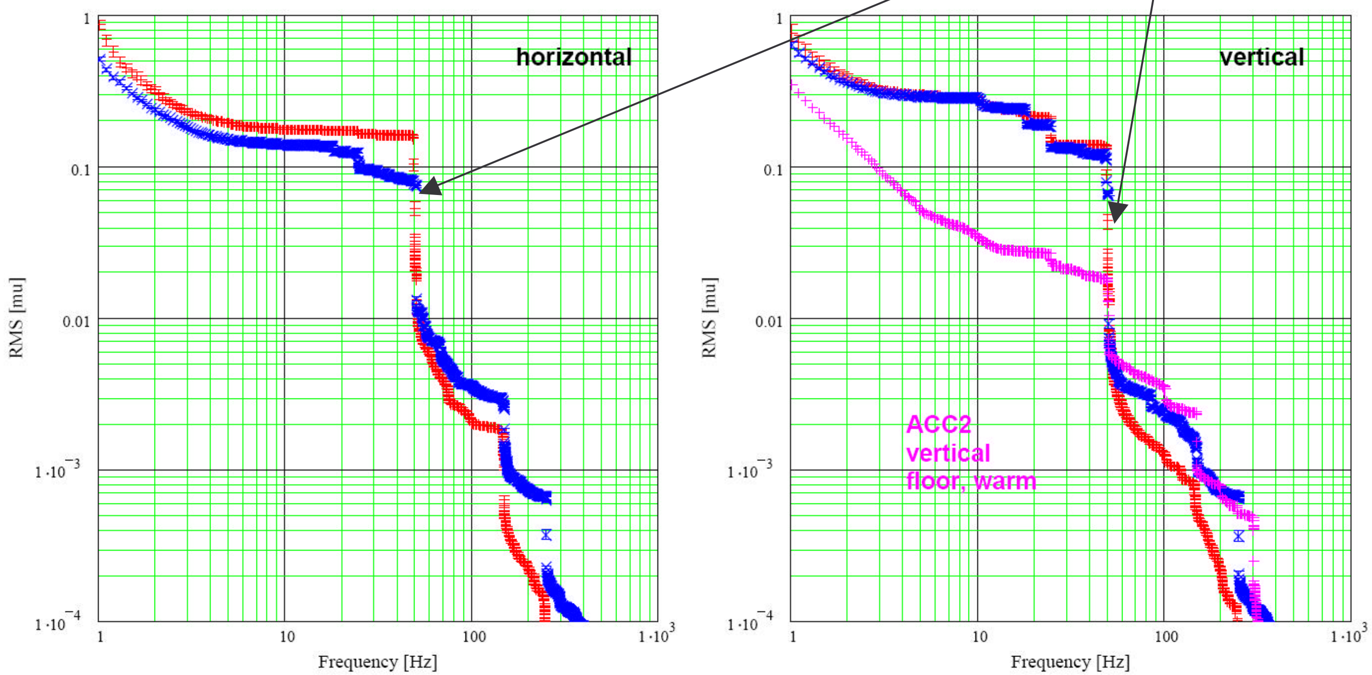
H. Ehrlichmann
W. Bialowons
(DESY)

Quadrupole Vibration in Module (Preliminary Results)



48 Hz (vacuum pumps)

Cold (~2K) and **Warm** RMS Data of ACC4



H. Brueck
DESY

Medium Time Scale Beam Motion

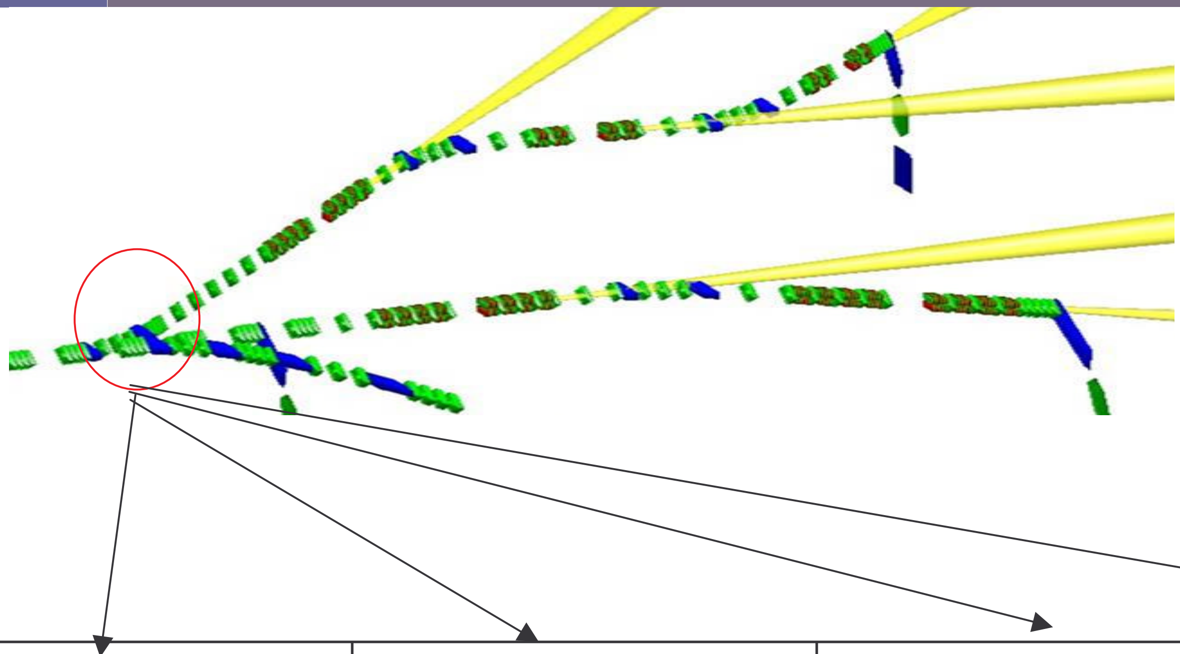
- With 70 nm (rms) linac quad movement:
  about **0.05σ** at linac end
- Additional quadrupole jitter in undulator and switch yard
  additional **0.02σ**

Single Bunch BPM Resolution at TTF 2 (1 nC)

- Button BPM (warm, undulator section) : < 10 μm
- Stripline BPM (warm, quadrupoles): < 30 μm
- Button BPM (cold): < 50 μm
- Cavity BPM (cold): < 50 μm

  potential for resolution increase to < 100 nm with small aperture design

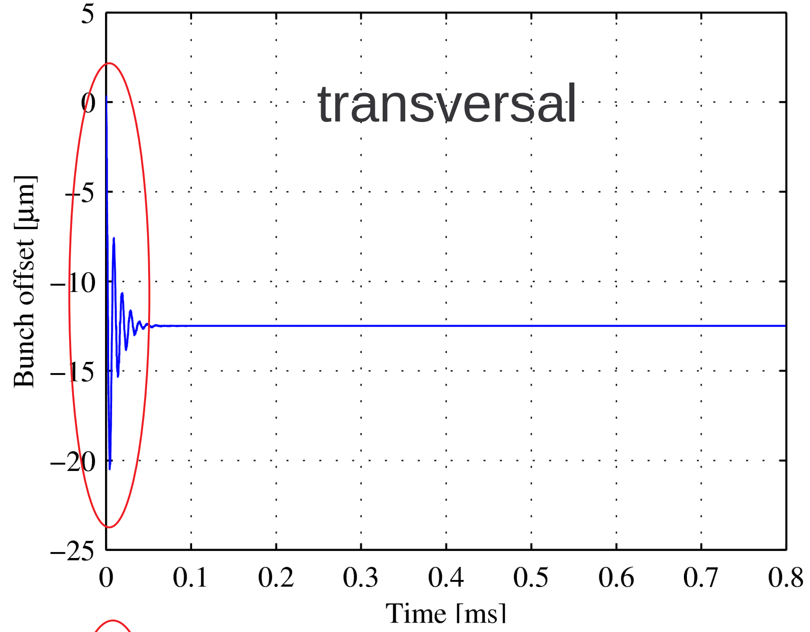
Active Electron Beam Switch

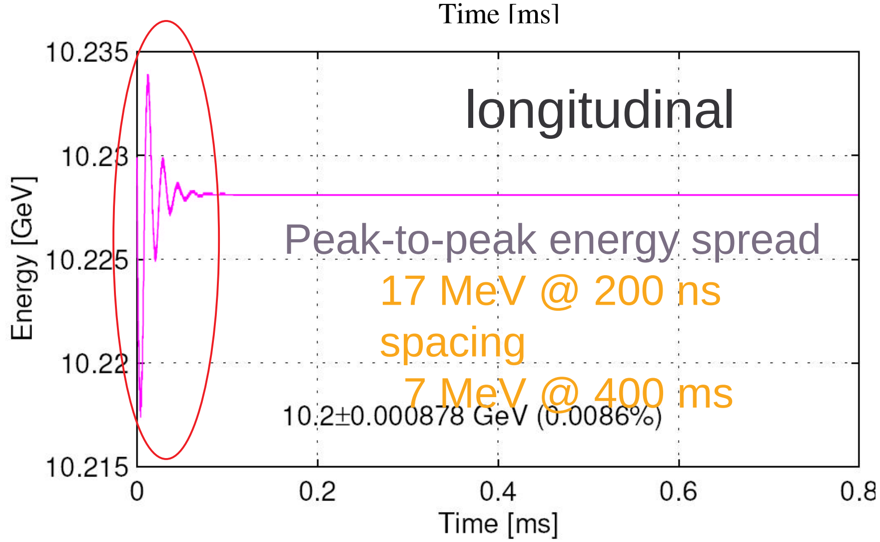


DC Magnet One beamline only Commissioning option	Slow switch pulse to pulse Duty cycle reduced by # beamlines TDR option	High Q Resonator Fixed bunch pattern, full duty cycle	Programmable fast kicker for individual bunches Flexible $\frac{\Delta\Theta}{\Theta} < 2\times10^{-4}$

Intratrain Jitter due to MB Wakefields

- For many XFEL applications the beam quality as obtained form these simulations may be good enough
- For best quality
  - Kick away the first part of the beam
  - This will reduce transverse multi-bunch emittance to 0
  - The multi-bunch energy spread will be eliminated as well

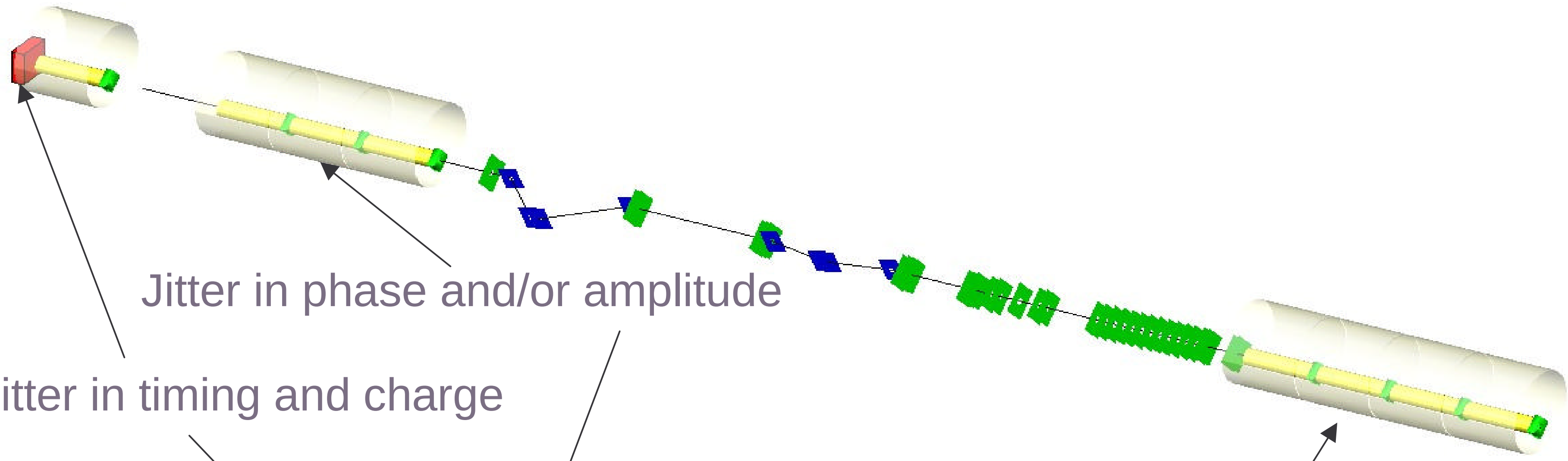




Detuning among cavities: 0.1 % rms
Misalignment: 500 mm rms
Inject beam on axis

N. Baboi - DESY

Jitter Investigations



Jitter in phase and/or amplitude

Jitter in timing and charge

Jitter in phase and/or amplitude
→ energy jitter at linac end

Change of longitudinal and transverse beam profile during bunch compression due to coherent synchrotron radiation and space charge → changes in FEL gain length and saturation power

Sensitivity Criteria

- Sensitivity Criteria Linac performance
  - Bunch length +10 %
  - Beam energy ±0.005 %
  - Variation of relative energy spread ±0.1 %
  - Bunch arrival time ±50 fs
- Sensitivity Criteria FEL performance
  - Radiation wavelength ±0.022 %
  - Saturation length ±1.6 %
  - Saturation power ±15 %
  - Bunch arrival time ±36 fs

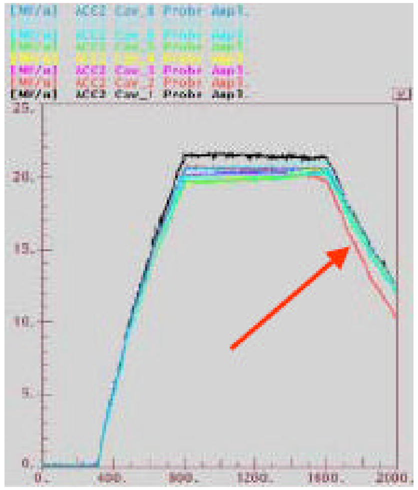
Example for Tolerances and Sensitivities

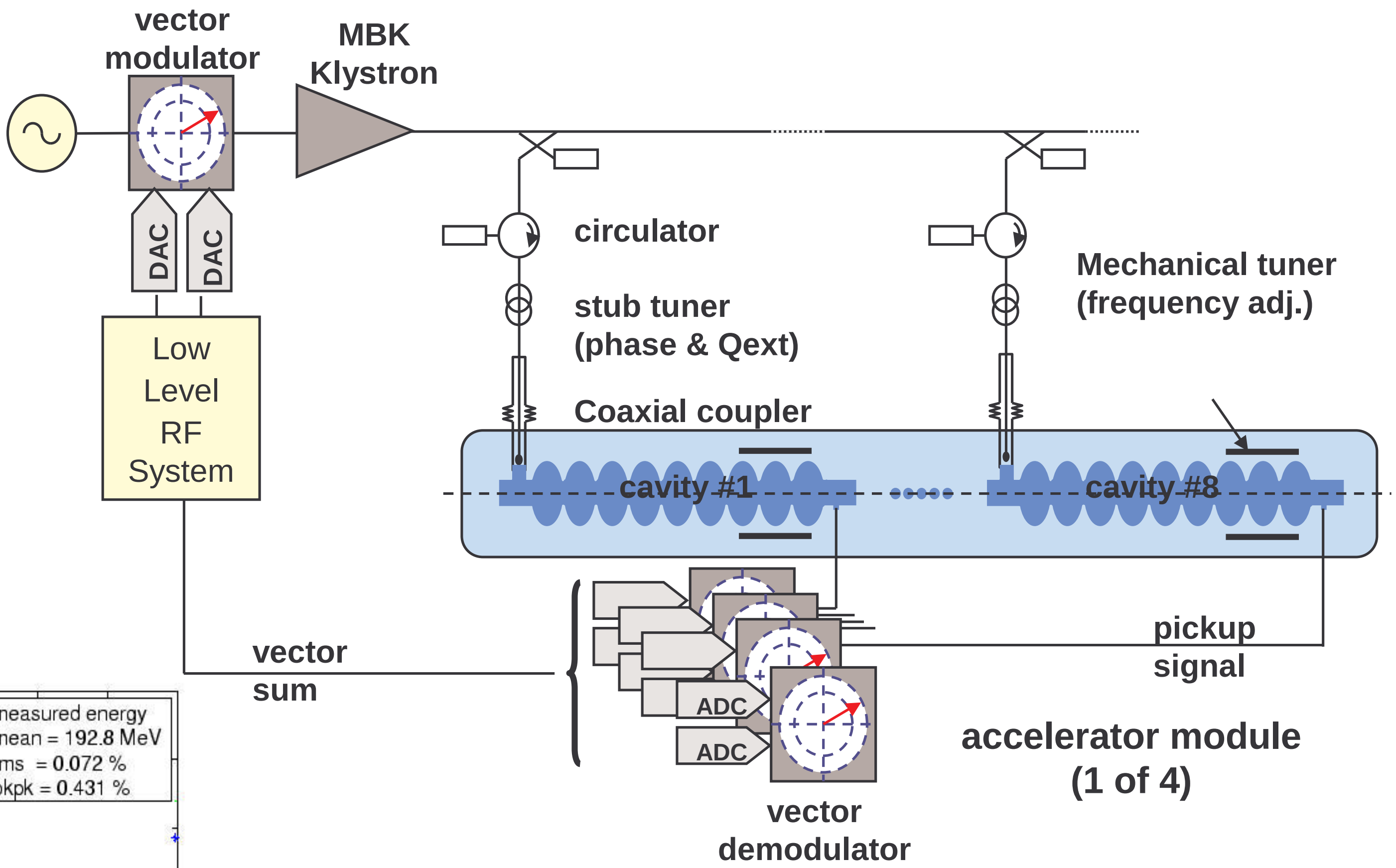
	Sensitivity(p2p)	Tol. (p2p)	Tol. (rms)	Threshold
dT	± 0.729 ps	± 0.300 ps	0.100 ps	saturation length
dQ/Q	± 5.452%	± 3.000%	1.000%	saturation length
ACC1C1234 phase	± 0.133 deg	± 0.045 deg	0.015 deg	saturation length
ACC1C1234 dV/V	± 0.129%	± 0.045%	0.015%	arriving time
ACC1C5678 phase	± 0.072 deg	± 0.045 deg	0.015 deg	saturation power
ACC1C5678 dV/V	± 0.063%	± 0.045%	0.015%	arriving time
ACC234 phase	± 0.048 deg	± 0.045 deg	0.015 deg	arriving time
ACC234 dV/V	± 0.045%	± 0.045%	0.015%	arriving time
ACC39 phase	± 0.064 deg	± 0.045 deg	0.015 deg	saturation power
ACC39 dV/V	± 0.142%	± 0.045%	0.015%	arriving time
BC1 dI/I	± 0.013%	± 0.012%	0.004%	arriving time
ACC56 phase	± 0.721 deg	± 0.045 deg	0.015 deg	arriving time
ACC56 dV/V	± 0.913%	± 0.045%	0.015%	saturation length
BC2 dI/I	± 0.201%	± 0.012%	0.004%	arriving time
ACC78910 phase	±10.037 deg	± 0.045 deg	0.015 deg	SASE wavelength
ACC78910 dV/V	± 0.060%	± 0.045%	0.015%	SASE wavelength

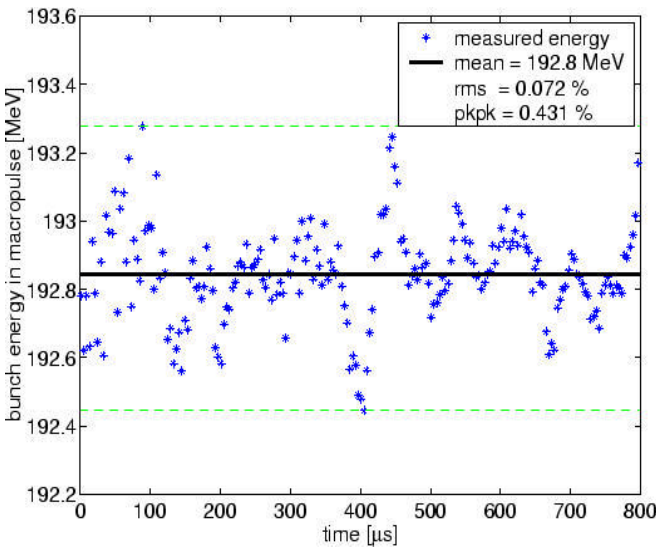
Based on 2 BC layout

Yujong Kim - DESY

LLRF: control & field stabilization

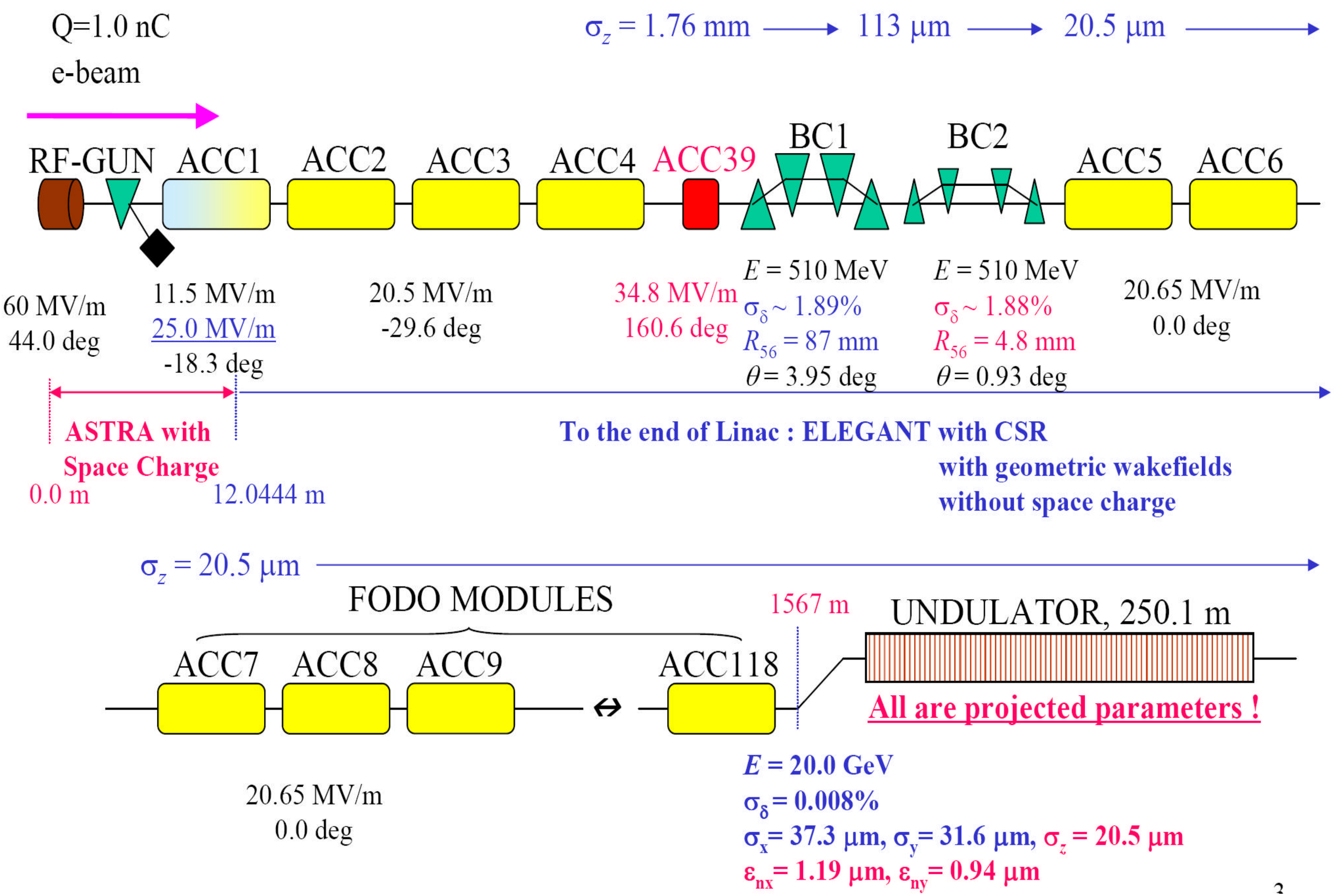






Remaining jitter today:
Amplitude $\Delta V/V$ = 0.01%
Phase $\Delta\phi/\phi$ = 0.02 deg

XFEL – Start two End (S2E) Simulations



Results of particle tracking (S2E simulations)

Start 2 End simulation of approx. 400 random seeds:

Yujong Kim - DESY

	RMS Error	Value
Radiation Wavelength	0.0068 %	0.1 nm
Saturation length	1.1 %	145 m
Saturation power	7.9 %	35 GW
Arrival time	32 fs	0 fs
Core slice emittance	0.1 %	0.9 nm
Transverse position	1 μm	0.5 μm
Bunch length	4.6 %	21 μm
Energy spread variation	4.5 %	0.0089 %
Energy	0.0034 %	20 GeV

An example, values will change with changes in layout

Conclusion

- Compare with 3rd generation light sources
  - No closed orbit, every bunch is different
  - Longitudinal properties important
  - Feedback systems with bandwidth closer to MB FB systems
  - Lots to learn from source hunt, long term stability, …
- Interaction with 'users'
  - Time to distinguish is over
  - Accelerator is integral part of user experiment
  - Beam properties have to be measured before each experiment – like in HEP
  - Photon beam properties are crucial input for accelerator operation and tuning

Conclusion

- Ompared to 3rd generation light soruces the endeavour to beam stability in SASE FEL just started
- Lots to learn from VUVFEL, LCLS and SPPS
- Keep an open mind

Thank you for your attention!

Thanks to the workshop organizers!