Using Higher Order Modes in the Superconducting TESLA Cavities for Diagnostics at FLASH @ DESY

N. Baboi, DESY, Hamburg

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- DESY
- FLASH
  - user facility - SASE-FEL
  - test facility for ILC and XFEL
- The TESLA cavity
  - superconducting technology
  - Higher Order Modes - HOM
- Higher Order Modes as diagnostics
  - beam position; cavity alignment; beam phase etc.
  - method
  - results
- Summary and outlook

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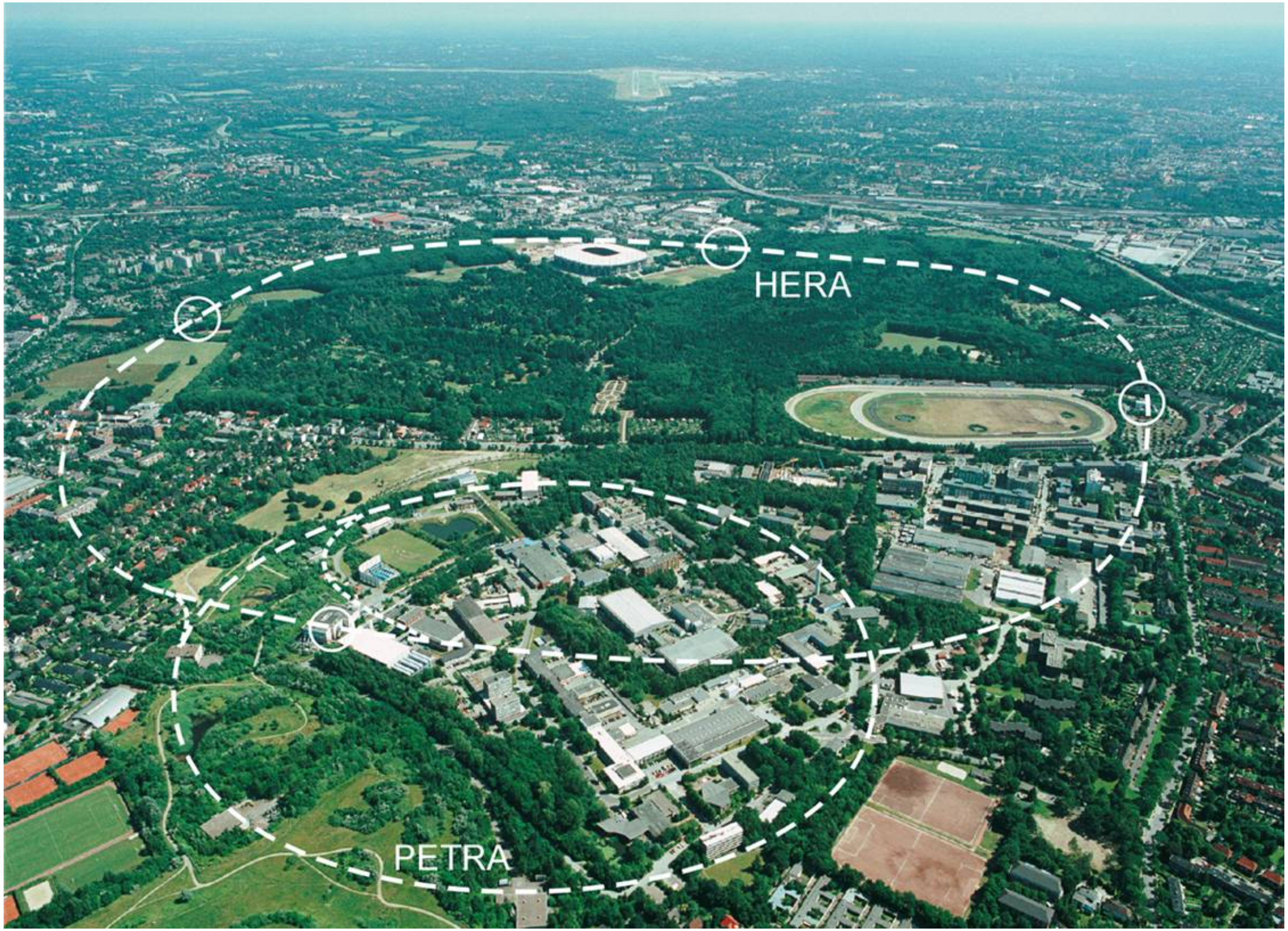
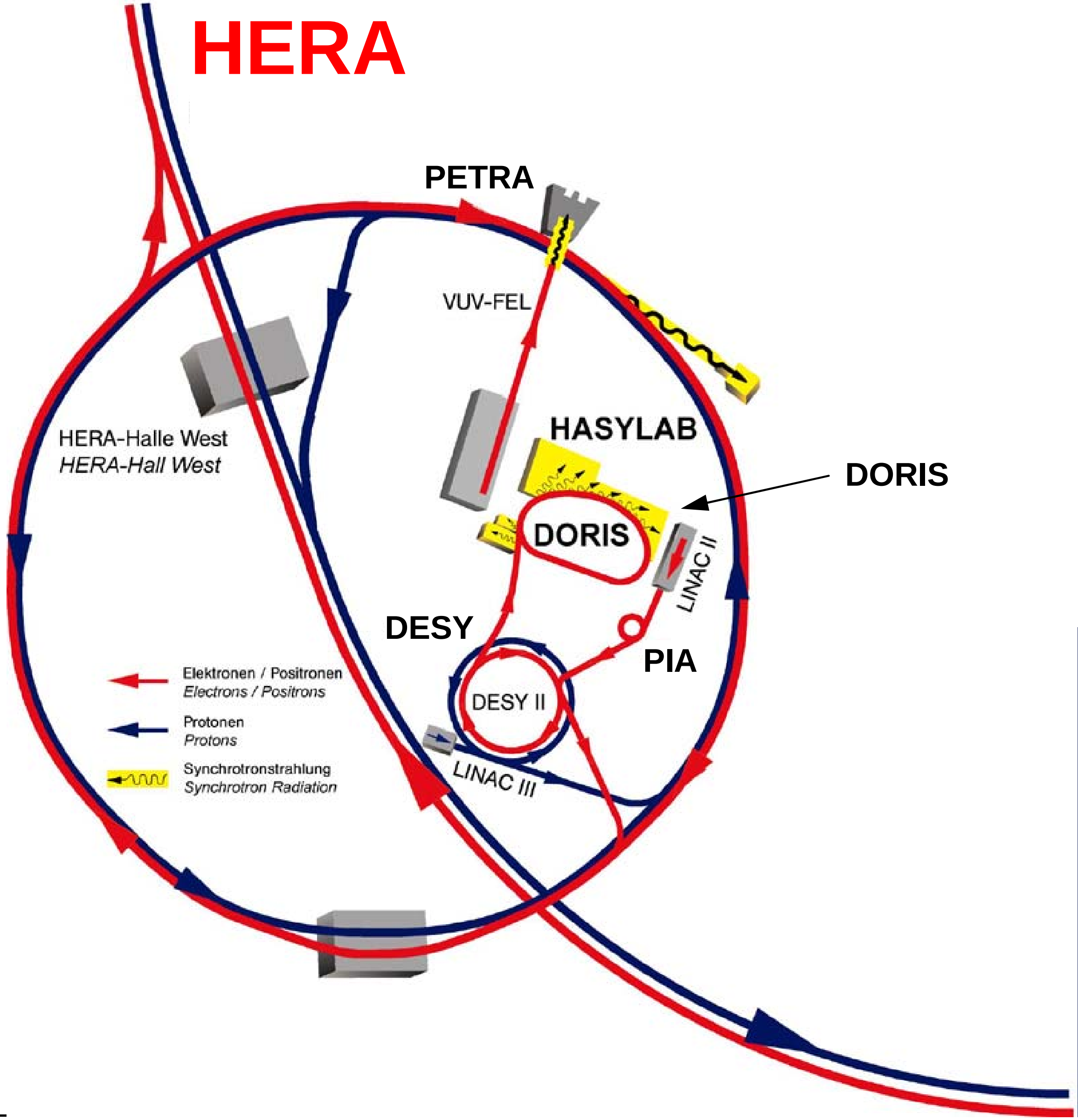
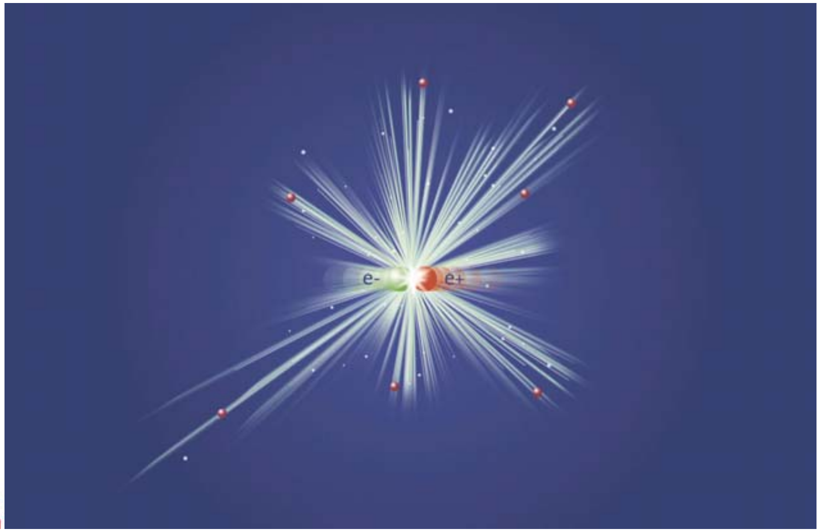
Deutsches Elektronen-Synchrotron - DESY



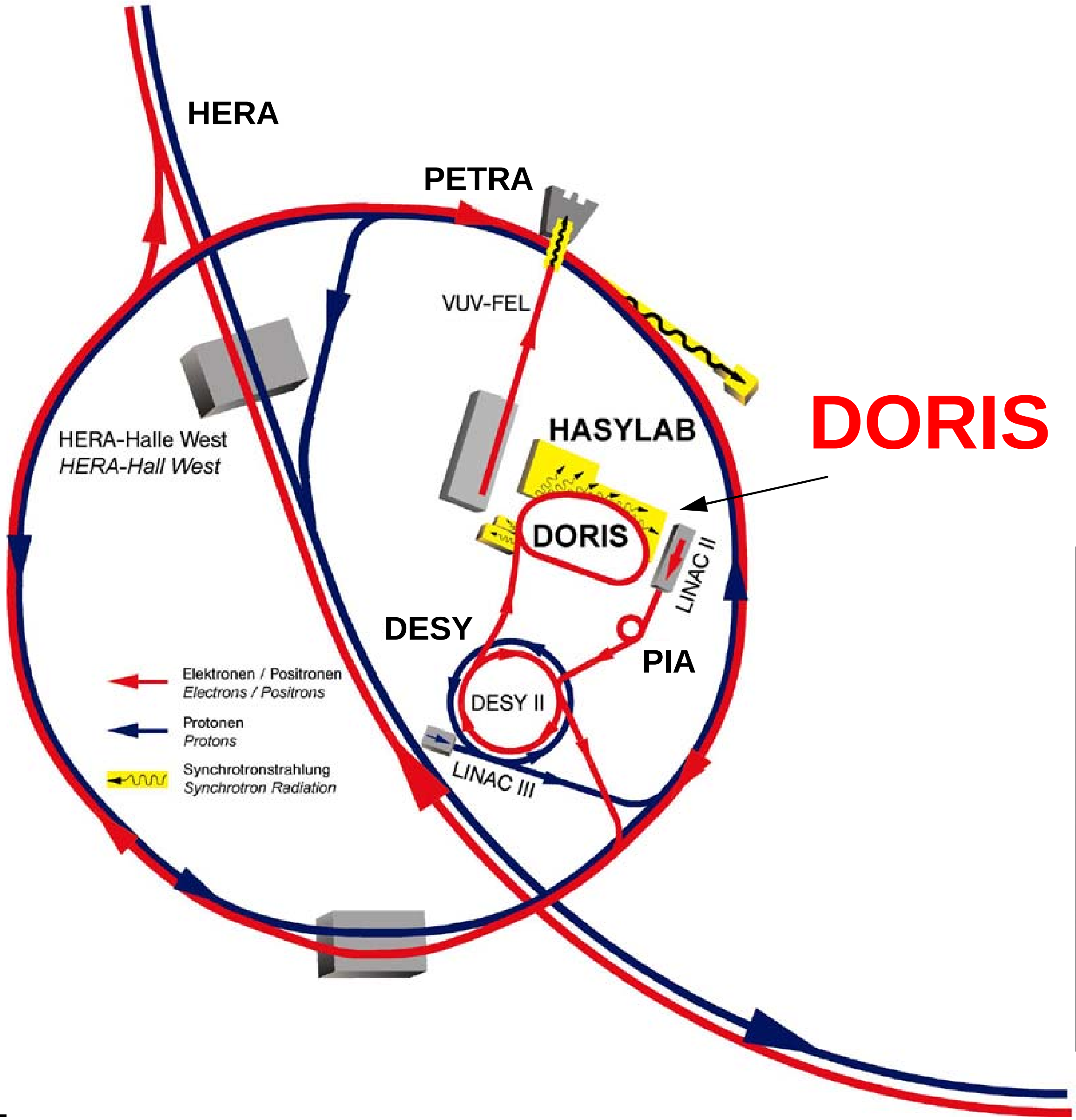
Particle Physics



- Present: HERA
  - proton-positron collider
  - protons: 920 GeV
  - e^+ or e^-: 27 GeV
- Future: LHC and ILC
  - ILC: 500 GeV e^--e^+ collider project study

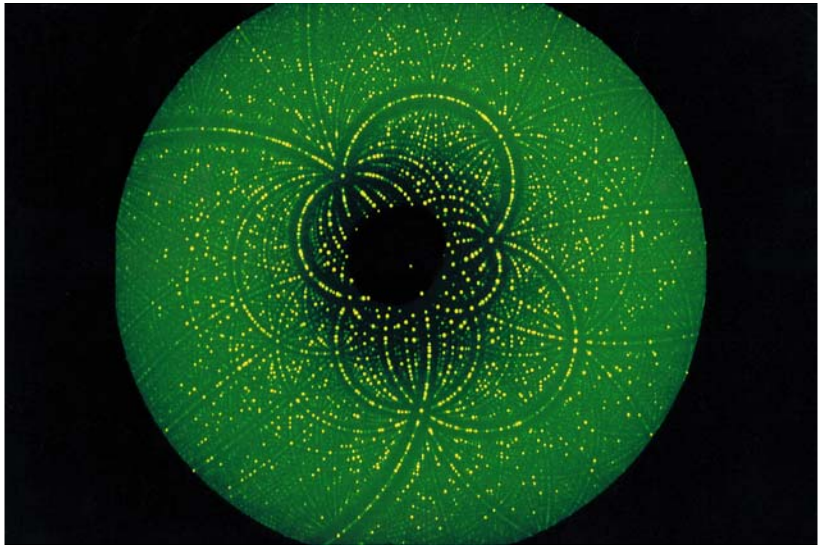


Research with Photons: Synchrotron Radiation

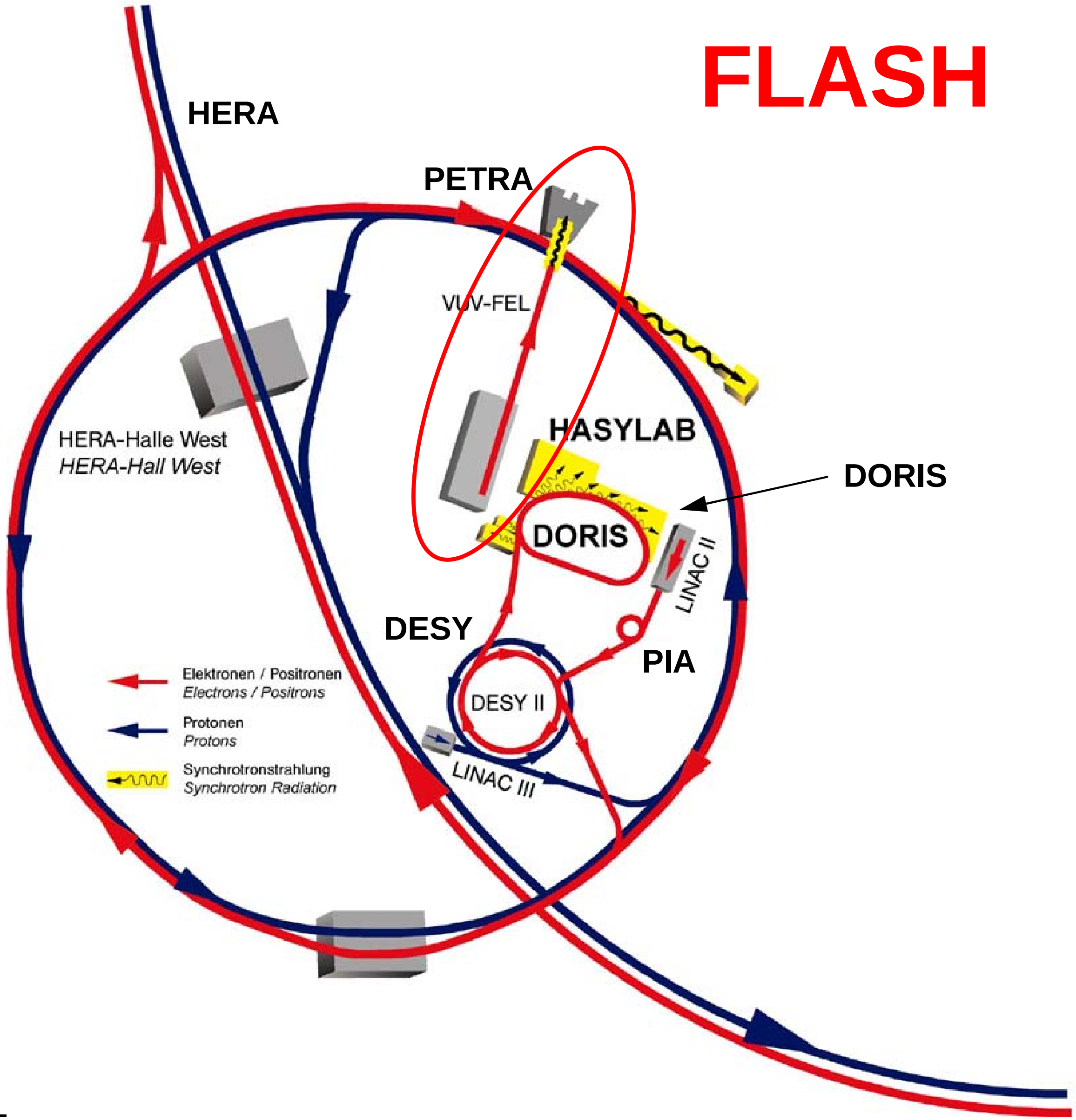


DORIS

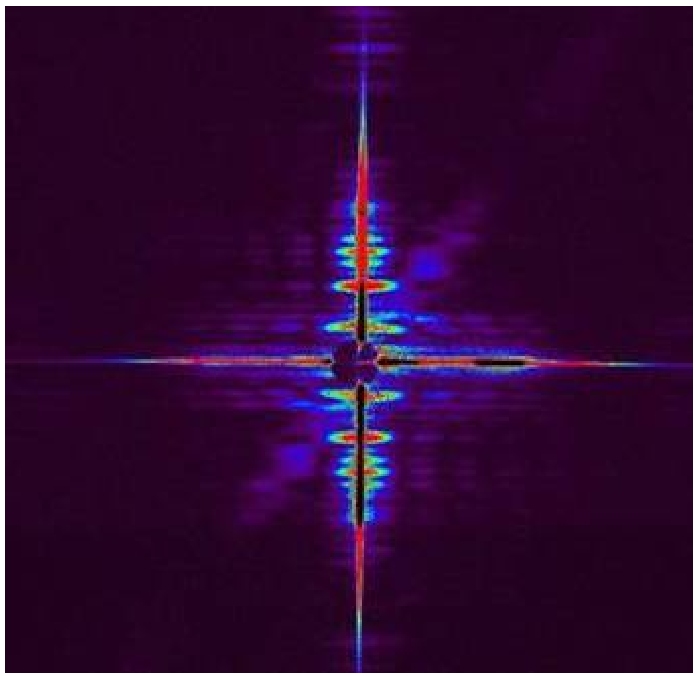
- Present: DORIS
  - positron synchrotron
- Future: PETRA3
  - 3rd generation light source



Research with Photons: SASE Free Electron Laser



- Present: FLASH
  - ≡ VUV-FEL and TTF2
  - 48-13 nm (later 6 nm)
- Future: XFEL
  - 6 nm - 1 Å



Hajdu, Chapman et al.

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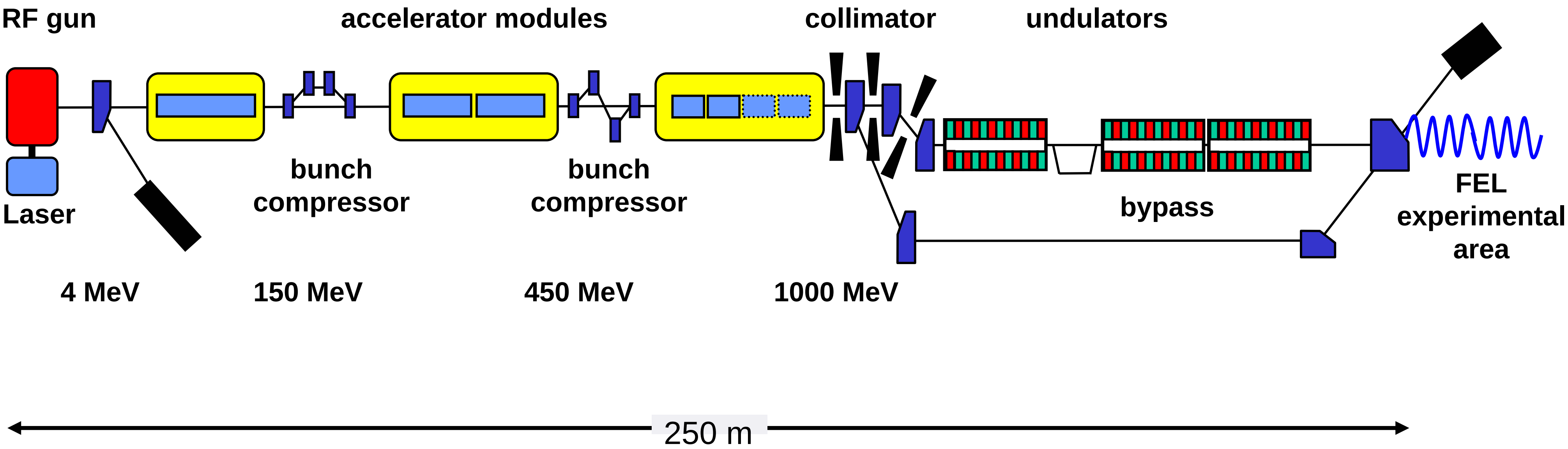
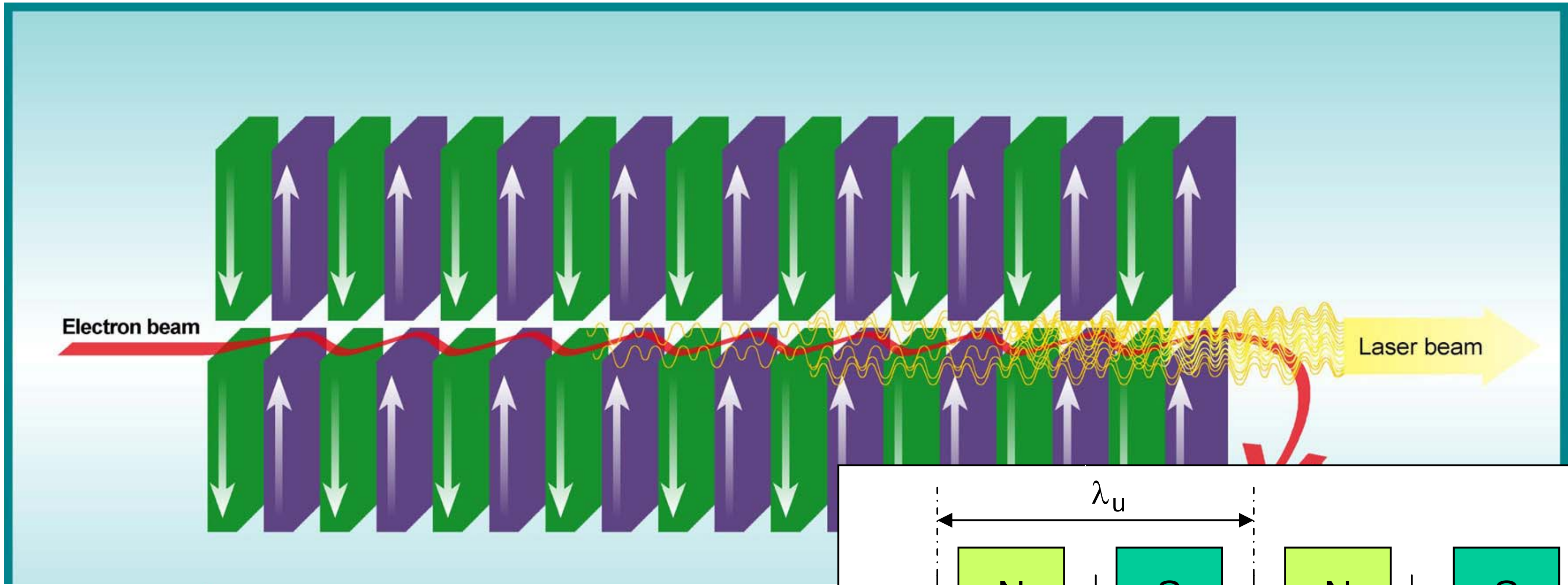
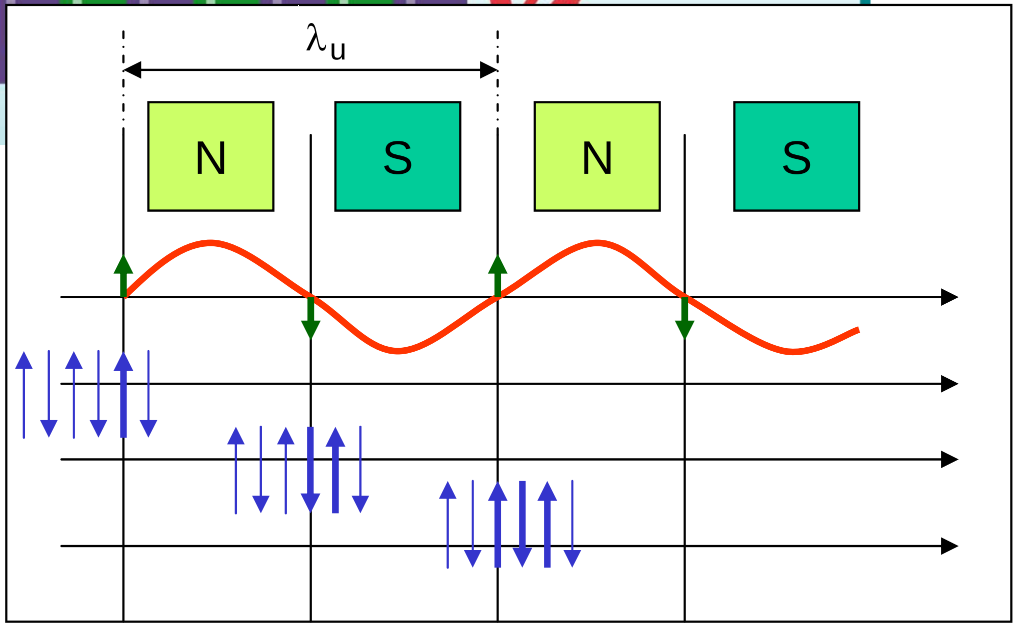
Free electron LASer in Hamburg
FLASH



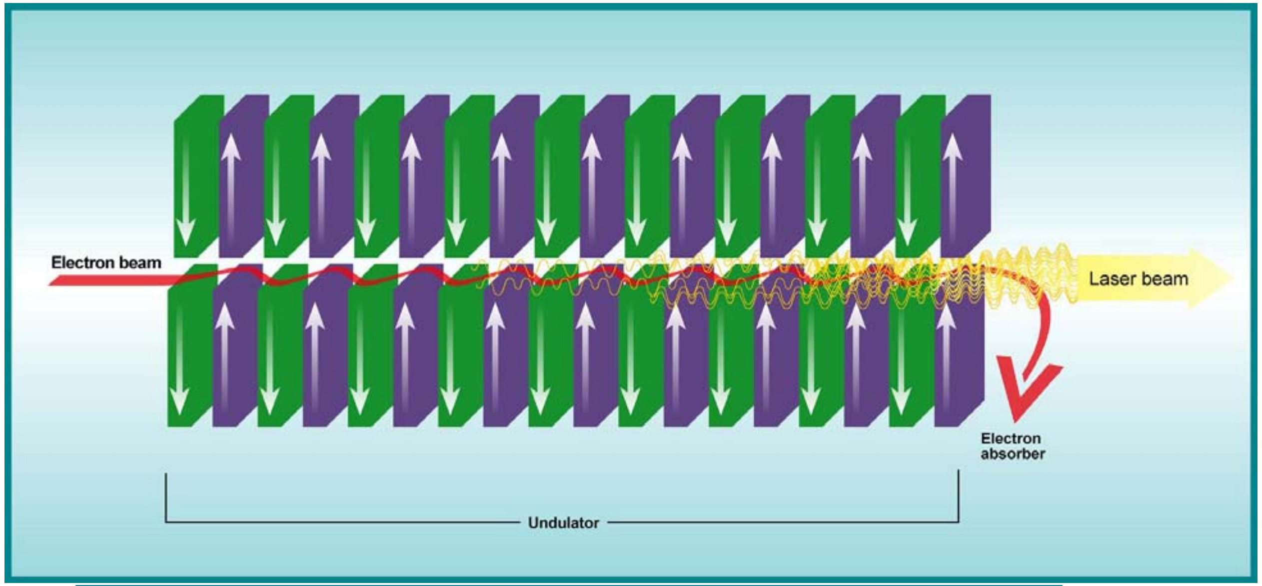
Self-Amplified Spontaneous Emission Free Electron Laser

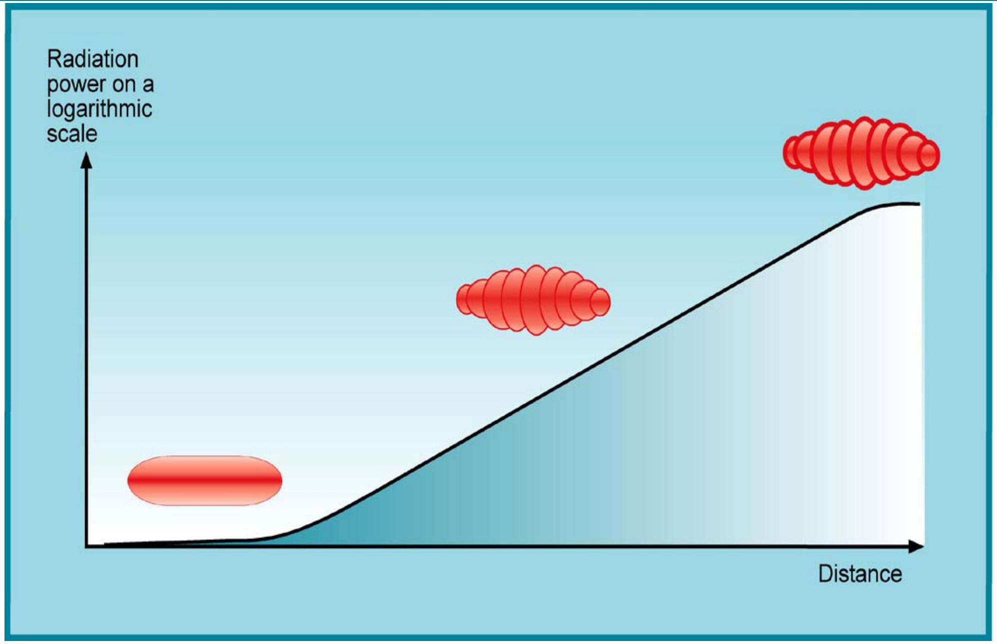


- spontaneous emission
- interaction with generated radiation
  - micro-bunching
- coherent emission of the micro-bunches



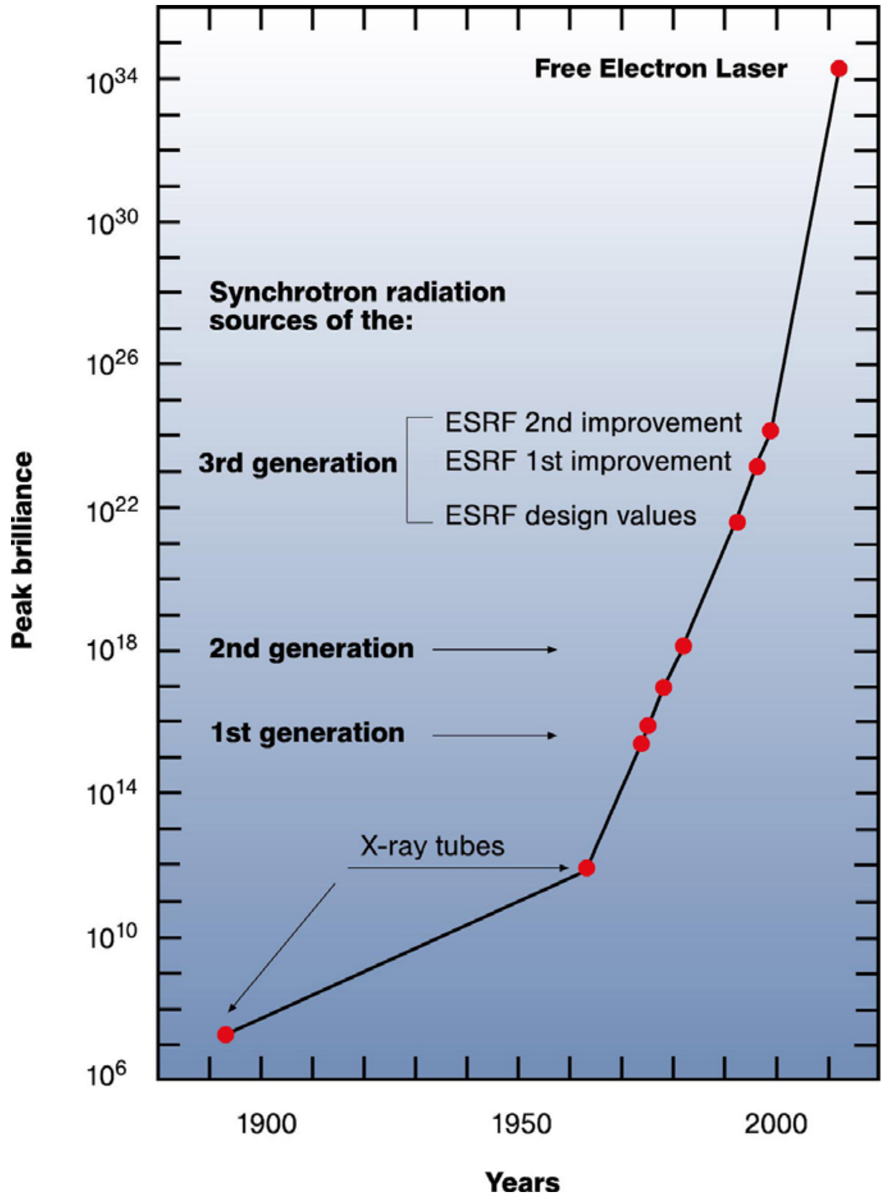
Self-Amplified Spontaneous Emission Free Electron Laser (2)





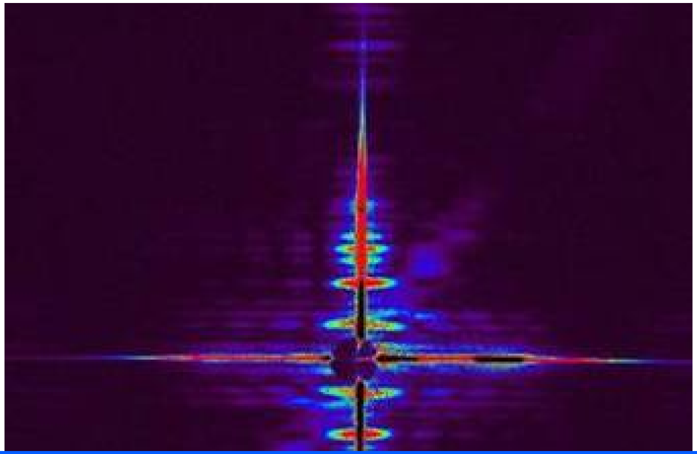
SASE-FEL Properties

- Properties
  - high intensity (brilliance)
  - ultra short pulses
  - tunable
  - monochromatic
  - coherent
- Performance up to now
  - at FLASH
  - 48 - 13 nm
  - 8.5 nm on 3rd harmonics
    - shortest wavelengths achieved worldwide
  - saturation at 13.7 nm
  - pulse length < 100 fs rms
  - power up to 100 μJ / pulse

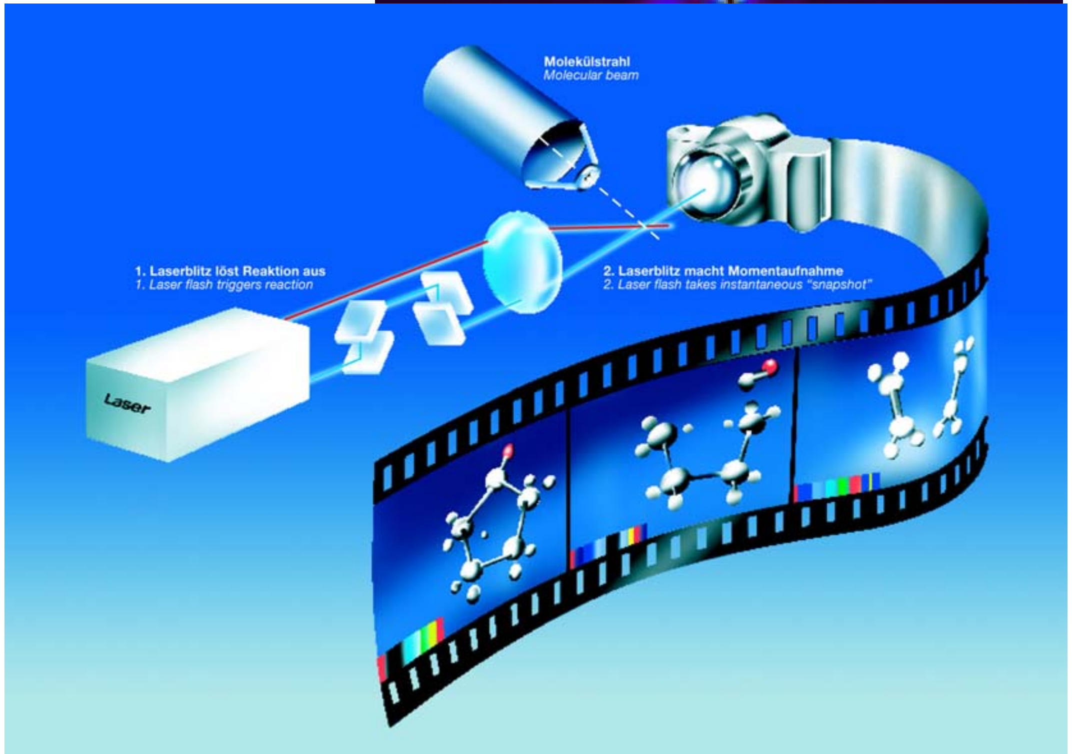


Application Examples of SASE-FELs

- Ultra-fast coherent X-ray diffraction
  - made possible by the high brilliance and short pulse length
  - recently - first demonstration



- Pump and probe
  - made possible by short pulse length
  - “make movies” of dynamic processes

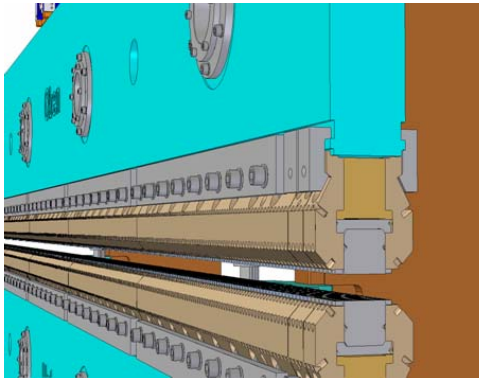


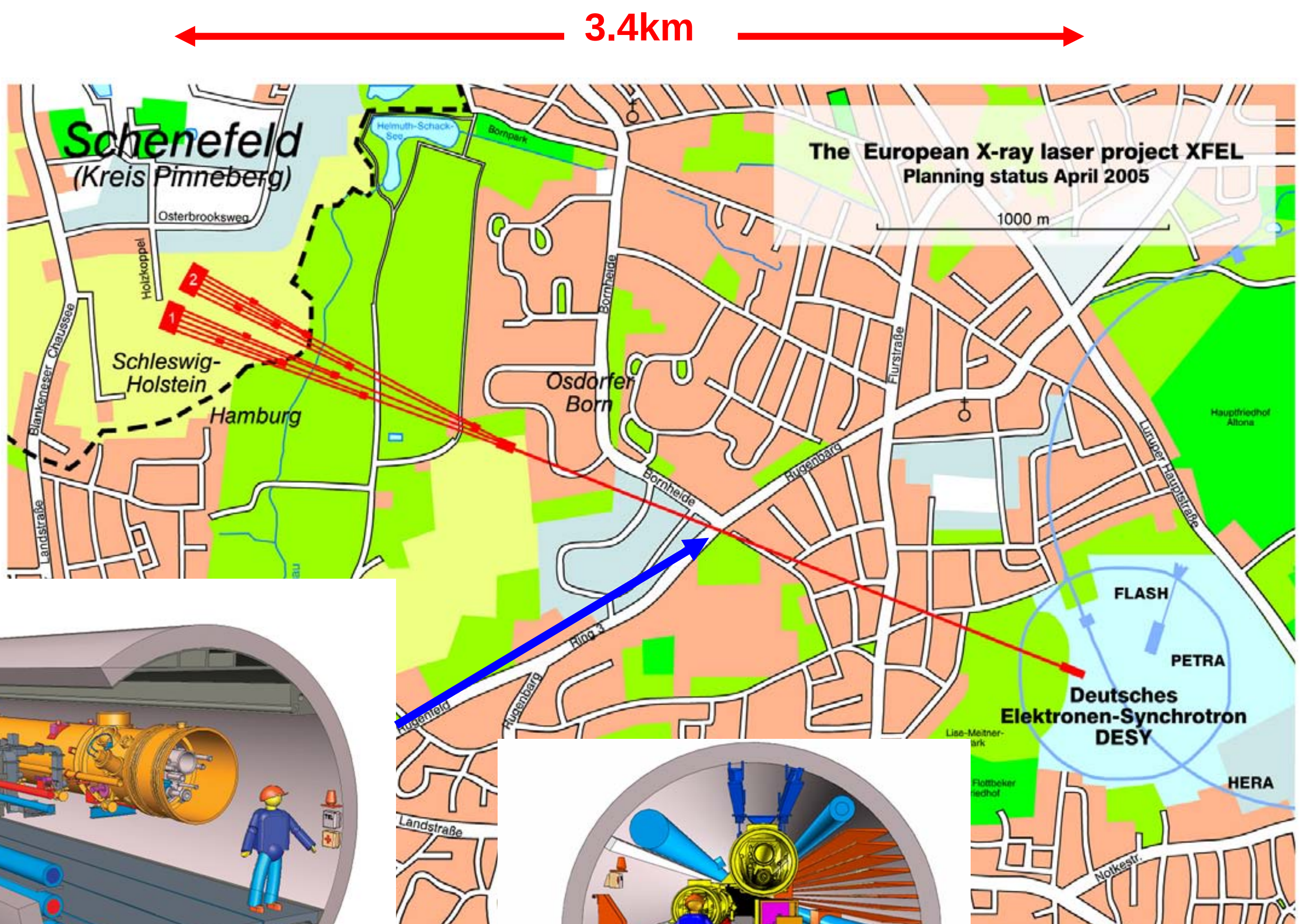
A Bit of History - The TESLA Technology

- TESLA: TeV Energy Superconducting Linear Accelerator
  - 500 GeV c.m. e^--e^+ linear collider project study
- TTF: TESLA Test Facility
  - test superconducting technology
- XFEL: X-ray Free Electron Laser at TESLA
  - SASE-FEL
  - proof of principle at TTF
  - approved as independent project

- ILC: International Linear Collider
- FLASH: Free electron LASer in Hamburg
  - new 'flashy' name
- TTF2 / VUV-FEL:
  - upgrade of TTF
  - test facility for TESLA and the XFEL+ user facility
    - TTF2: linac
    - VUV-FEL: light

The European XFEL





Status of the European XFEL

- SASE FEL: 6 nm – 1 Å ; with 20 GeV superconducting linear accelerator, based on the TESLA technology,
  - proposal Oct. 2002
  - approved by German government in Feb. 2003 as European project
  - Commitment by:
    - 50%: German gov.
    - 10%: Hamburg & Schleswig-Holstein
    - >= European and International partners
  - 2006: final Technical Design Report
  - “Planfeststellungsverfahren” ended
  - start building next year
  - planned start for 2012

- FLASH as test facility for the XFEL
  - also for the ILC

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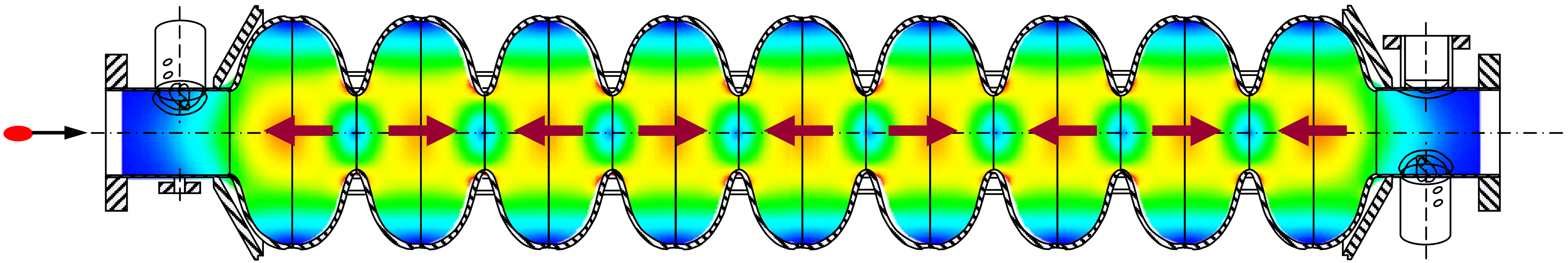
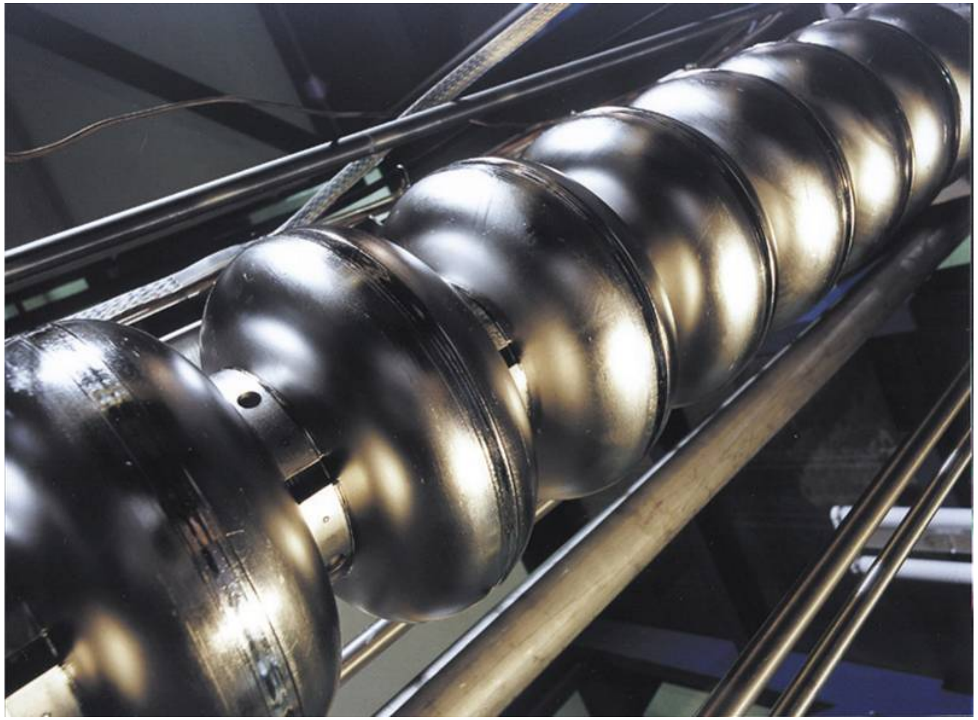
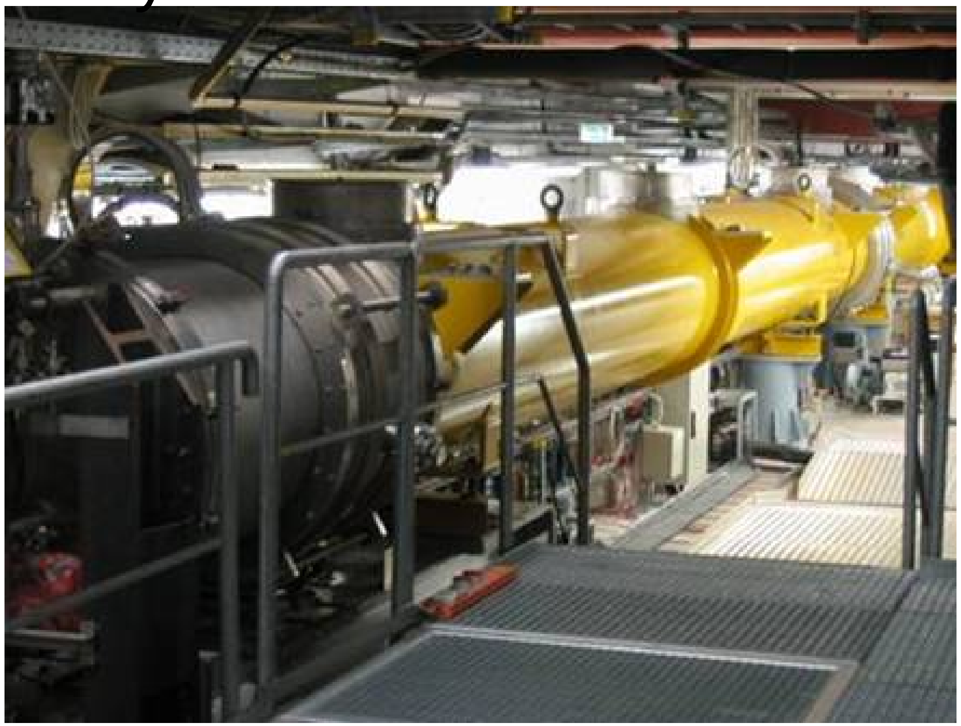
The TESLA Cavity



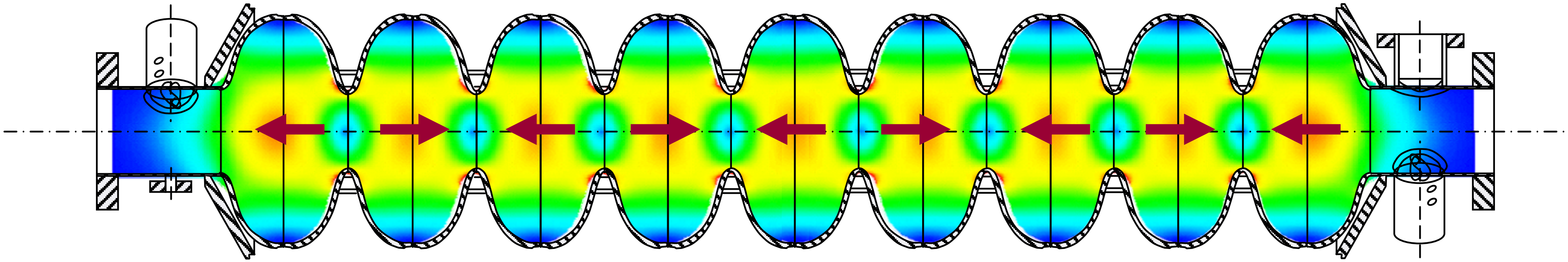


Cryo-module with 8 cavities



Higher Order Modes (HOM) in Accelerating Cavities

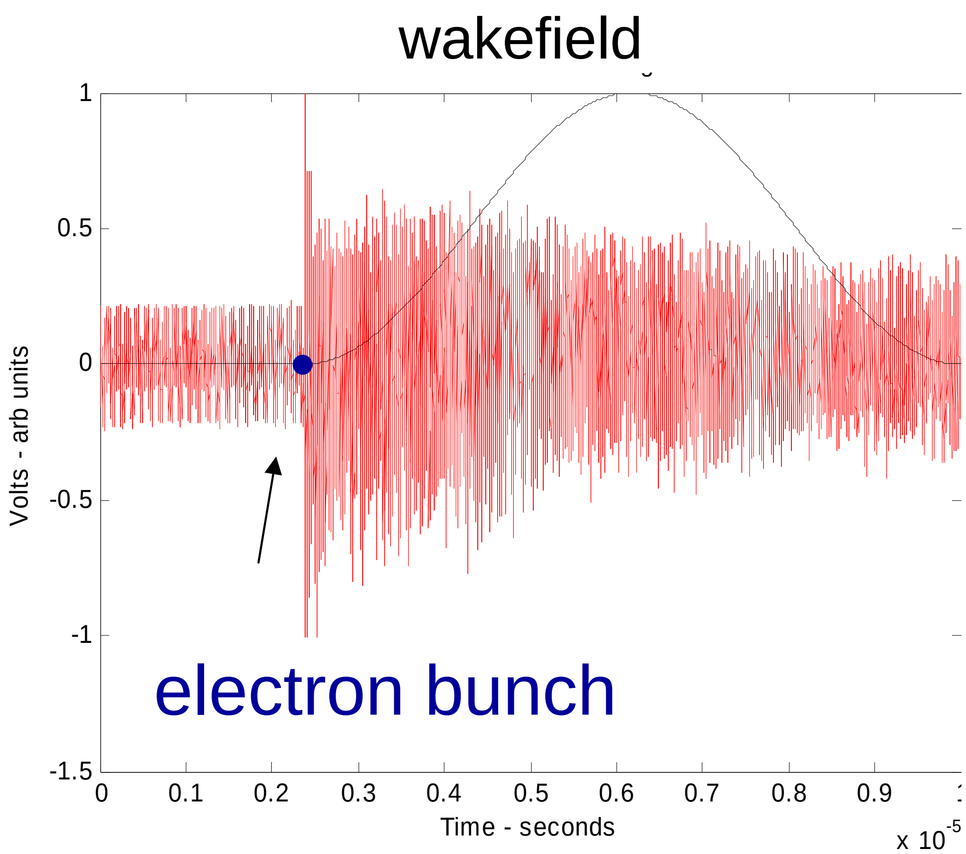
- Accelerating Cavity = RF EM-Resonator
  - ➢ accelerating wave (monopole mode) at 1.3 GHz
    - generated by a klystron and injected into the cavity

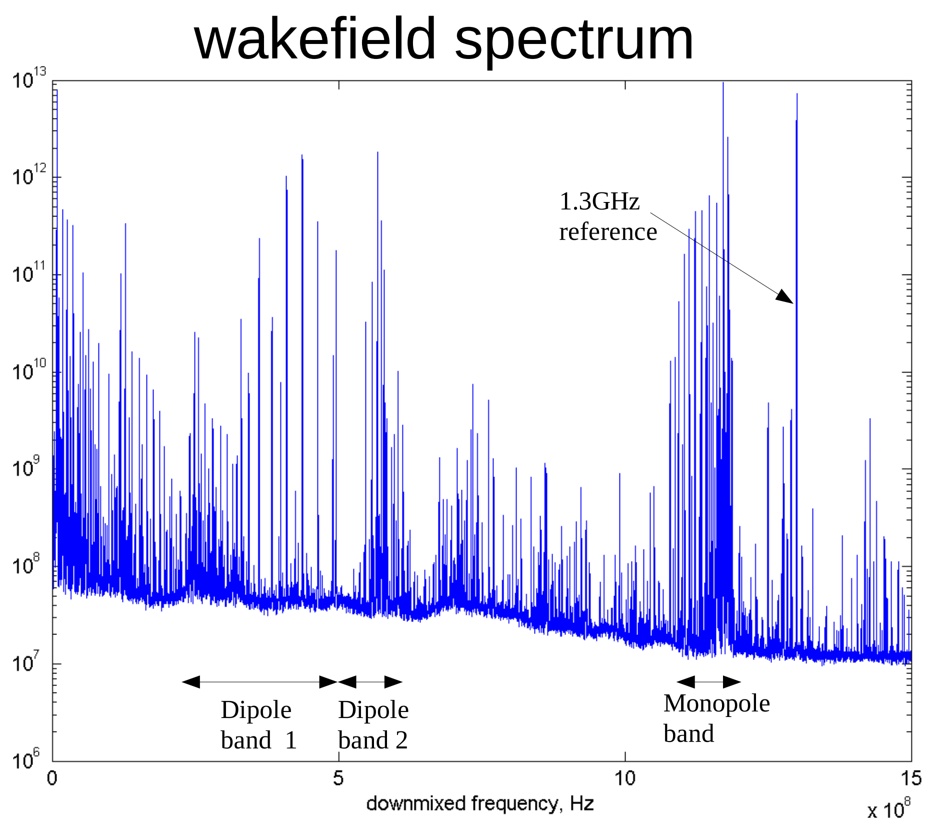


- other modes: Higher Order Modes (HOM)
  - ➢ excited by the electron beam
  - ➢ monopole, dipole, quadrupole etc. modes

Higher Order Modes (HOM)

- Effect of HOMs / wakefield (= Σ HOM)
  - damaging to the beam
  - try to keep them low by damping (HOM coupler) and beam alignment





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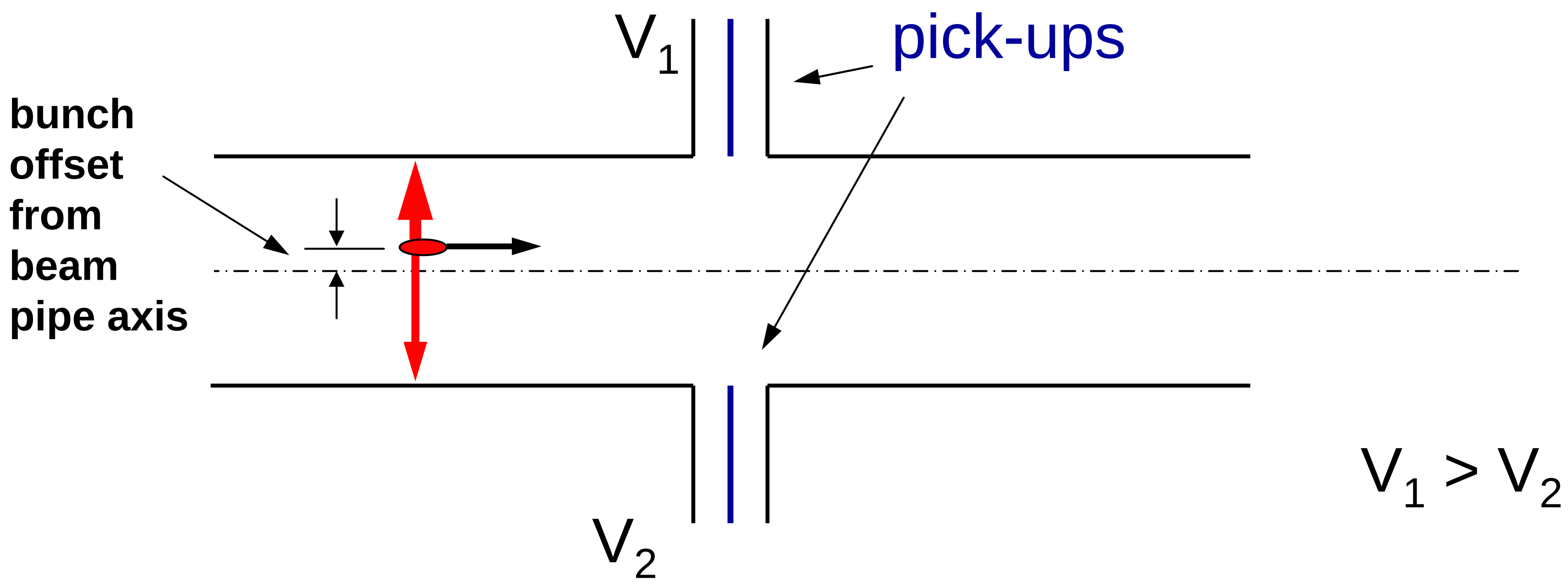
HOM used for Diagnostics

- Can use HOM signals for:
  - beam position monitoring, similar to cavity BPMs
  - minimizing the HOMs
  - measuring the cavity alignment inside the cryo-modules
  - monitoring the beam phase etc.
- Advantage:
  - large proportion of linac length occupied by TESLA cavities
  - special couplers already provide the HOM signals
  - no need to install new beamline hardware

Beam Position Monitors (BPMs)

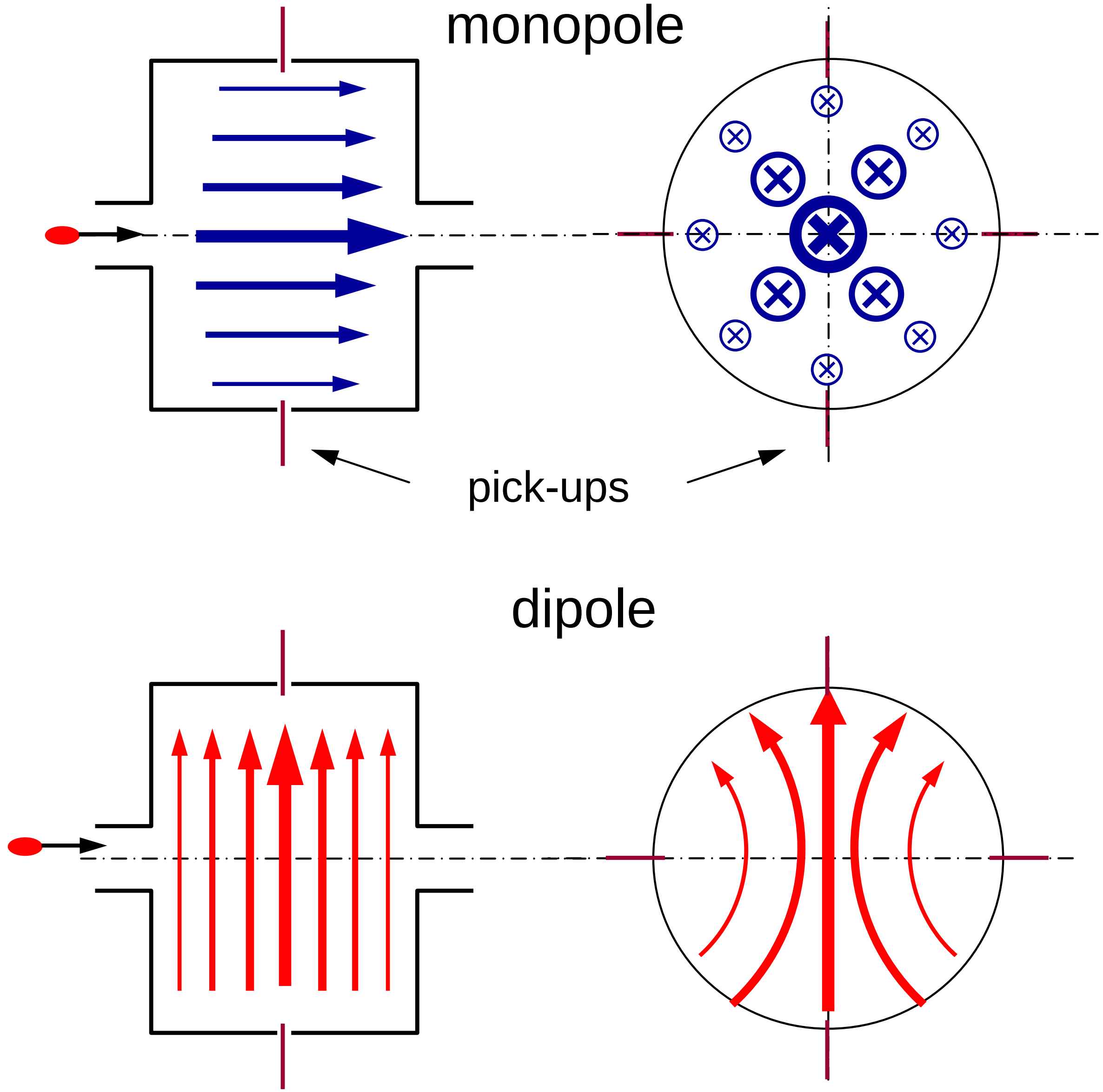


- compare signals from two opposite antennas and calculate transverse beam position

- more than 60 BPMs currently in FLASH, mostly button and stripline type

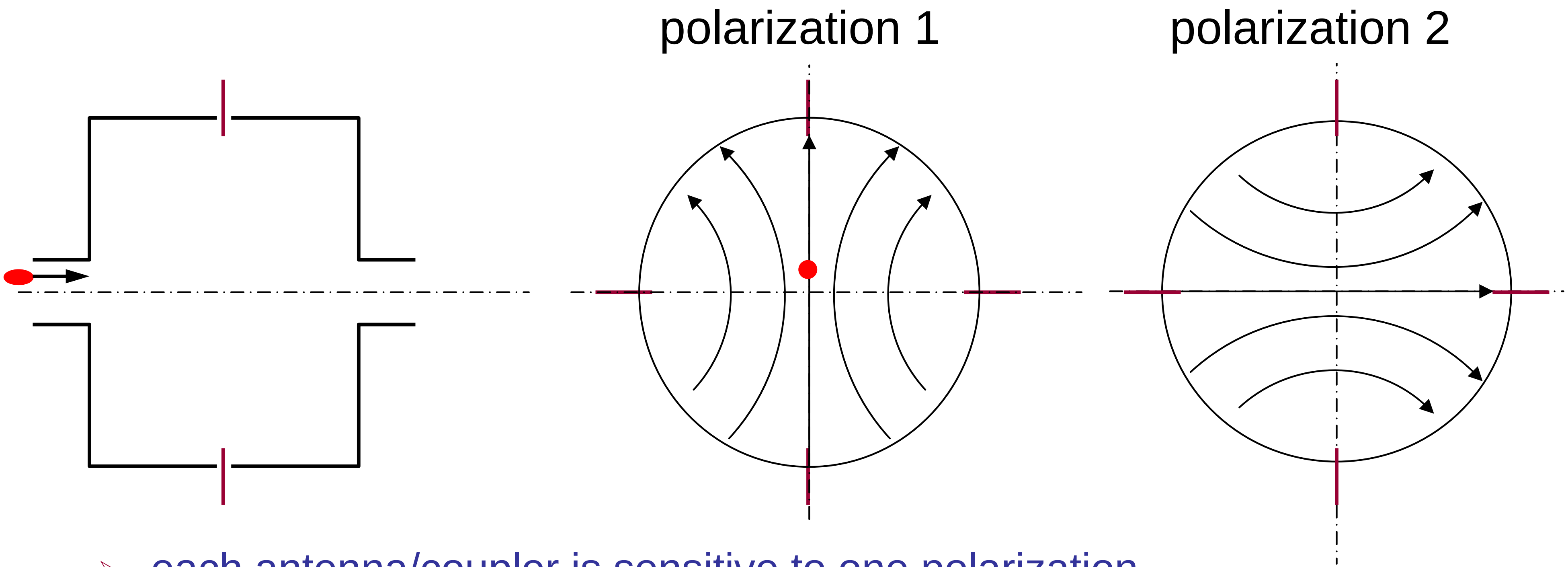
Cavity Beam Position Monitors

- full spectrum of EM resonances excited by beam itself
  - monopole, dipole, quadrupole, … modes



Cavity Beam Position Monitors (2)

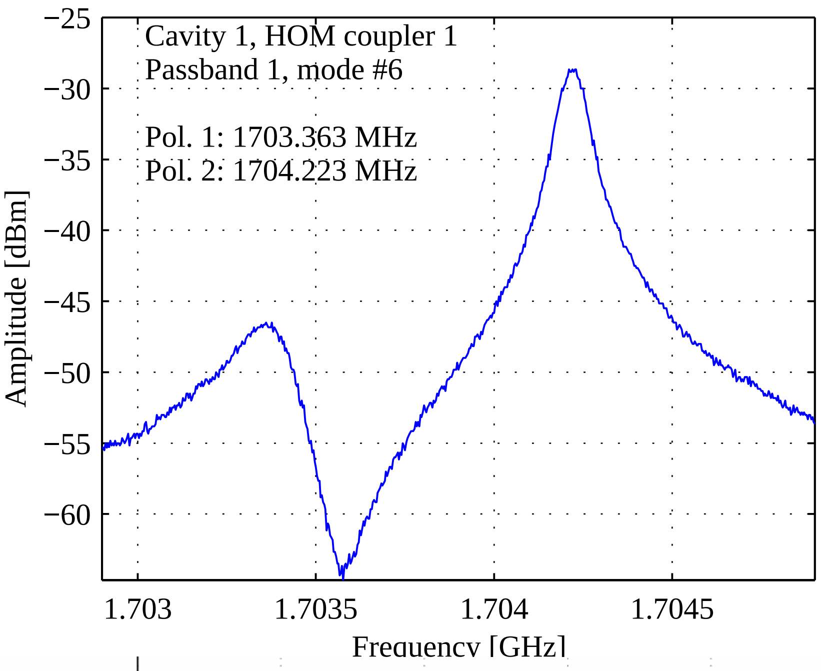
- Dipole modes
  - excited by off-axis beam
  - proportional to beam position and angle ⇒ used for monitoring

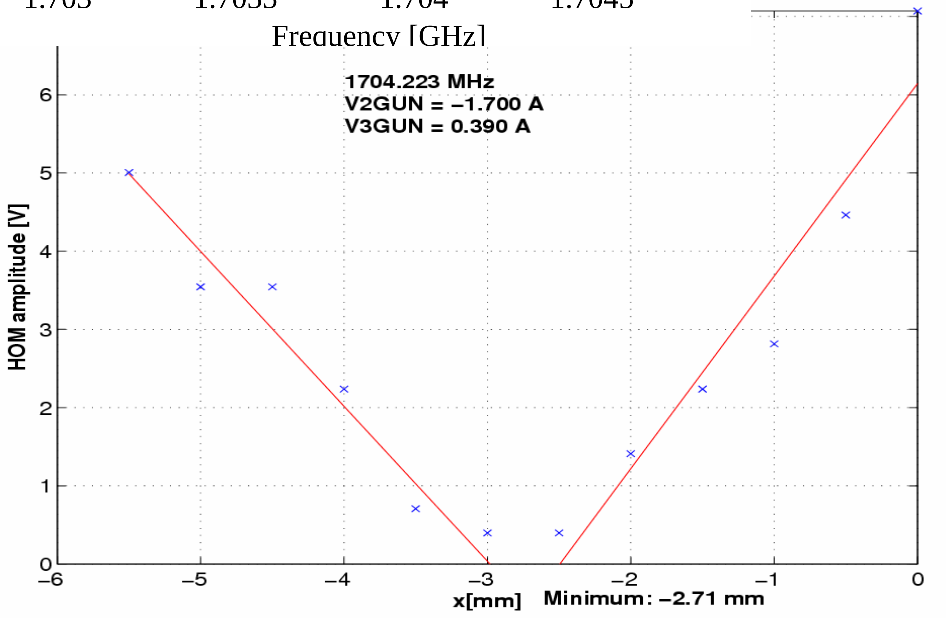


- each antenna/coupler is sensitive to one polarization, i.e. beam movement in the horizontal OR vertical plane
- Note: can achieve very good resolution

Dipole Modes in the TESLA Cavities

- Dipole modes
  - excited by off-axis beams
  - amplitude is proportional to beam position
  - ⇒ can use for beam position monitoring
  - ⇒ find beam position for which they have minimum amplitude ⇒ minimum damaging effect

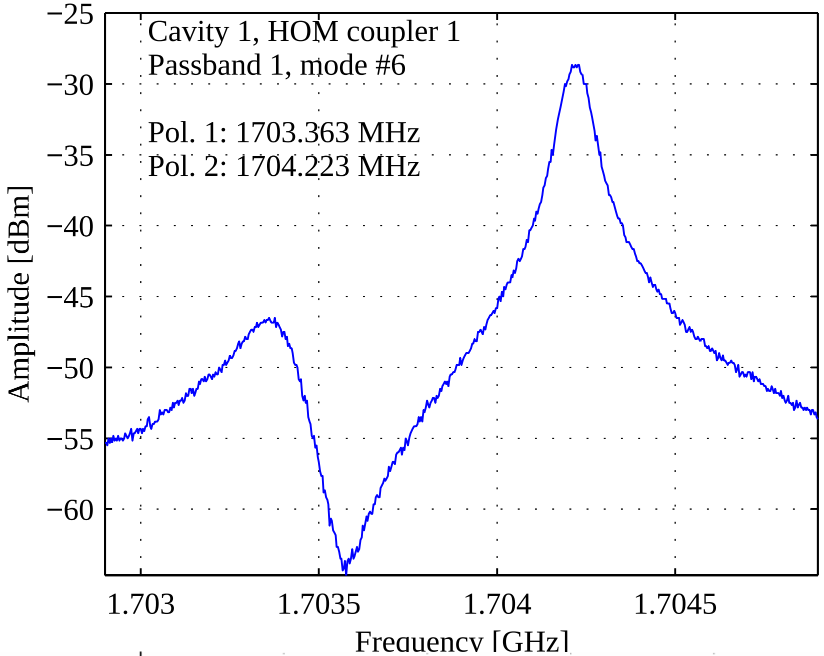


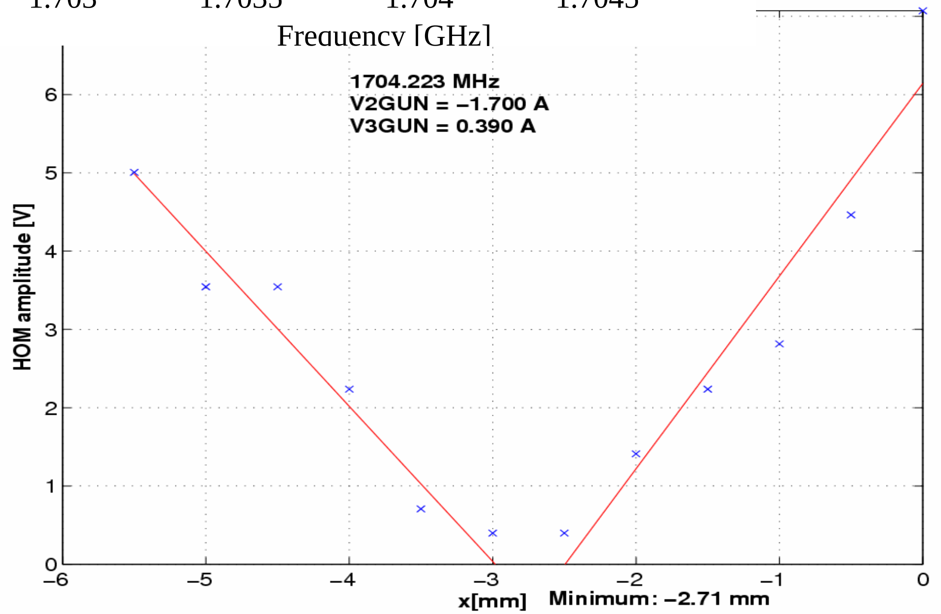


HOM as BPMs

- more complicated than conventional cavity BPMs
  - the two polarizations of dipole modes are coupled
  - cavities are not axially symmetrical
  - $\Rightarrow$ more complicated calibration

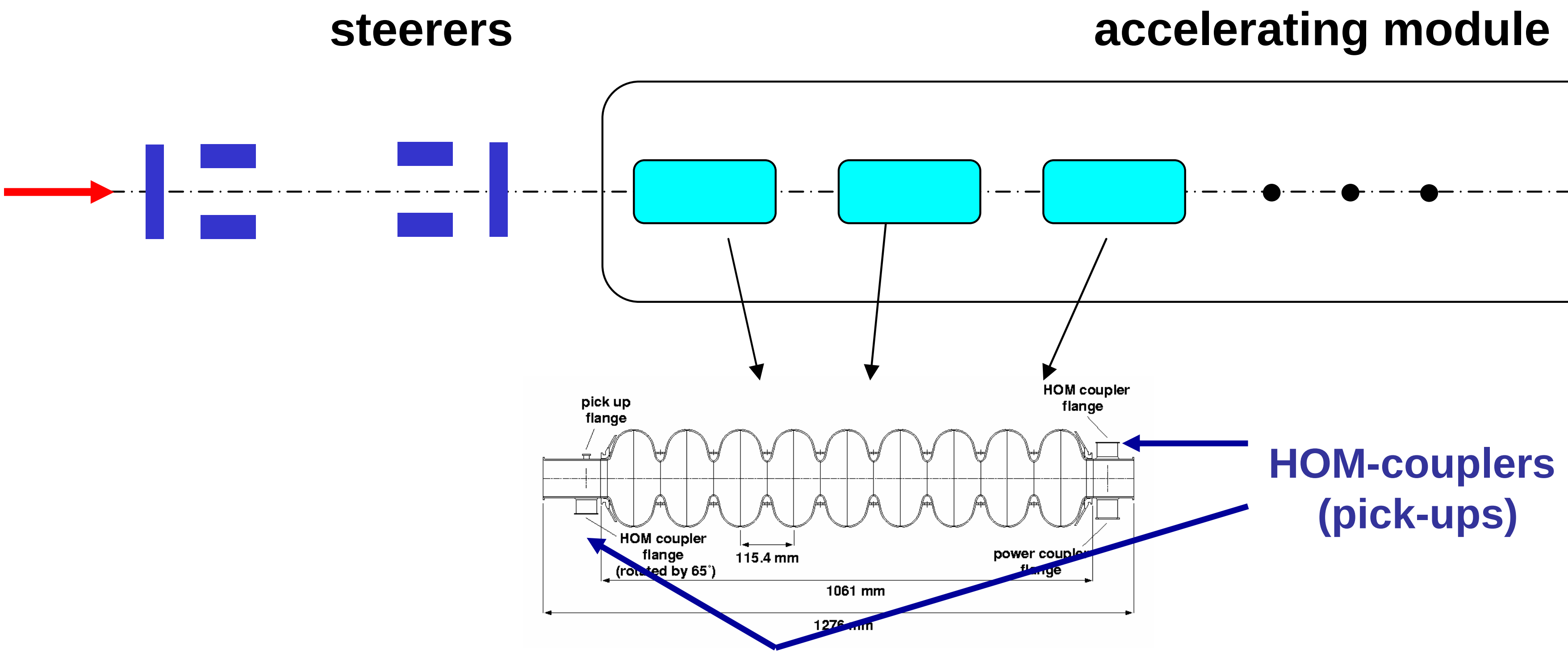
- but already available
  - $\Rightarrow$ no need for extra space or development, low costs
  - potential for sub-μm resolution



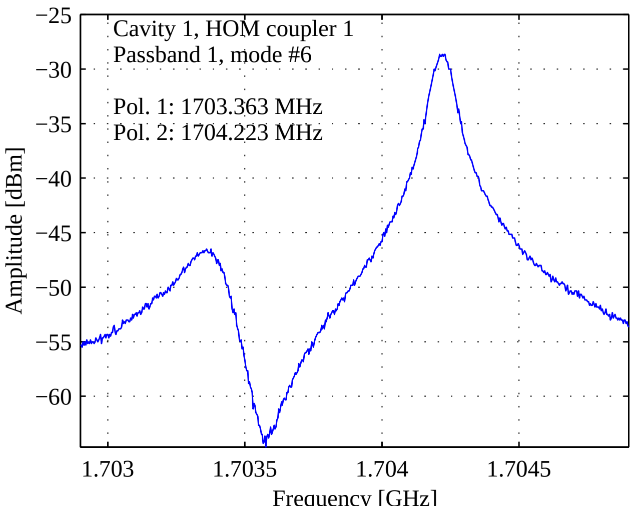


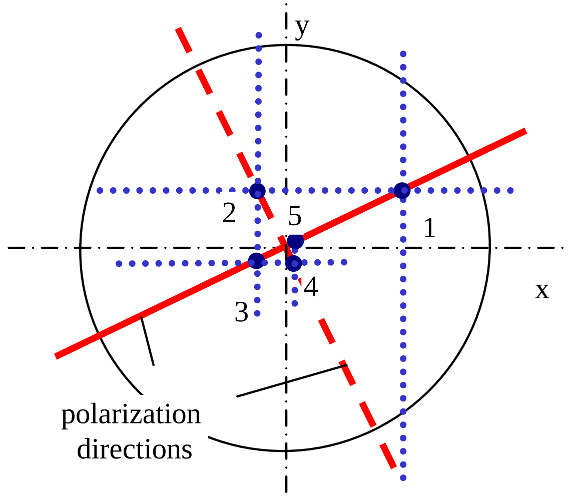
HOM Measurement Setup

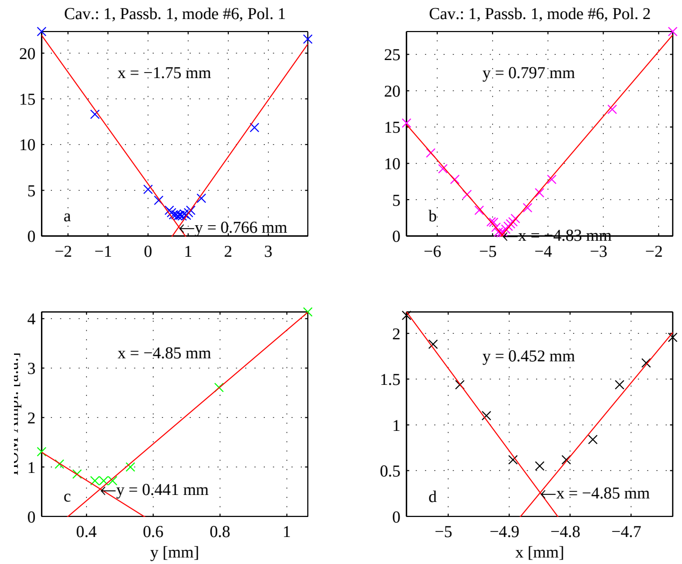
- Move beam with magnetic steerers
  - measure amplitude of dipole mode with spectrum analyzer



HOM Measurement



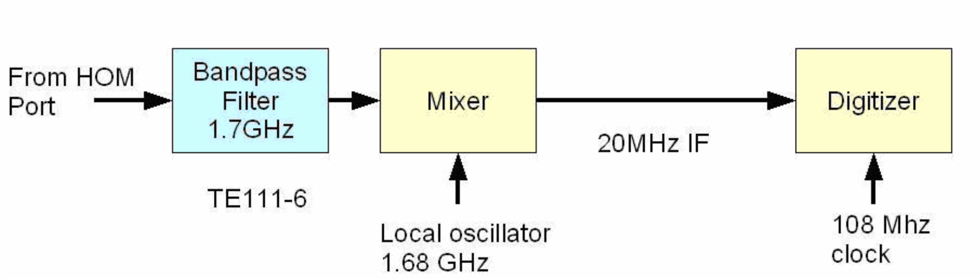


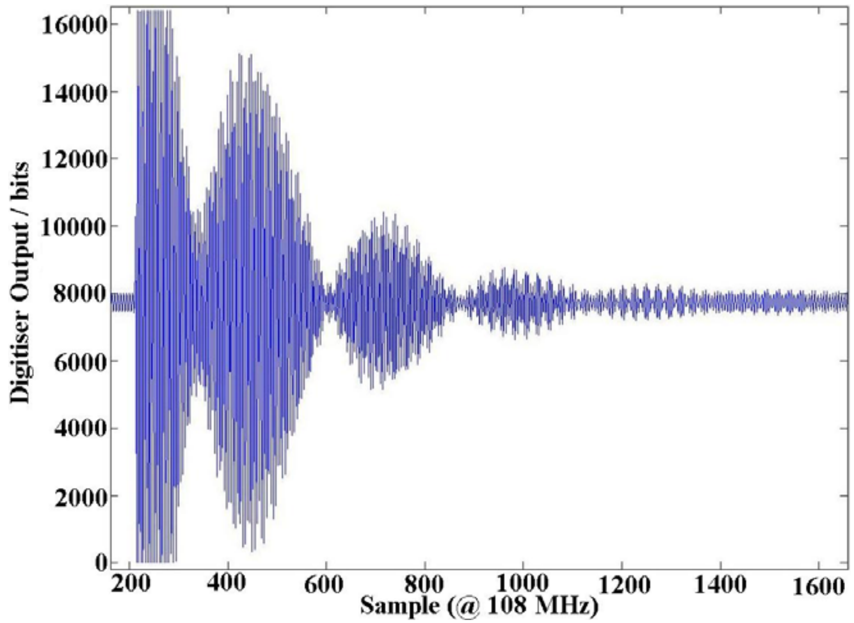


- Proof-of-principle for superconducting cavities ⇒
  - ➢ can find axis of dipole mode = beam trajectory generating minimal amplitude of both polarizations
    - can minimize wakefields
  - ➢ can calibrate the HOM signals in beam position

HOM Electronics

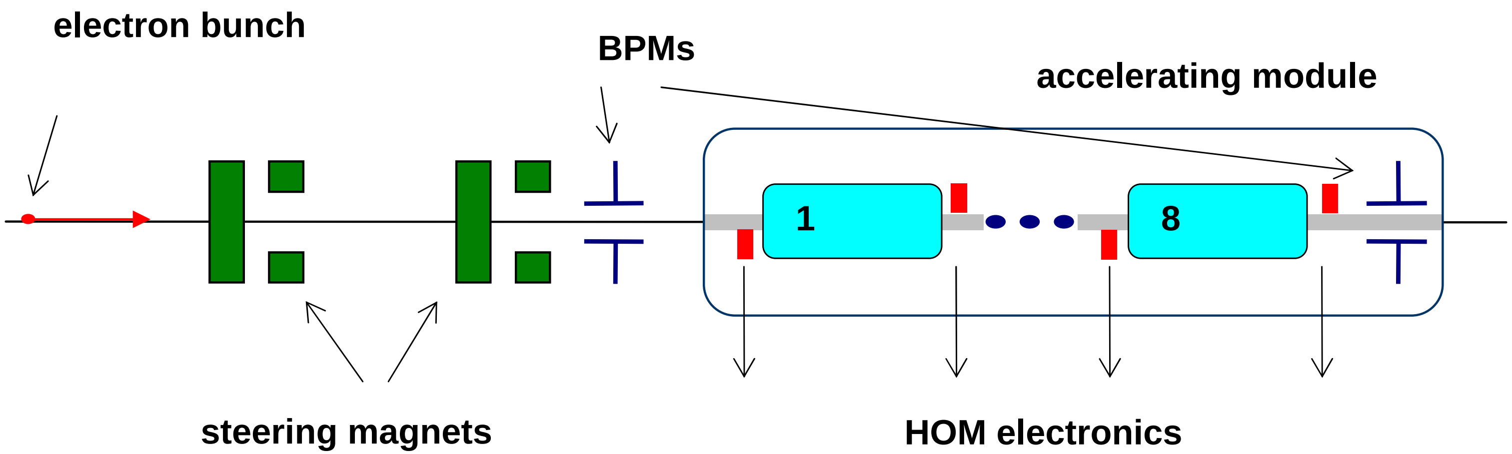
- similar to typical BPM electronics
- filters one dipole mode out of cavity spectrum and converts it from ~ 1.7 GHz to ~ 20 MHz → digitized
- also phase information is measured, needed to tell if bunch is left or right
- installed at both HOM couplers of all 40 FLASH cavities





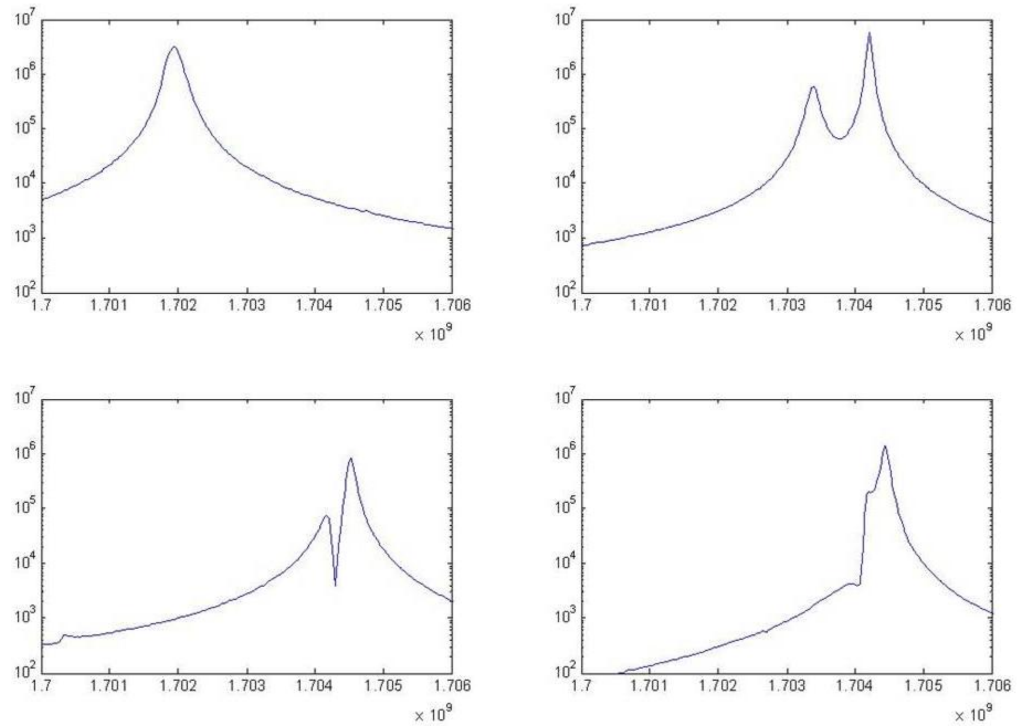
HOM-BPM Calibration Setup

- same as for previous measurements, except electronics instead of network analyzer
- simultaneous measurement from all 8 cavities in a cryo-module
- generate many beam offsets and angles:
  - try to generate large range of values in the (x,x') and (y,y') space



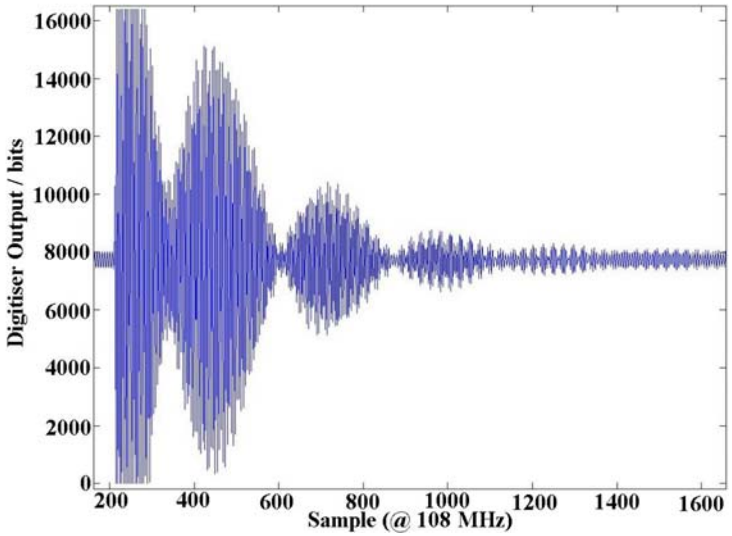
HOM-BPM Calibration

- Straightforward method
  - correlate amplitudes of the mode polarizations with the beam positions interpolated from BPM readings
  - **<u>but</u>**, complicated since:
    - polarizations have ~ random, unknown polarizations
    - each of the 40 cavities are different



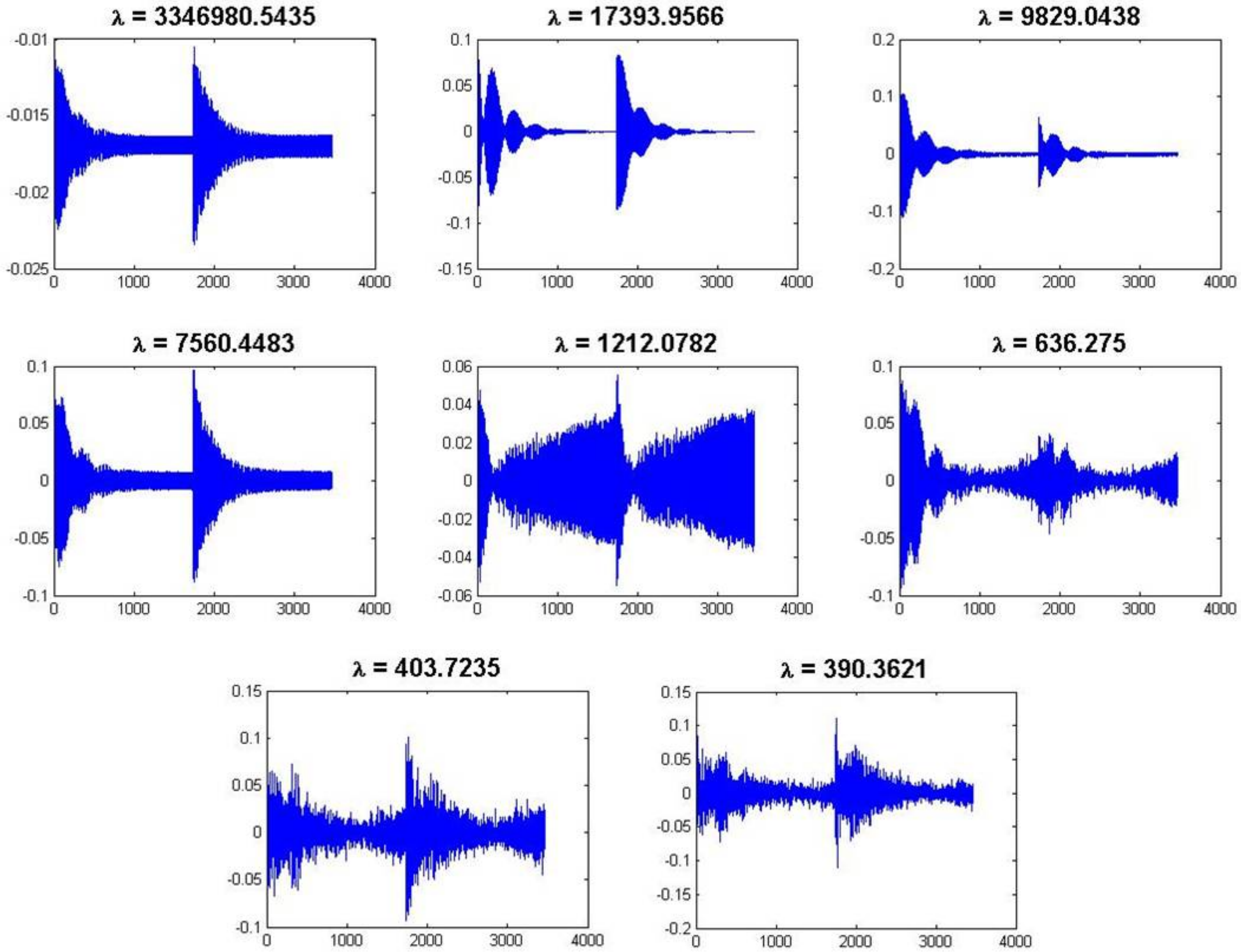
- Need for more universal and robust method → SVD

Singular Value Decomposition - SVD



- Form matrix, *X*, of all measurement sets in time
- SVD decomposes *X* into the product of matrices:
  - $X = U \cdot S \cdot V^T$
  - *U*, *V* - unitary → eigenvectors
  - *S* - diagonal → eigenvalues
- U and V: "normal eigenvectors"
  - i.e. "modes" whose amplitude changes independently of each other.
  - These may be linear combinations of the cavity dipole modes.
- Does not need *a priori* knowledge of resonance frequency, Q, etc.
  - Model Independent Analysis

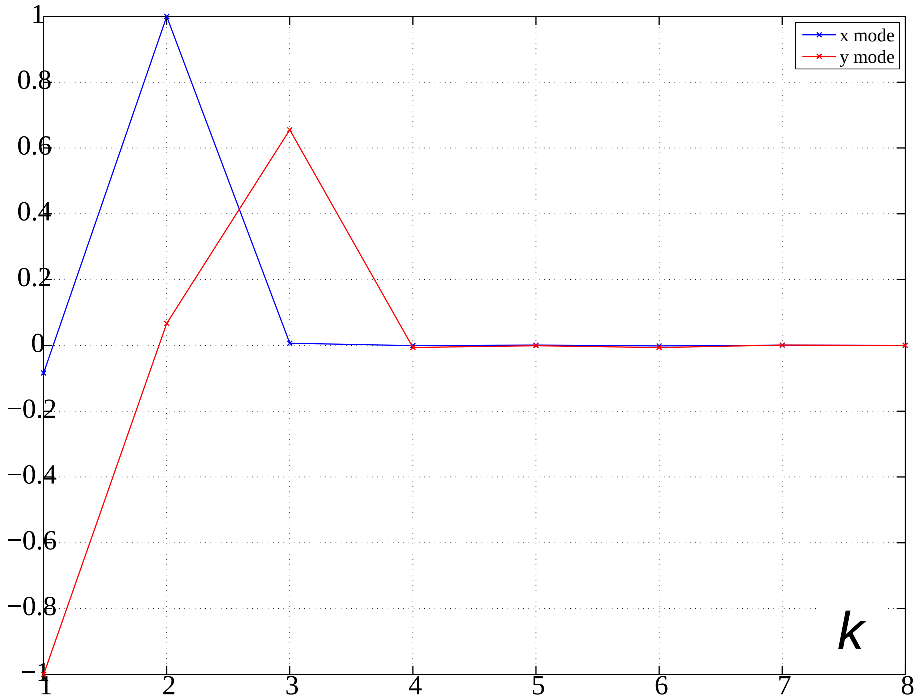
SVD Modes with Largest Eigenvalues λ

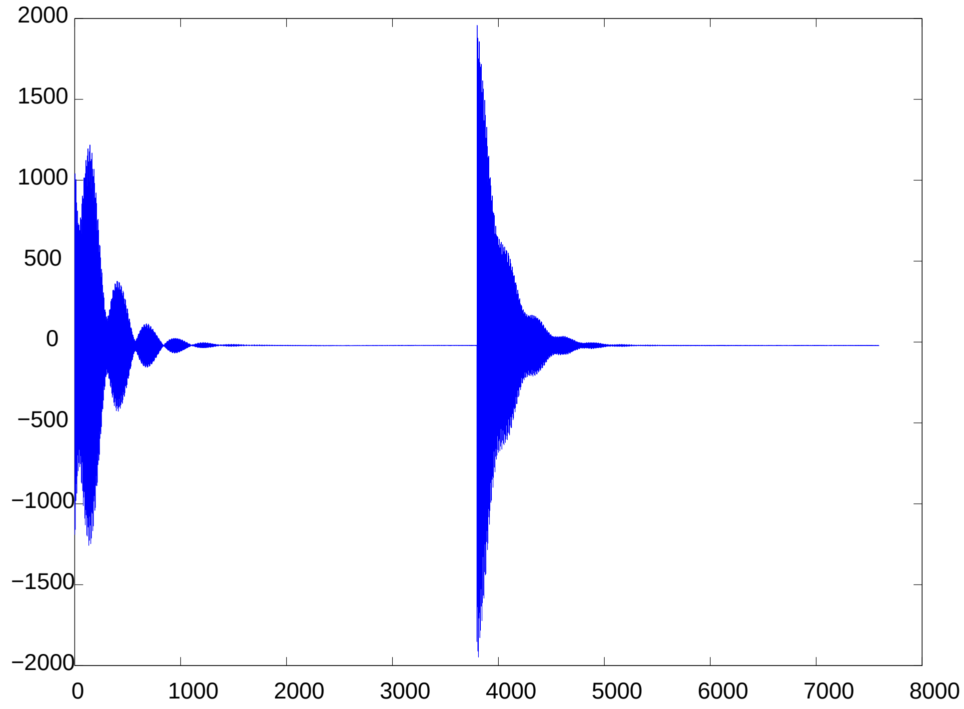


- Note: signals from both couplers are combined into one vector

Calibrating the HOM

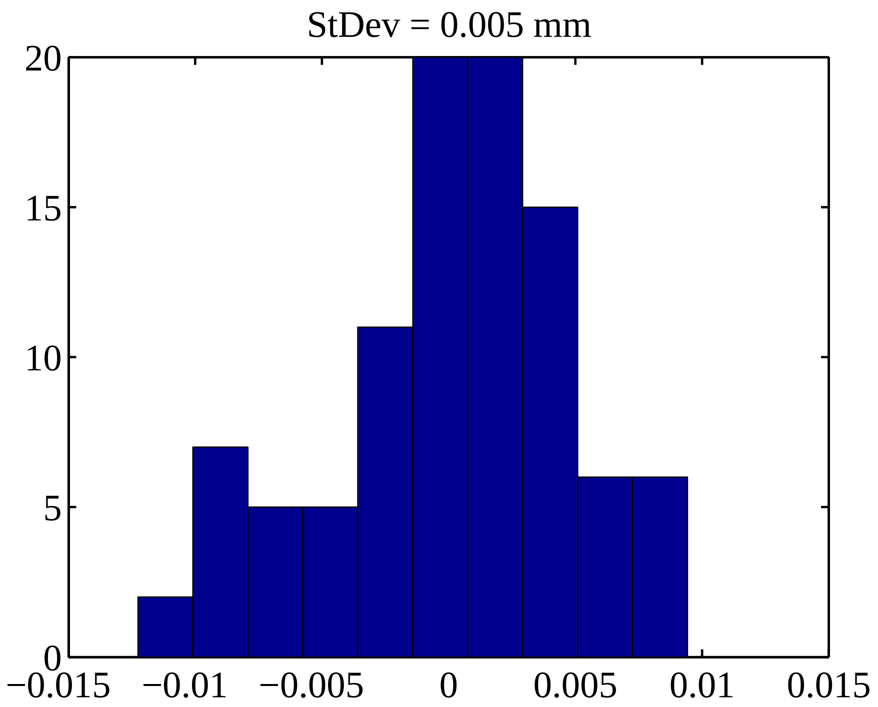
- Dot product of largest eigenvectors with beam pulses: $X \cdot V_k = A_k$ (A_k is a vector)
- then correlate by linear regression each A_k to beam position (x and y) as interpolated from BPM reading
- $\Rightarrow$ mode 2 – horizontal; mode 1+3 - vertical





HOM-BPM Resolution

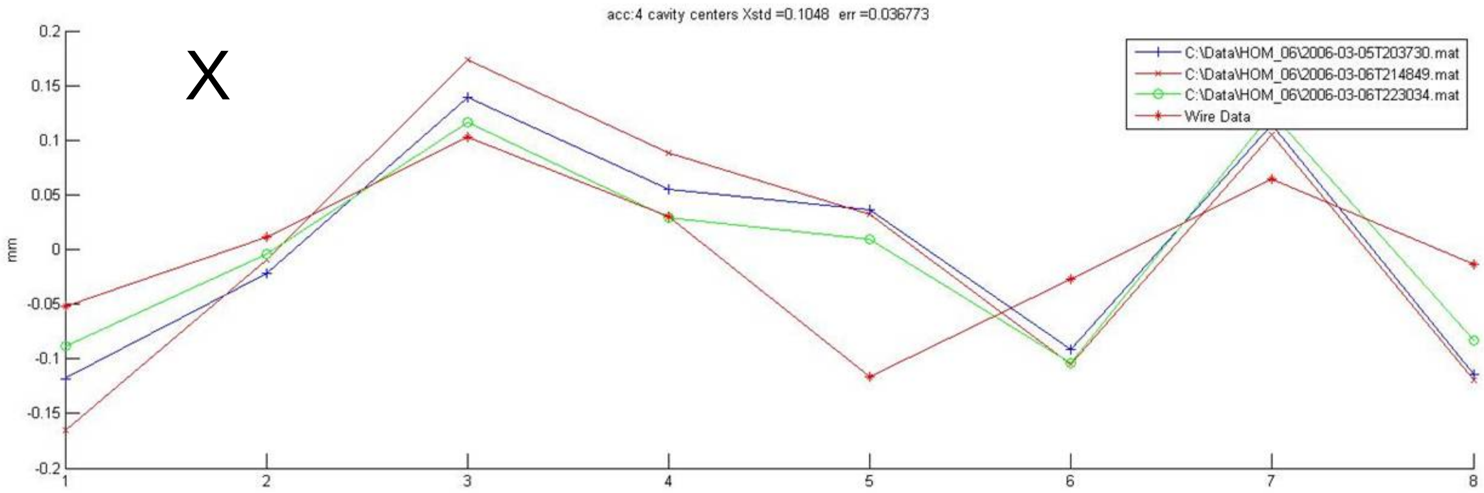
- compare measurement with one cavity, to prediction from adjacent cavities
- 5-10 μm rms observed
  - improvement of electronics → expect 1 μm resolution or better

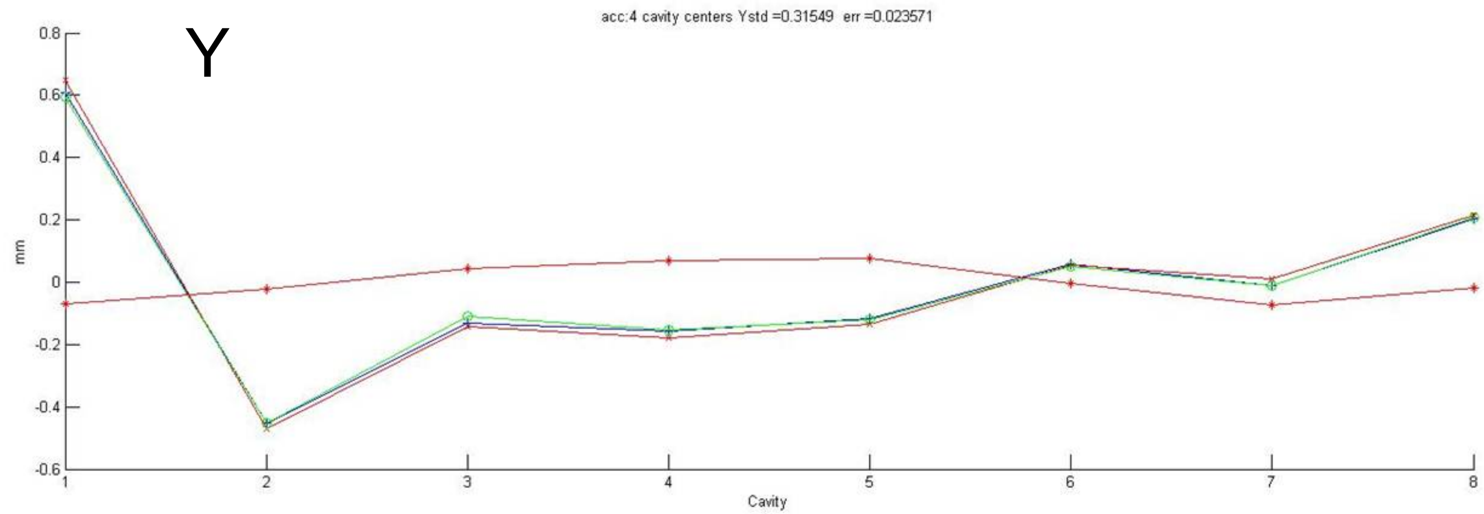


Measurement of Cavity Alignment

- Same method based on SVD
  - Find beam trajectory for minimum dipole signal
  - This is the centre of that dipole mode in that cavity.
- Measure the axis of a dipole mode for the 8 cavities within a cryo-module.
  - Can compare the centre of a particular mode in many cavities.
  - Gives in situ alignment data on the internals of the accelerating module.

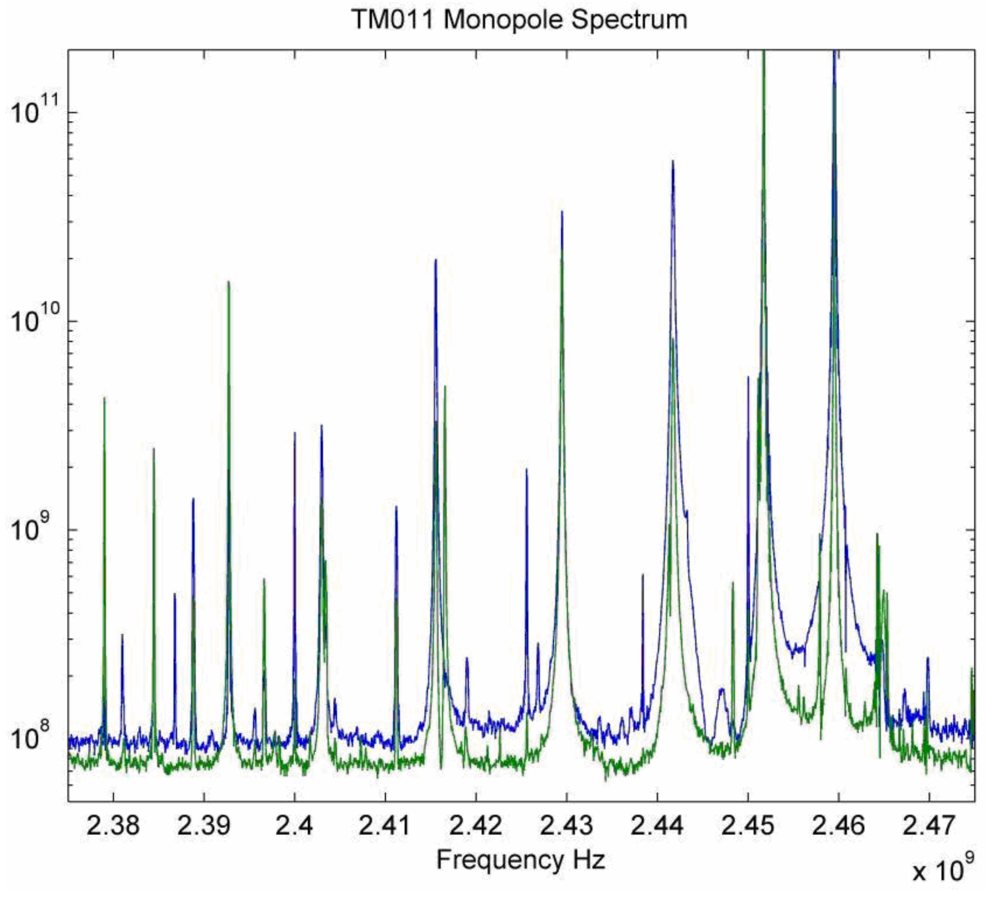
Measurement of Cavity Alignment - Results





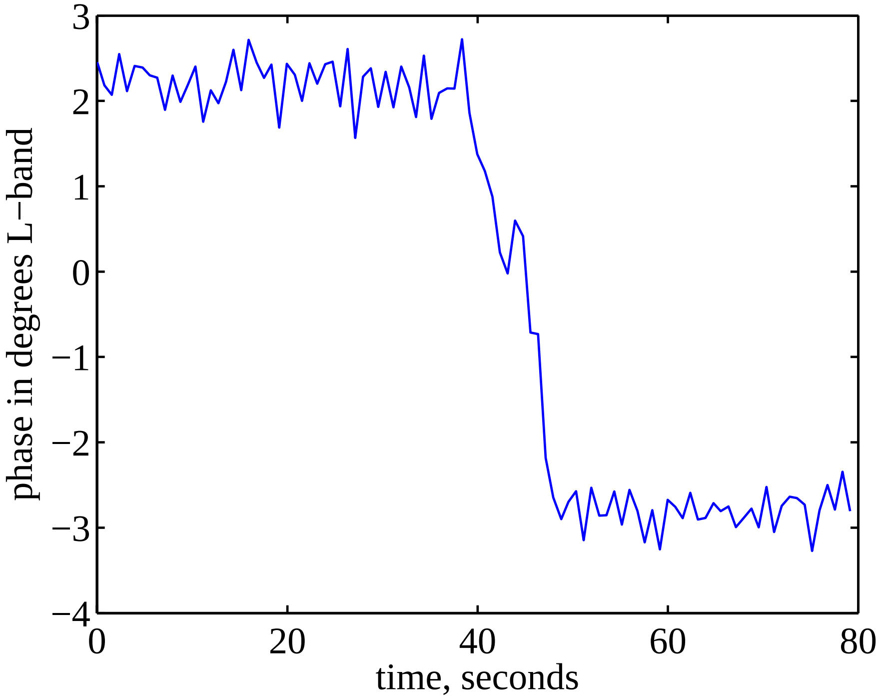
Measurement of Beam Phase

- Digitise the HOM signal with a broadband scope,
  - 5 GS/s, 2.5 GHz
- Can measure phase of beam induced monopole lines.
- HOM coupler allows a small amount of the fundamental to leak through.
  - Accelerating RF and beam induced HOMs exist on same cable.
  - No cable expansion issues.



Measurement of Beam Phase (2)

- Measurement of the 1.3 GHz phase wrt beam
  - 5 degree phase change command from the RF control system.
- Noise is 0.08 degrees at 1.3 GHz
  - Estimated by comparing the measurement from two couplers from the same cavity.
  - When the beam phase is compared to the RF phase of two cavities on the same klystron, RMS of 0.3 degrees.
    - not understood



Summary and Outlook

- FLASH and the XFEL
  - SASE FEL
  - based on the TESLA technology (also base for ILC)
- HOM as diagnostics
  - HOM-BPMs
    - use dipole fields excited by beam in the TESLA cavities as BPMs
    - successful proof-of-principle
    - resolution: 5-10 μm rms observed, potential for < 1 μm
  - beam alignment
  - cavity alignment in cryo-module
  - beam phase
- Outlook for HOM-BPMs
  - currently work to integrate them in the accelerator control system
  - can be used in the XFEL, the ILC and other accelerators