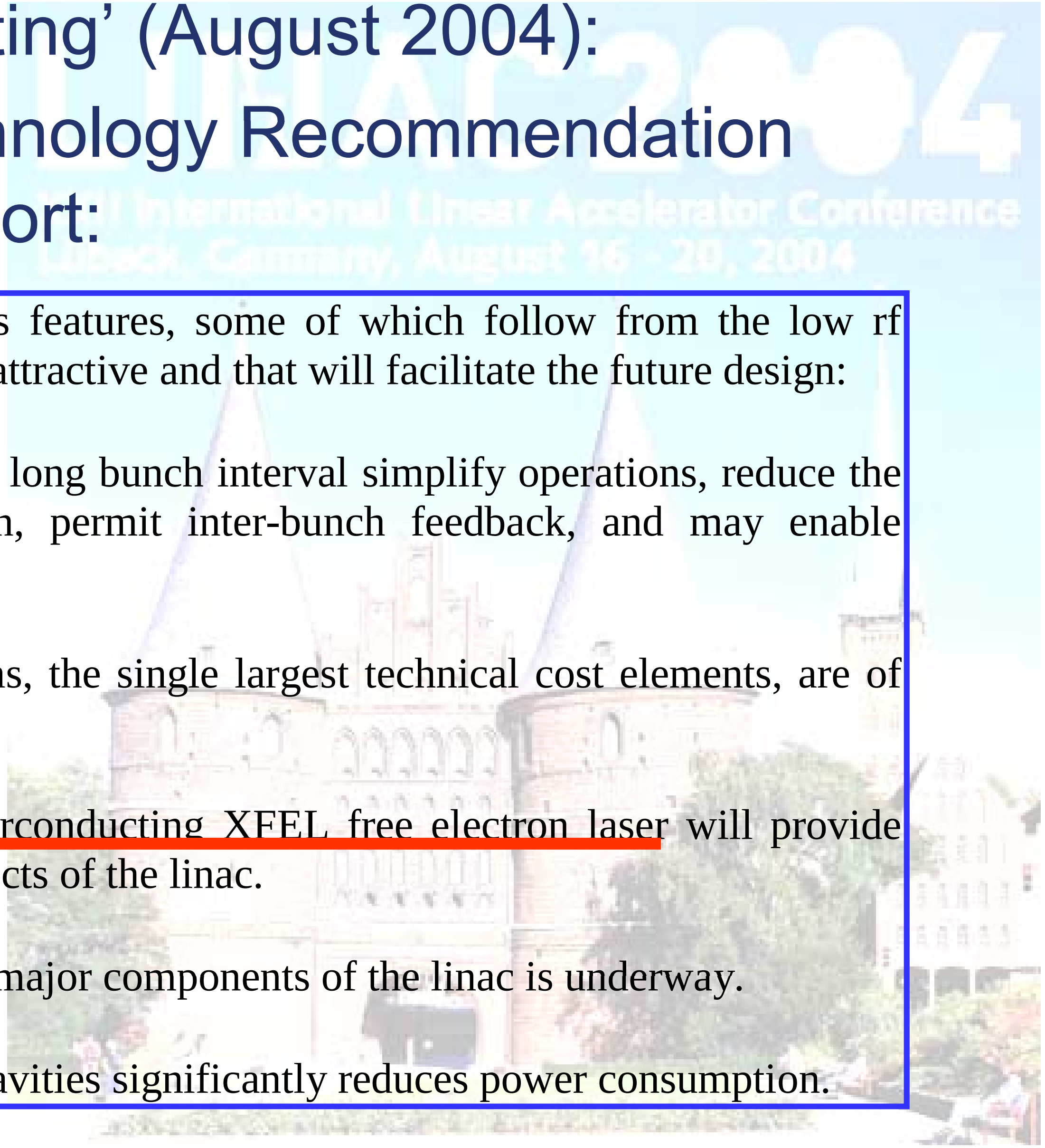
ILC Instrumentation Overview

Marc Ross (Fermilab);

International Linear Collider – Global Design Effort

Background: Linac 2004

- The ‘Lübeck Meeting’ (August 2004):
- International Technology Recommendation Panel (ITRP) Report:



The superconducting technology has features, some of which follow from the low rf frequency, that the Panel considered attractive and that will facilitate the future design:

- The large cavity aperture and long bunch interval simplify operations, reduce the sensitivity to ground motion, permit inter-bunch feedback, and may enable increased beam current.
- The main linac and rf systems, the single largest technical cost elements, are of comparatively lower risk.
- The construction of the superconducting XFEL free electron laser will provide prototypes and test many aspects of the linac.
- The industrialization of most major components of the linac is underway.
- The use of superconducting cavities significantly reduces power consumption.

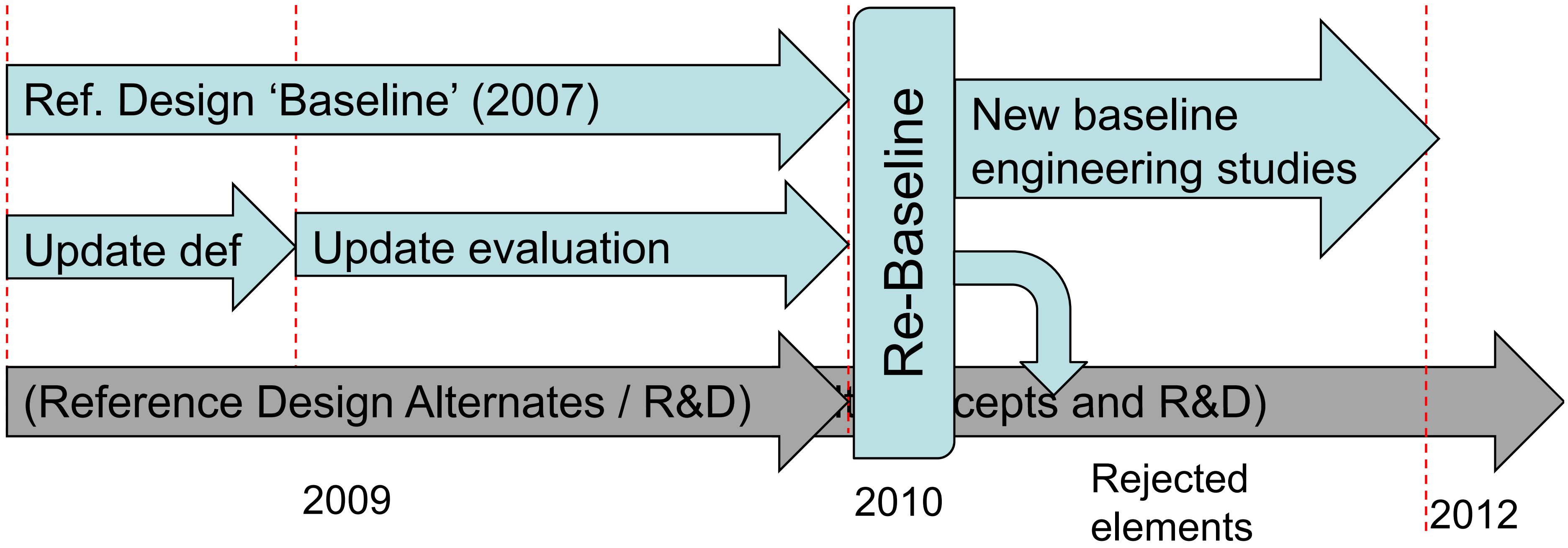
The role of R&D:

- in a mature, low risk project
- the ongoing, increasing global investment in SCRF
  - **the big impact of the ITRP decision**
  - **Improve performance, reduce cost, challenge limitations, develop inter-regional ties, develop regional technical centers**
    - Both a 'project-based' and a 'generic' focus

The ILC has:

- A Baseline Design; to be extended and used for comparison
  - **But ready for deployment**
- Research on and Development of Alternates to the Baseline
  - **Continues to strongly engage the community**
- Plug – compatibility / modularity → flexibility between the 2
  - **The critical role of associated projects – XFEL, Project X, SNS, JLab12, ERLs, …**
- Models of 'project implementation'
  - **The transition from R&D to a real project**
  - **The link between Technical Phase R&D and the project political process**

Towards a New Baseline in 2010

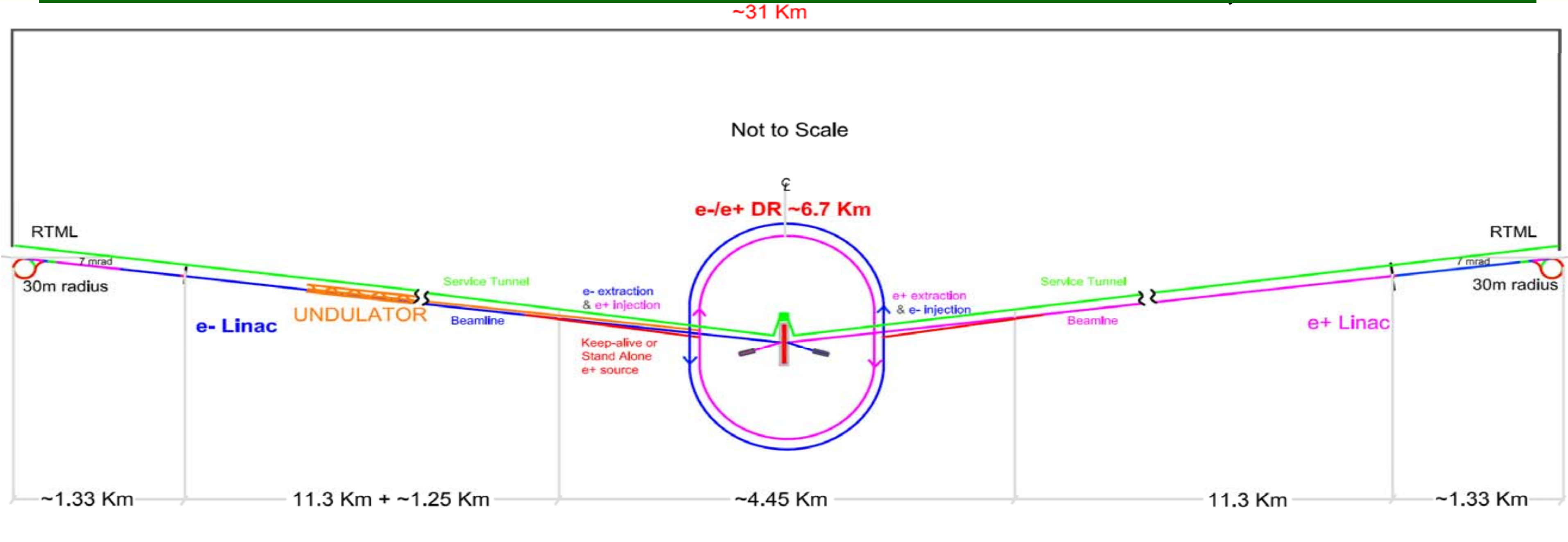


- Process:
  - **Baseline & its cost estimate are maintained**
  - **Proposed updates → to be studied/reviewed internationally**
    - Formal review and re-baseline process beginning of 2010
  - **Development of Alternates continues**
    - Definitive project timeline unknown

Intro: ILC Beam Parameters

Beam Parameters:

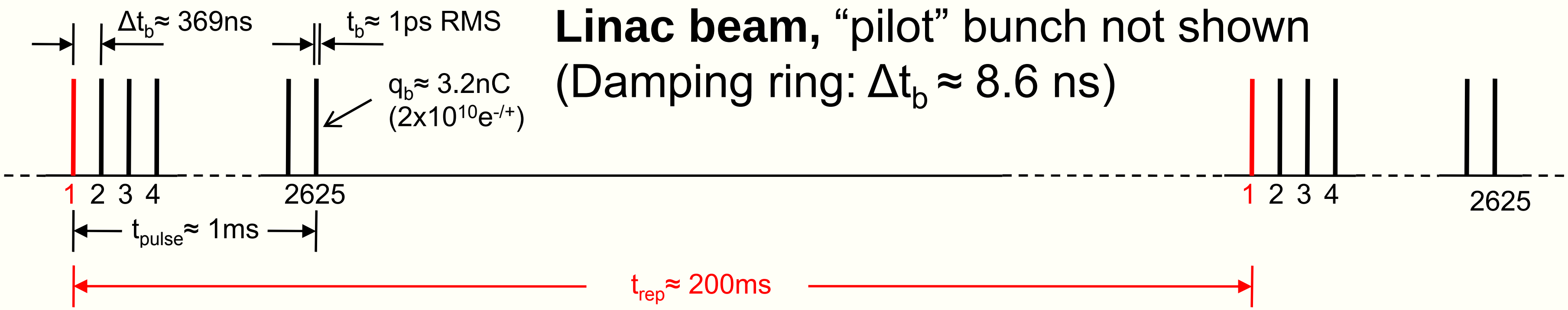
beam energy	=	2 x 250 GeV	bunch length σ_z	≈	300 μm *(187 GHz)*
luminosity L	=	2 x 10^{34}	vert. emittance $\gamma\,\varepsilon_y^*$	=	0.04 mm mrad
rep. frequency f_{rep}	=	5 Hz	RMS energy spread	=	0.1 %
macro pulse length t_{pulse}	=	969 μs	β_x^* (IP)	=	21 mm
# of bunches per pulse	=	2625	β_y^* (IP)	=	0.4 mm
bunch spacing Δt_b	=	369 ns *(2.2 MHz)*	hor. beamsize (IP) σ_x	=	620 nm
bunch charge	=	3.2 nC	vert. beamsize (IP) σ_y	=	5.7 nm



Schematic Layout of the 500 GeV Machine

Intro: Beam Characteristics

Linac beam, "pilot" bunch not shown
(Damping ring: $\Delta t_b \approx 8.6$ ns)



- **Charged particle bunches of ~ $2x10^{10}$ e^- or e^+**
- **"Ribbon" bunch, Gaussian-like profile**
  - **Along linac sections ~1 µm range vert., ~100 µm range hor.**
  - **RMS bunch length ~ 300 µm (1 ps)**
- **Non-linear field effects result in non-Gaussian particle distributions in the bunch**
  - **e.g. off-crest acceleration, CSR-effects (bunch compressor), wakefields**

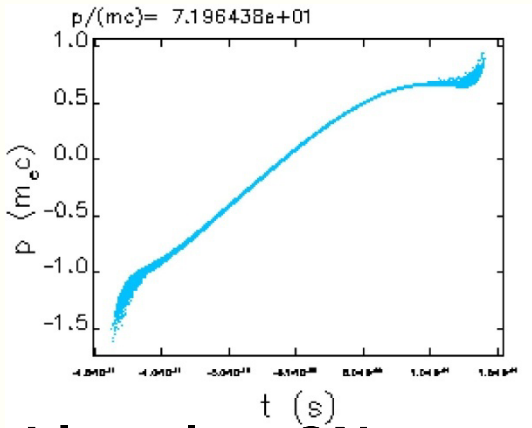
Intro: Long. Bunch Gymnastics

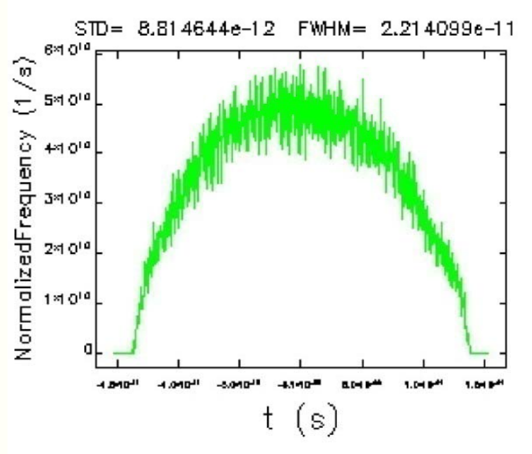
Energy chirp linearization using a 3rd harmonic cavity

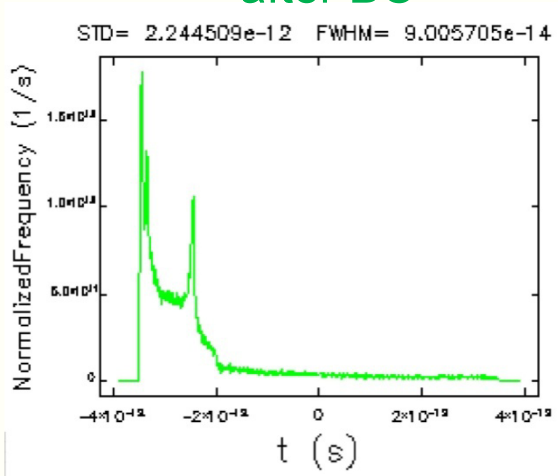
- **Linearizer OFF**

before BC

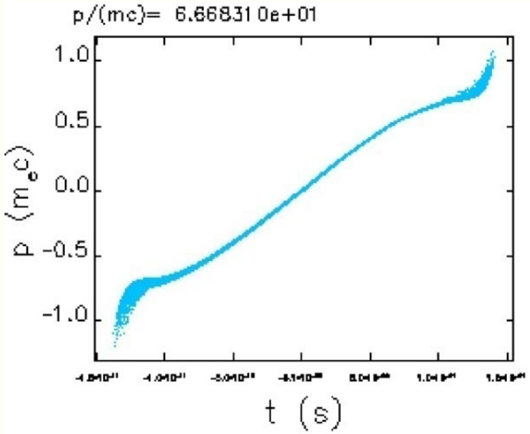
after BC

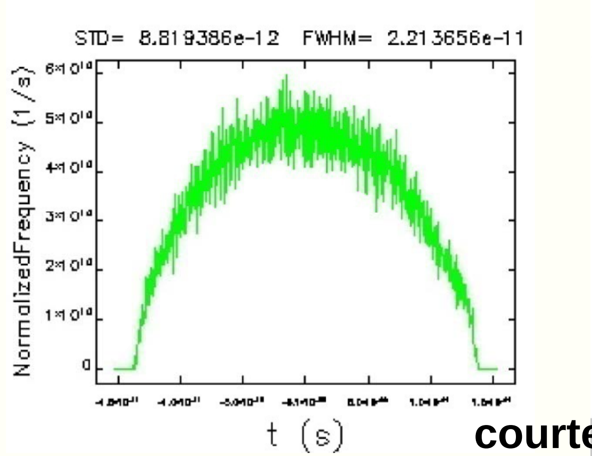


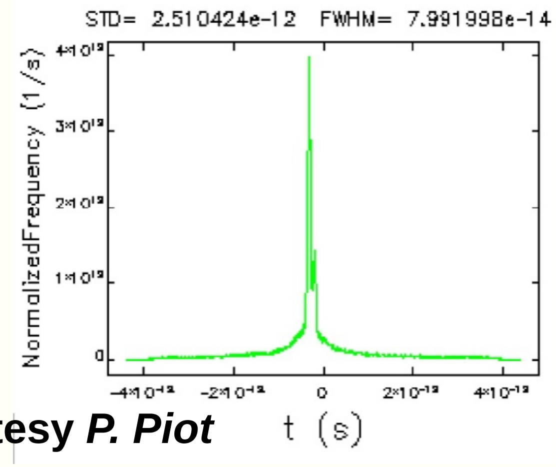




- **Linearizer ON**







courtesy *P. Piot*

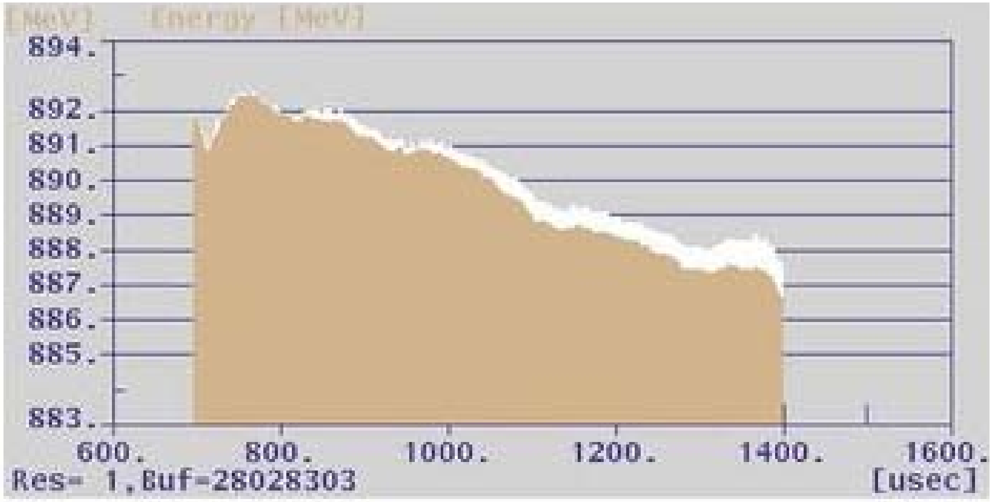
Intro: Beam Diagnostics

- **Machine commissioning, error detection**
  - Fundamental beam instruments, e.g. beam intensity (bunch charge), beam orbit (BPM), beam profile (screens, wire scanners)
  - Dynamic range, single bunch / single pass signal processing, time stamped data acquisition
  - Beam parameter characterization in each area
- **Emittance preservation, luminosity optimization**
  - High resolution instrumentation for beam position & energy, trans. and long. beam profile, bunch arrival timing
- **Stable machine operation**
  - Various slow and fast feedback systems, transverse intra-train IP feedback
- **Machine protection (11 MW beam power, linac: 20 kW)**
  - Beam loss monitor (BLM) system

Intro: ILC Beam Instruments

- ~ 2000 Button/stripline BPM's (10-30 / 0.5 µm resolution)
- ~ 1800 Cavity BPM's (warm, 0.1-0.5 µm resolution)
- 620 Cavity BPM's (cold, part of the cryostat, ~ 1 µm)
- 21 LASER Wirescanners (0.5-5 µm resolution)
- 20 Wirescanners (traditional)
- 15 Deflecting Mode Cavities (bunch length)
- ~ 1600 BLM's
- Other beam monitors, e.g. toroids, bunch arrival / beam phase monitors, wall current monitors, faraday cups, OTR & other screen monitors, sync light monitors, streak cameras, feedback systems, etc.
- Read-out & control electronics for all beam monitors

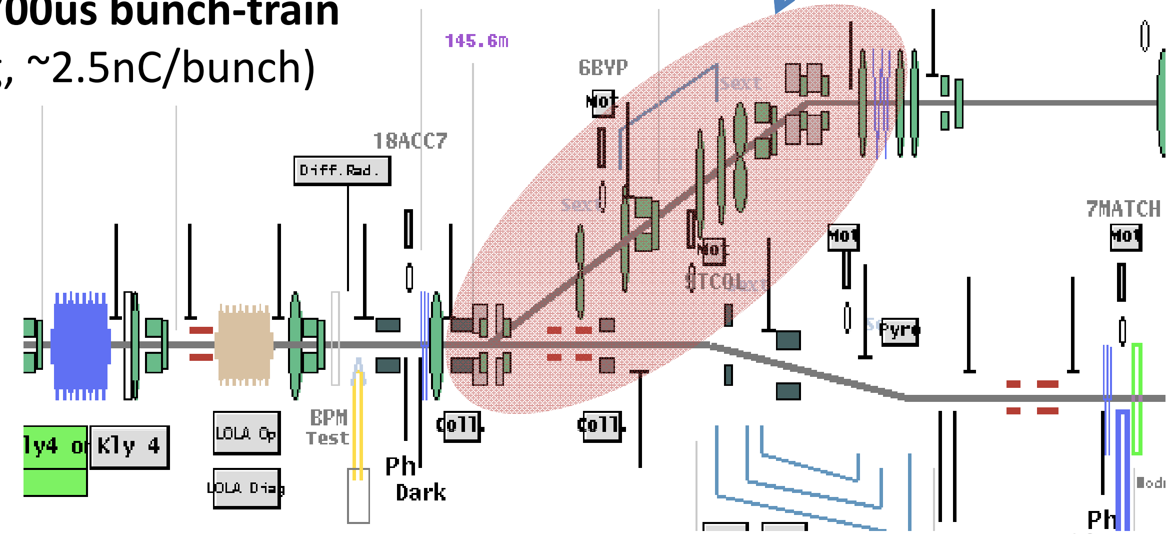
FLASH Energy Server (bypass line)



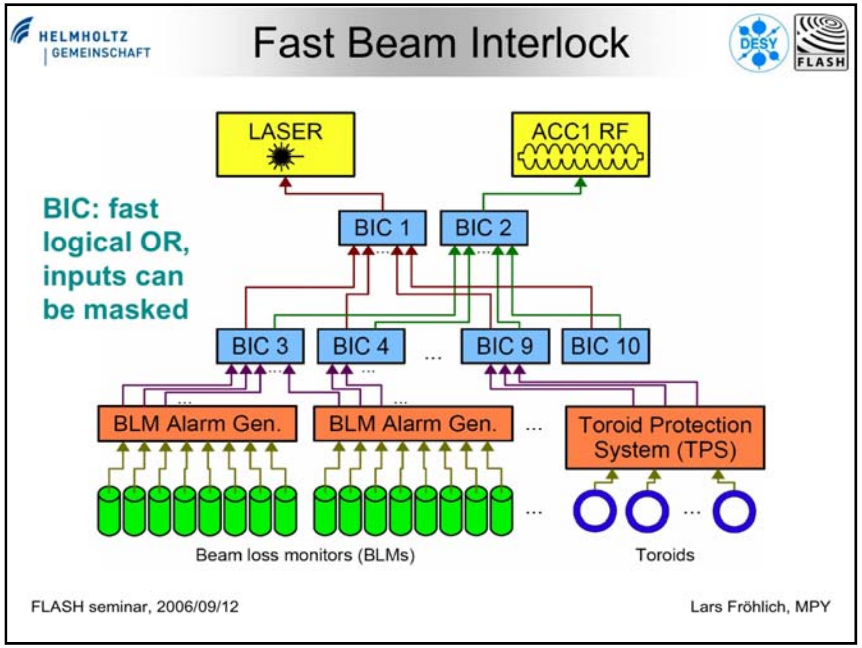
Bunch-by-bunch energy for 700us bunch-train
(350 bunches at 2us spacing, ~2.5nC/bunch)

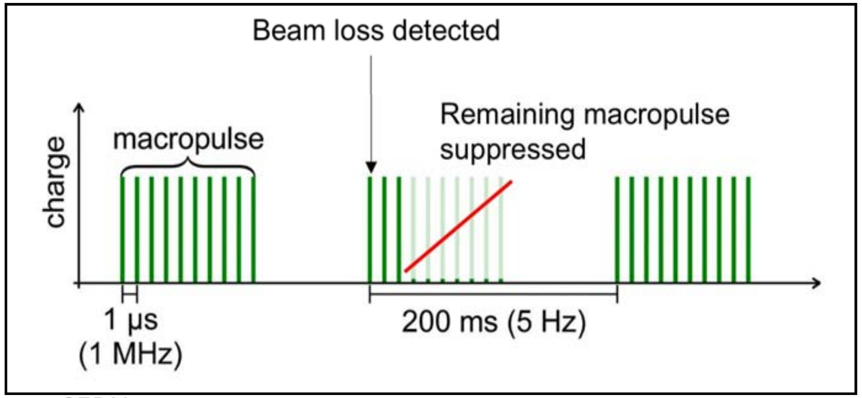
- Computes electron beam energy for each bunch using the measured trajectory through two chicane dipole magnets

- Measured spectrum of FEL photons provides a calibration reference

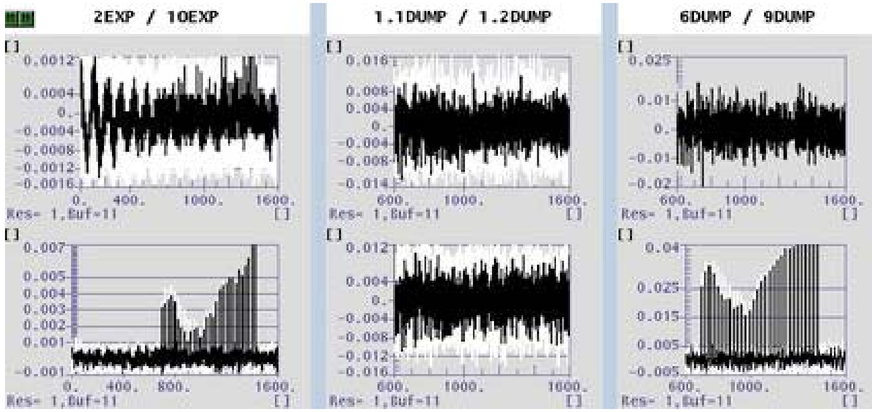


FLASH beam loss monitoring

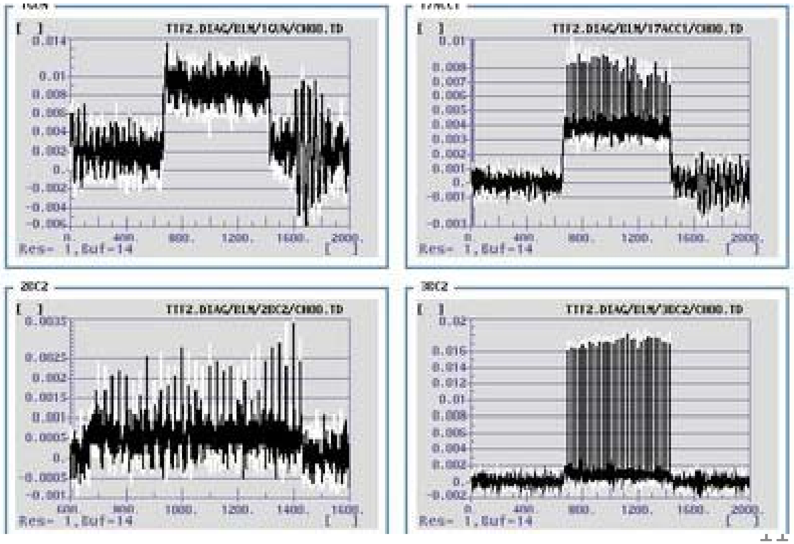




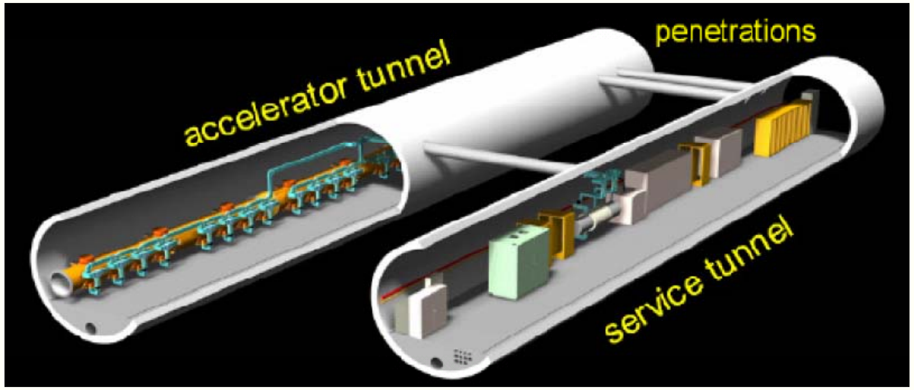
Example of losses in beam dump line

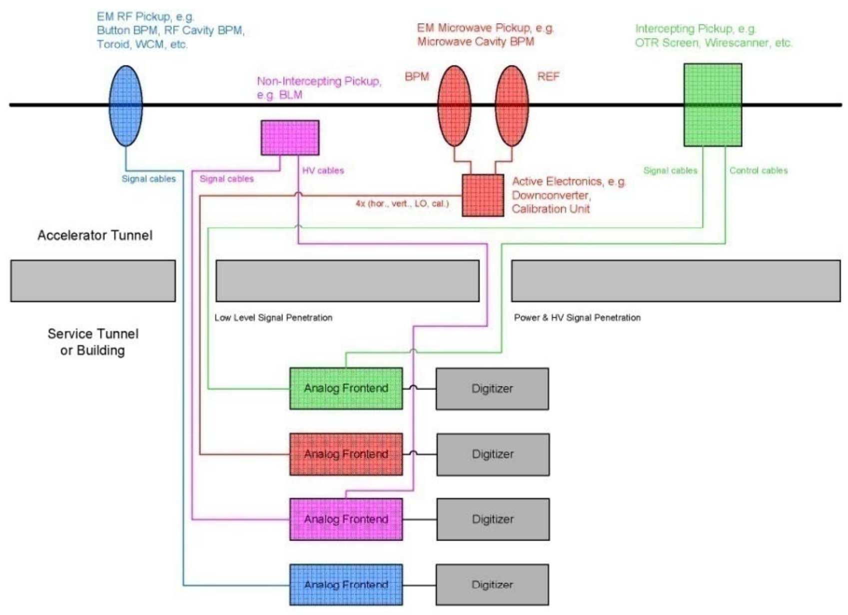


Example of losses from Gun to ACC1



Intro: Tunnel Hardware



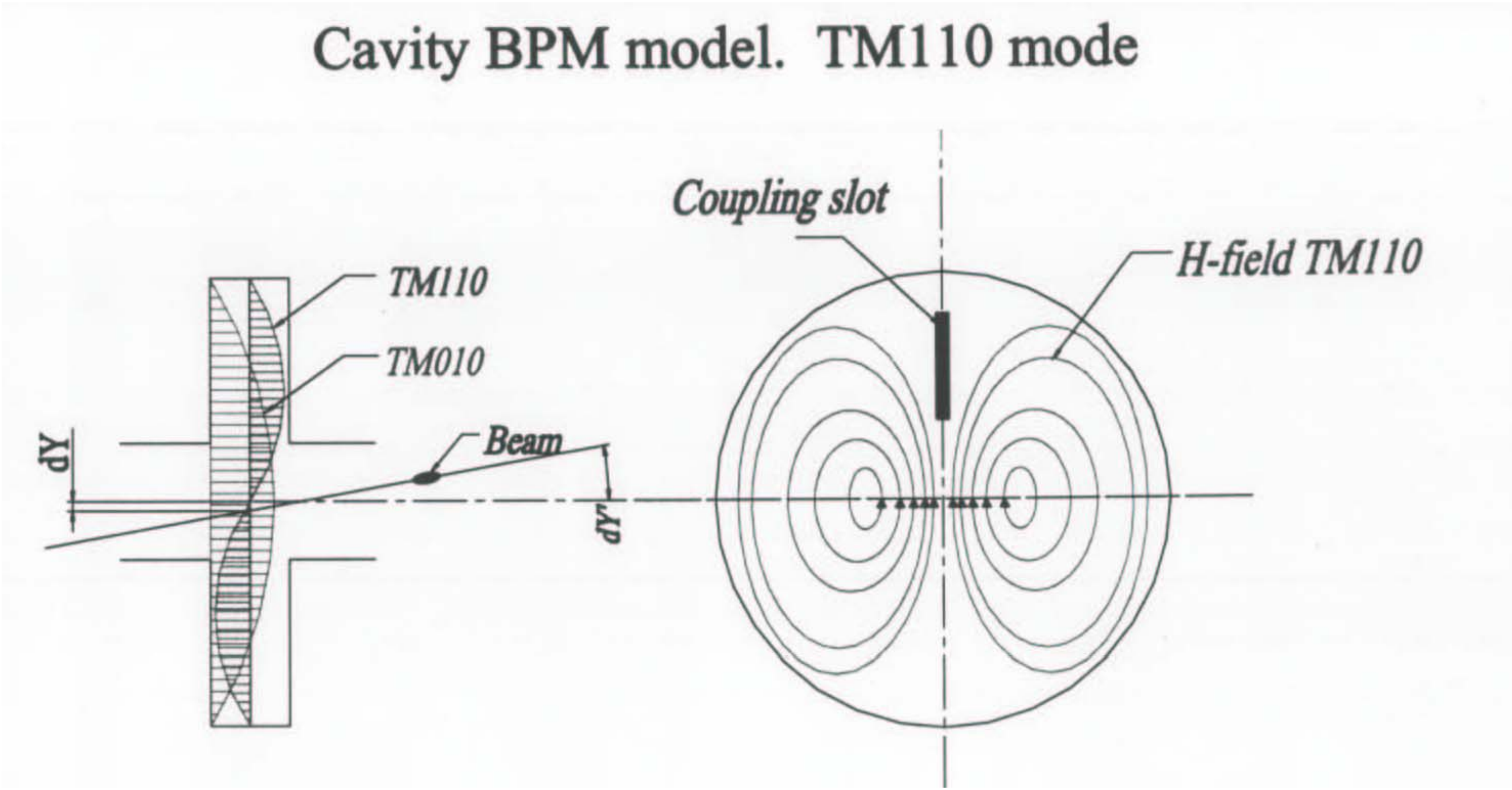


- **Beam Instruments:**
  - **Intercepting or non-intercepting pickup stations, often part of the beam vacuum system, located in the accelerator tunnel.**
  - **Read-out, control, and data acquisition electronics, located in the service tunnel, wire connections through penetrations.**
  - **Auxiliary system, e.g. racks, crates, PS, timing,…**

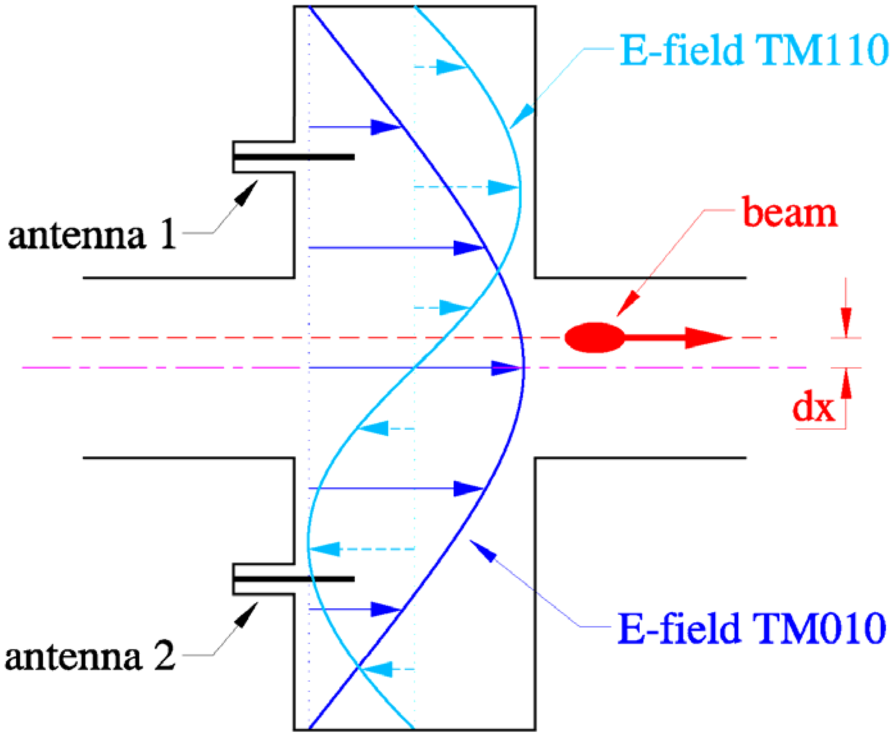
Distort the beam pipe → resonant cavity with output coupler

- Begin the process of adapting the signal for waveform processing → *in the beam pipe*
- This will help remove the *'difference between 2 large signals'* problem
  - all in one design makes detailed diagnostic studies difficult…
  - 'monopole' (TM010) signal can be suppressed through coupler design and frequency filtering
  - Residual is very small
    - Maybe a few microns in present design
    - The equivalent 'monopole' for buttons is r/2 (~cm)

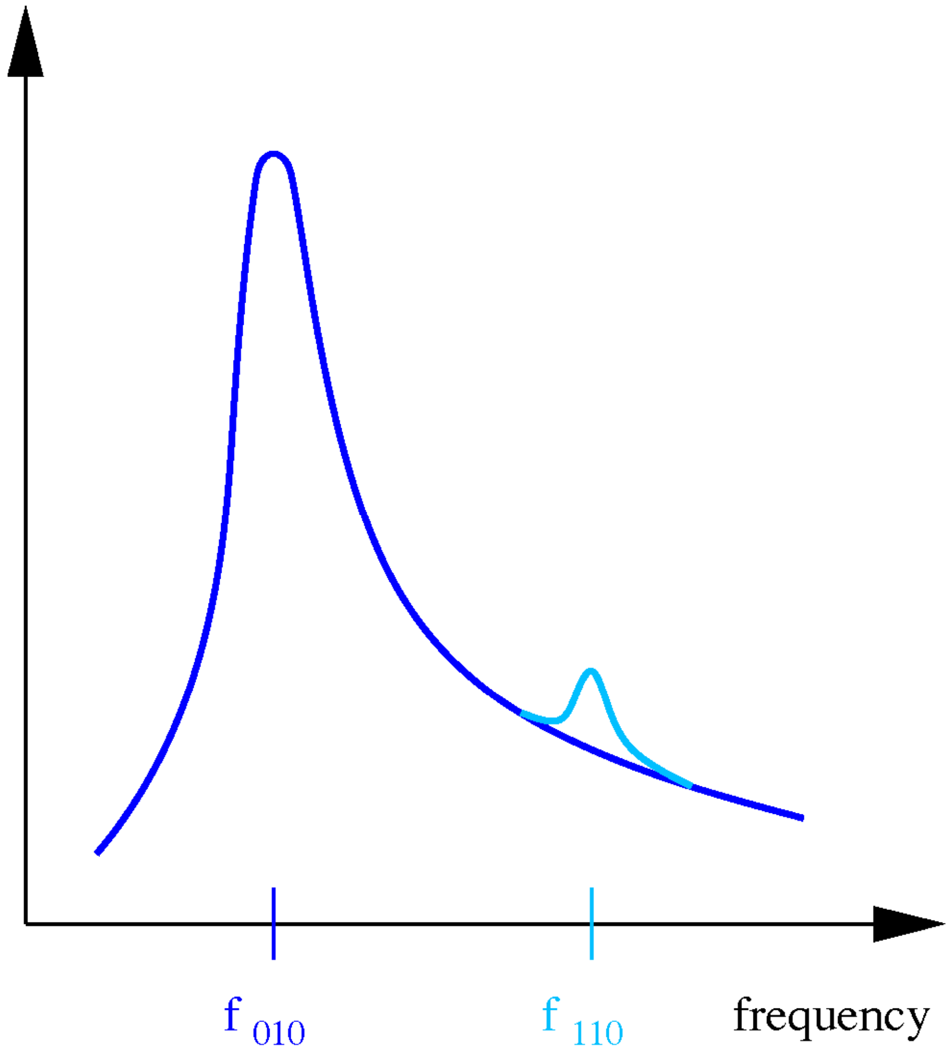
‘Pillbox’ Cavity BPM lowest order modes:



Modes in the pilbox cavity BPM



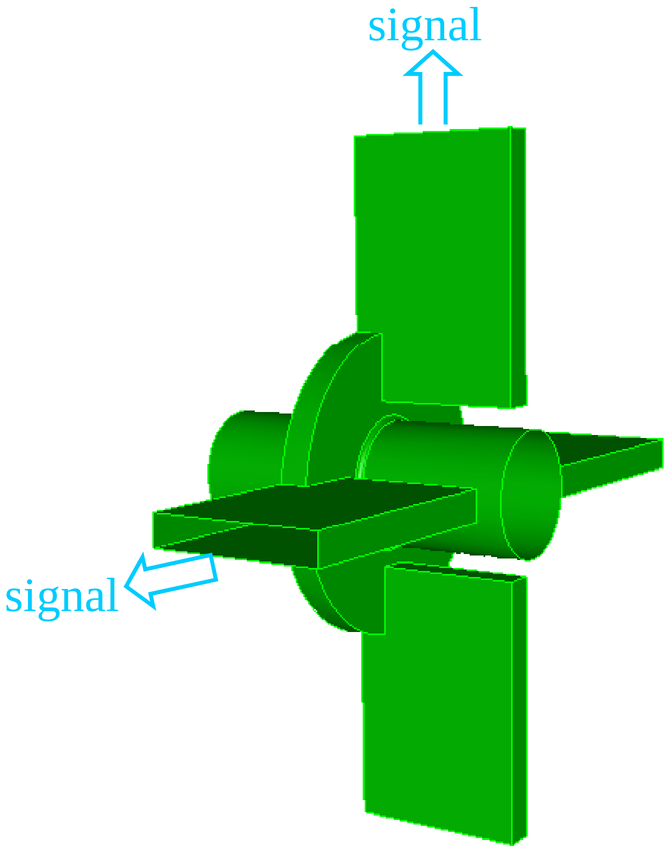
- Cylindrical harmonic expansion
- ‘difference of large’ numbers problem reduced to rejection of the primary fundamental peak
- typical f_{110} / f_{010} ratio 1.4
- only one antenna is needed
- the 110 mode flips phase on either side of the central trajectory



Cavity BPM With TM_{11}-mode Selective Coupler

$$P(q,x) = \frac{V^2}{Z_0} = q^2 \frac{\beta}{1+\beta} \frac{\omega_0 k_{loss} x^2}{Q_L}$$

Charge & position ^2
Power coupled out
Decay time
'loss factor'

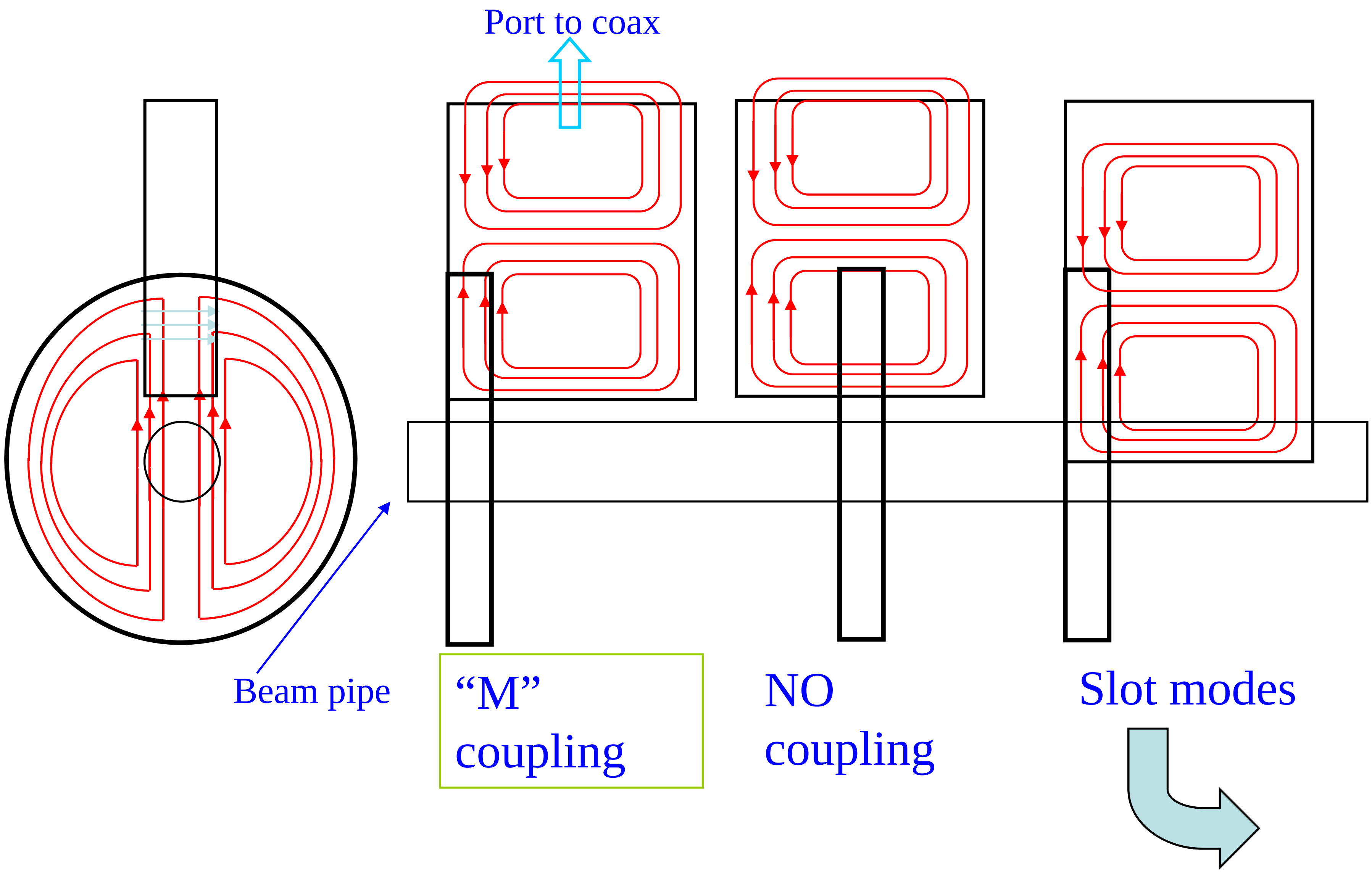


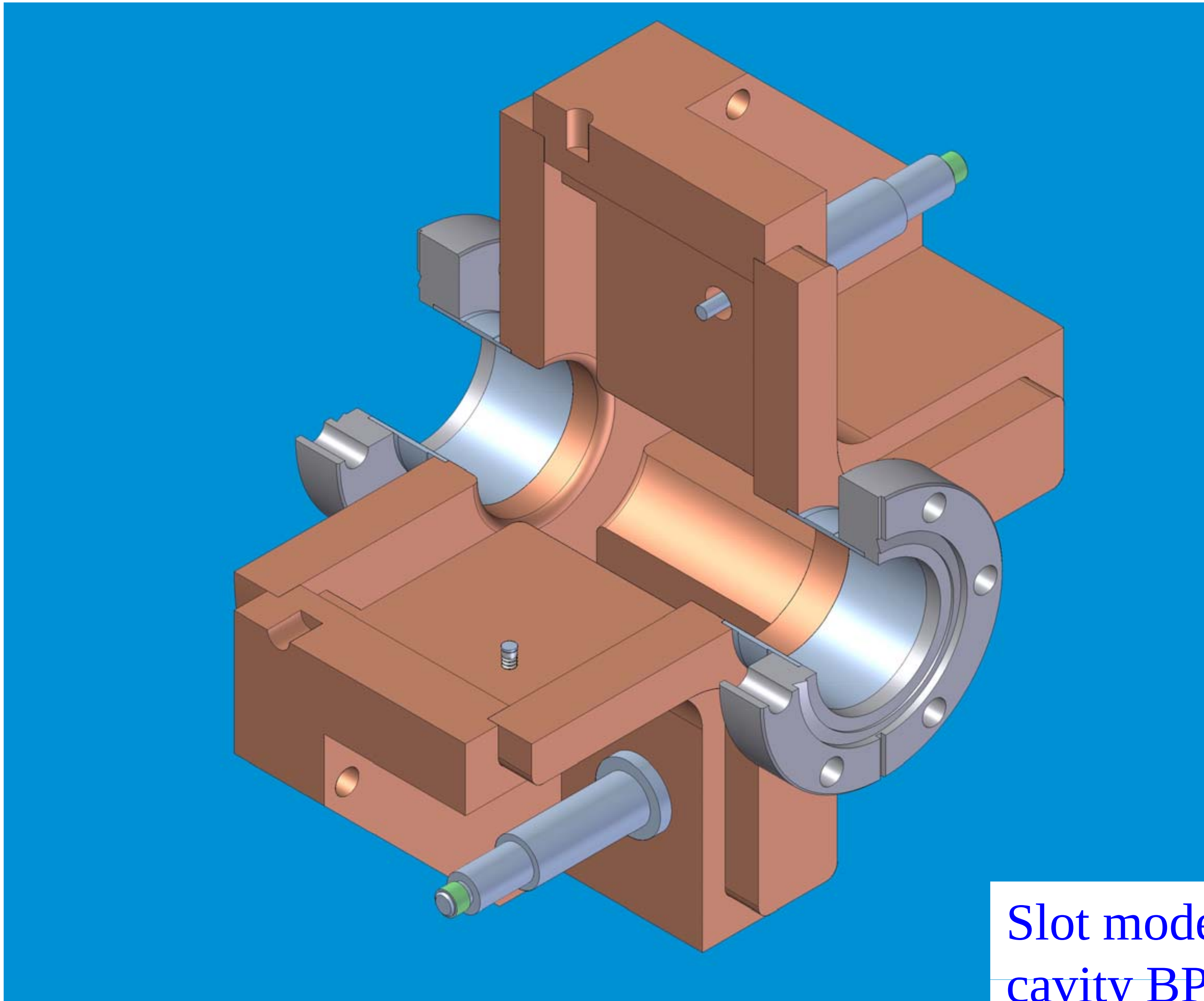
- Dipole mode: TM_{11}
- Coupling to waveguide: magnetic
- Beam x-offset couple to y port

- Sensitivity: 1.6$mV/nC/\mu m$
  ($1.6\times10^9 V/C/mm$)

- Couple to dipole (TM_{11}) only
- Does not couple to TM_{01}

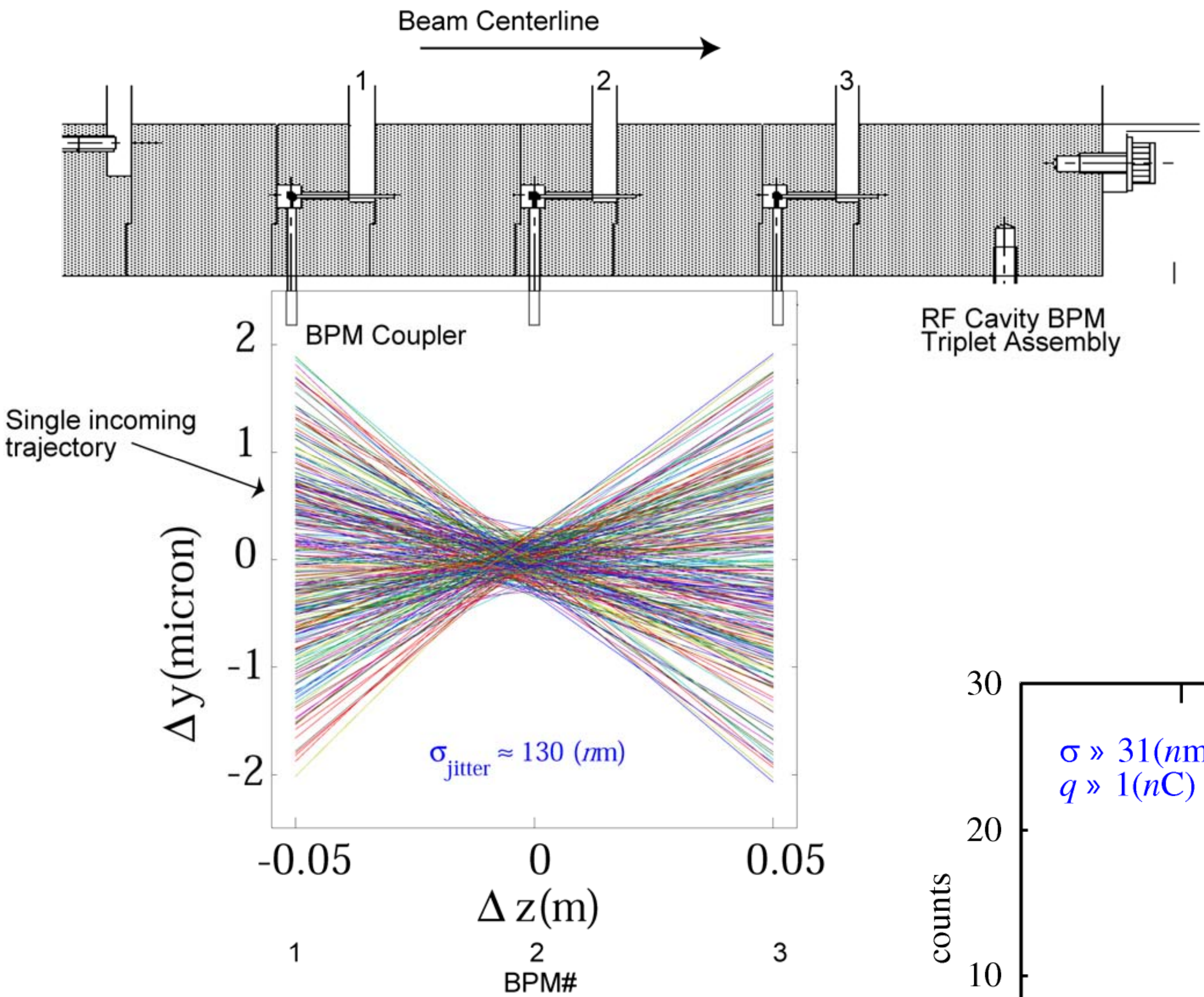
TM_{11} Selective-coupling Scheme

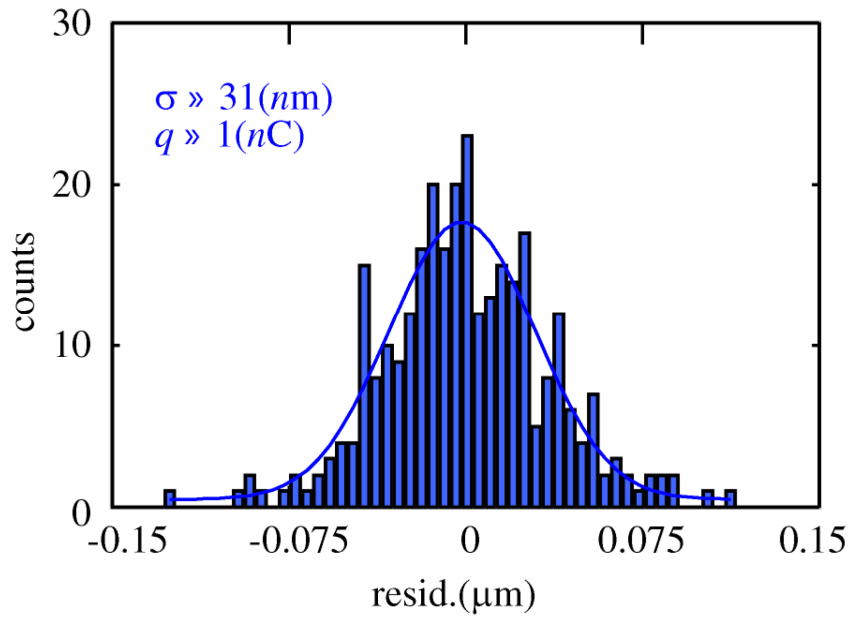




Slot mode
cavity BPM

FFTB IP C-band cavity BPM triplet – this is the way to test BPM performance …

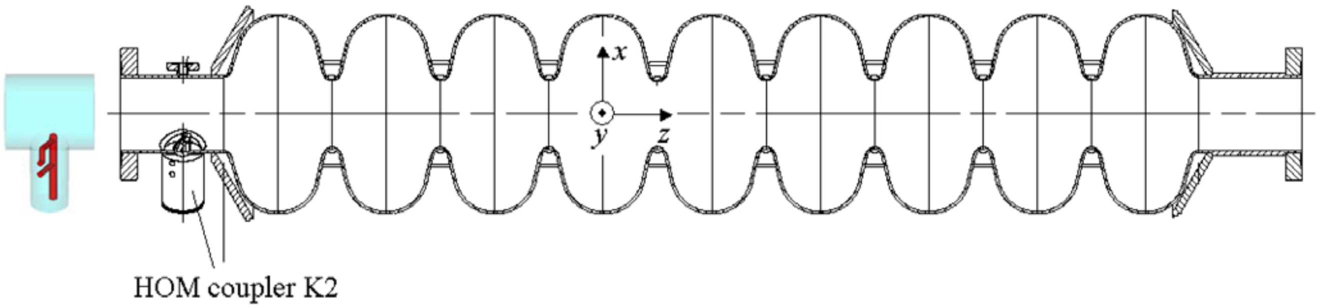


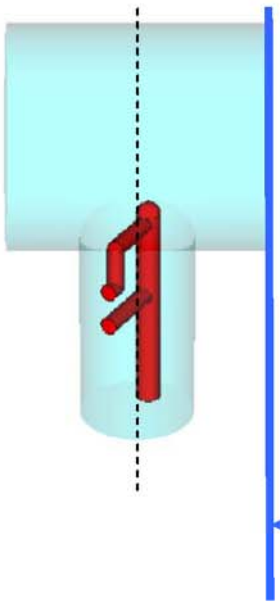


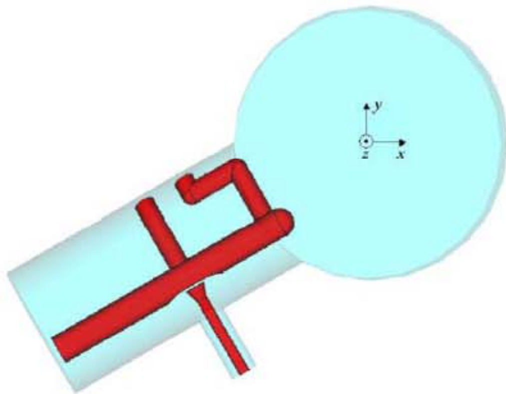
Superconducting RF cavity Higher Order (read dipole) Modes: 'HOM's

- A superconducting cavity also provides position signals
- The 9 cell 'pill-box' accelerating structure has a 'cylindrical' harmonic set of electromagnetic fields
  - a series of 9 eigen-mode bands
  - 'shock excitation' by strong 'delta function' electron bunch excites them all with varying strength
- Some can be coupled out with field probes
  - Careful not to extract the *extremely strong* accelerating field
- The beam can be used to probe the *assembly* of the cryomodule

perfect TTF cavity + upstream HOM coupler

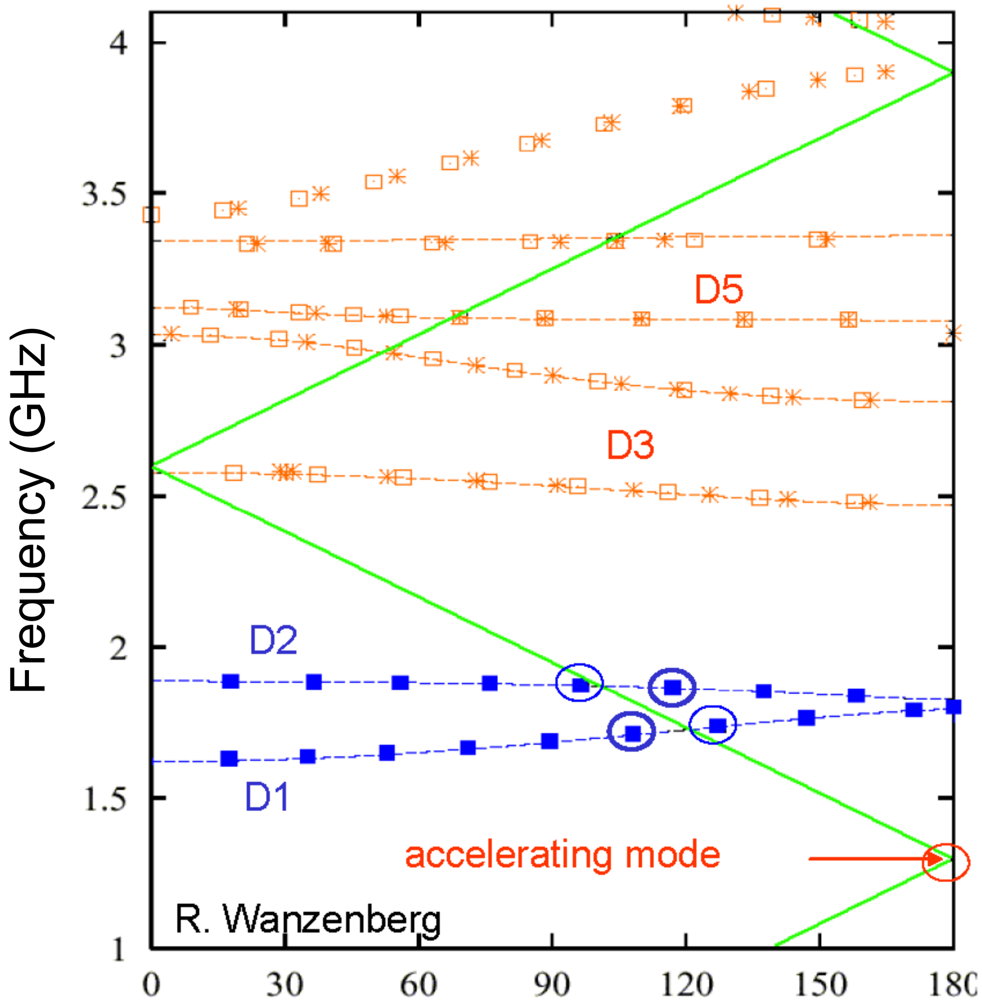






stimulation of dipole mode with horizontal polarization

TTF 9-cell cavity HOMs

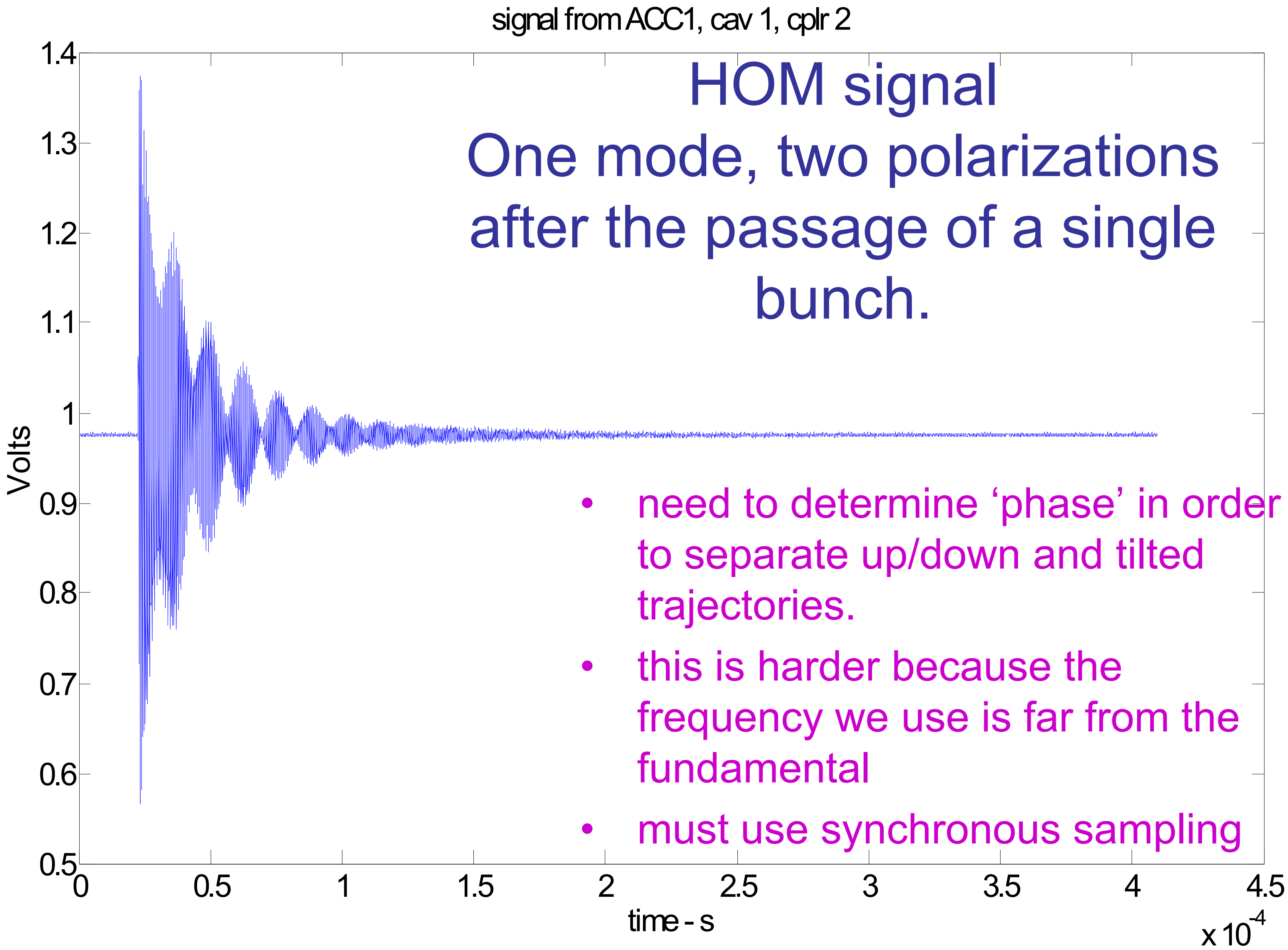


Modes Below cutoff

⇒ no propagation

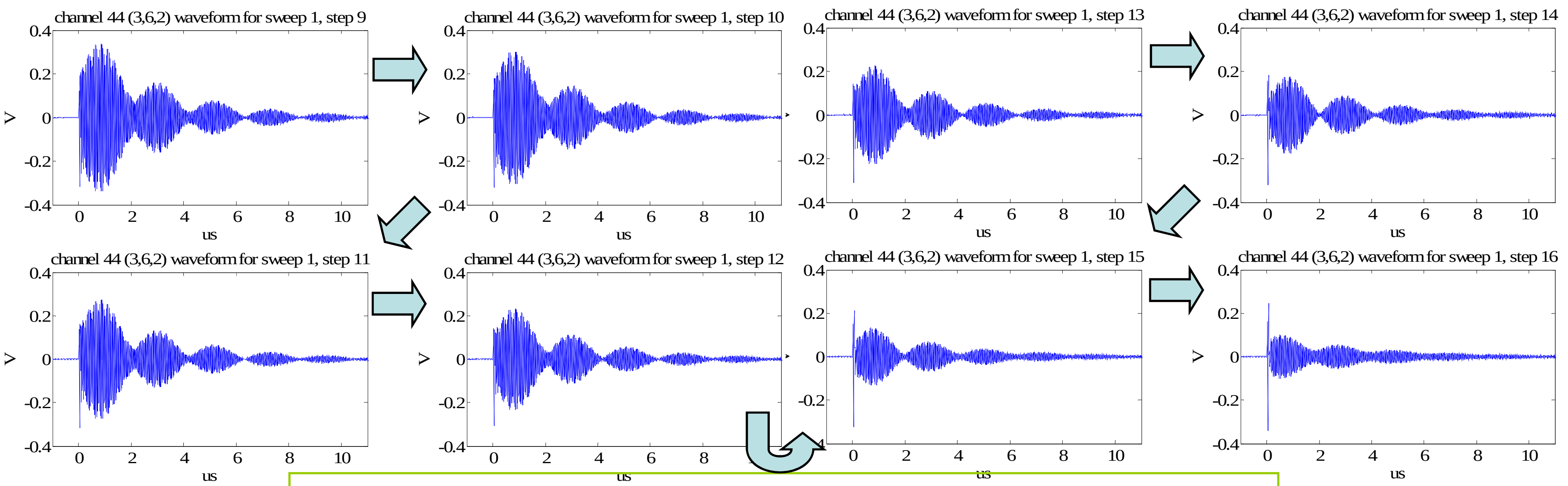
⇒ R/Q easy to compute in one cavity.

	Frequency [GHz]	R/Q [Ω/cm2]
TE111_6	1.705	11.1
TE111_7	1.730	15.6
TM110_4	1.865	6.4
TM110_5	1.875	9.0

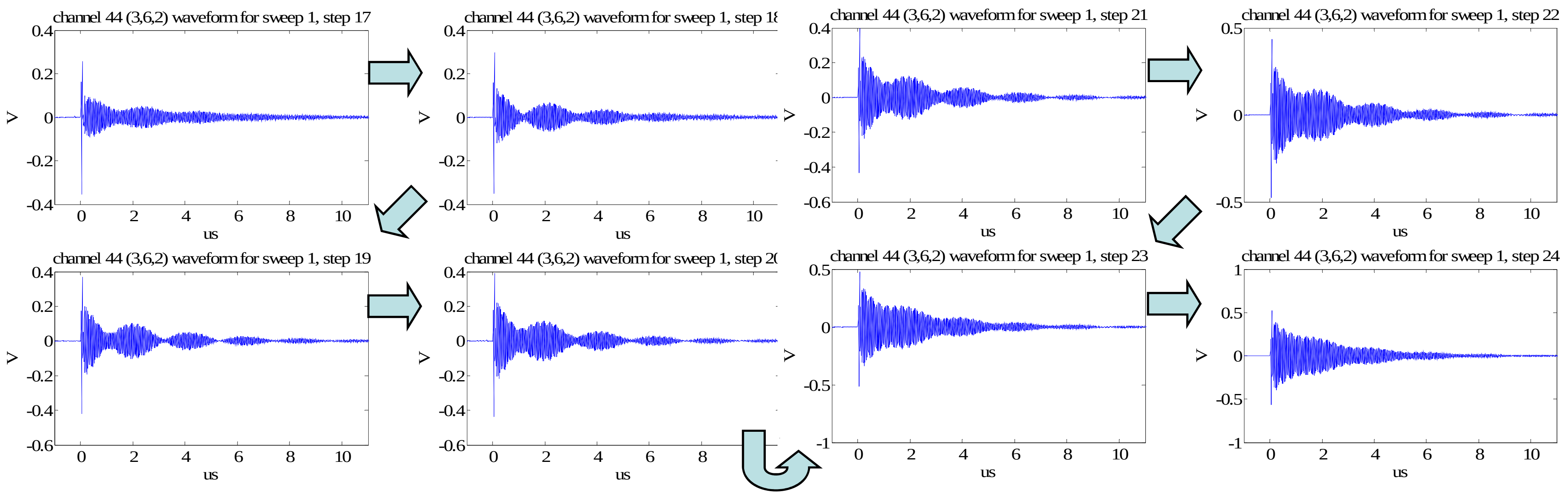


HOM signal
One mode, two polarizations after the passage of a single bunch.

- need to determine ‘phase’ in order to separate up/down and tilted trajectories.
- this is harder because the frequency we use is far from the fundamental
- must use synchronous sampling

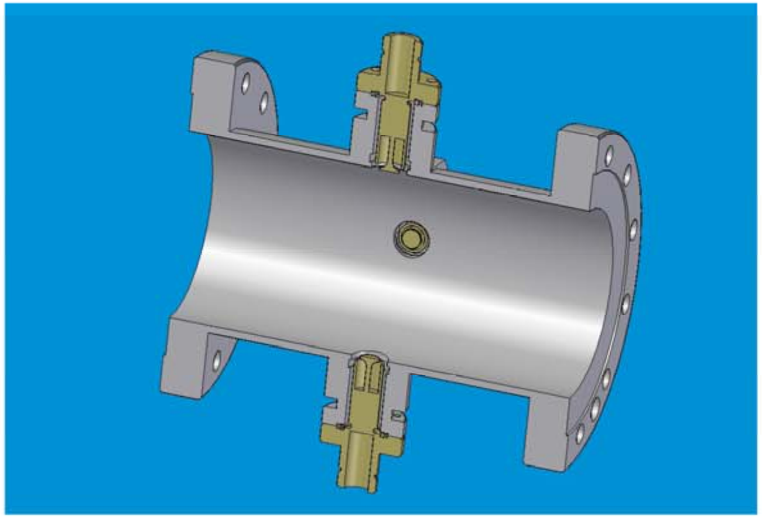


Sequence of HOM signals vs trajectory…



Cold BPM: ButtonType

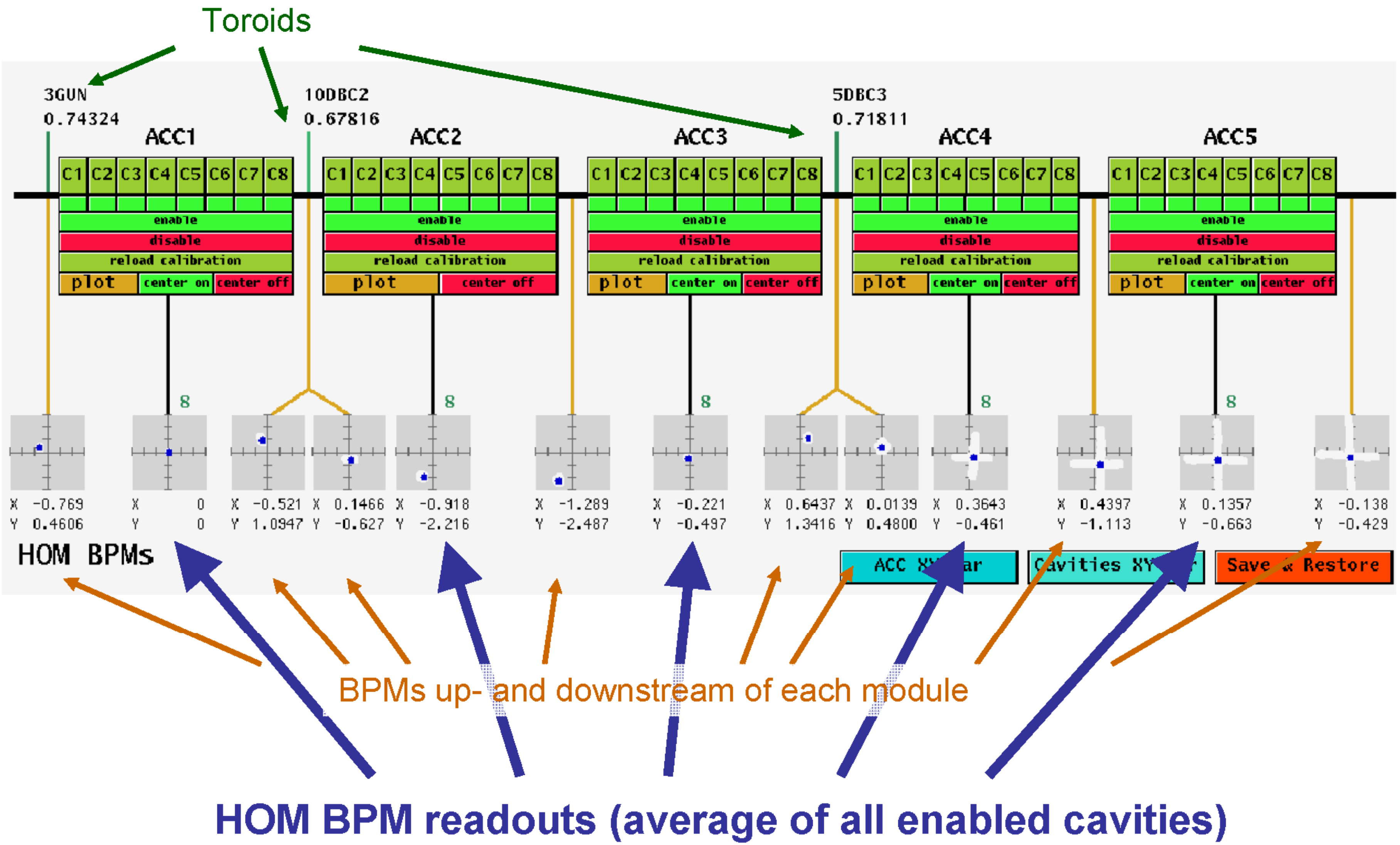
- Main parameters
  - charge: 0.1 – 1 nC
  - bunch spacing: ≥ 200 ns
  - rep. rate: ≤ 50 Hz
  - pulse length: ≤ 650 μm
  - resolution: < 50 μm
  - position range: ± 20 mm
  - coupling: < 1 %
  - interbunch interf.: < 1 %
  - drift max.: < 10 μm/month



- button diameter: 16 mm
- diameter: 78 mm
- length: 170 mm

- More info
  - "Update on the Cold BPM"
    - presentation of Dirk Noelle at the XFEL meeting on March 21, 2007: http://xfel.desy.de/projectgroup/meetings/e811
  - XFEL-Wiki
    - http://ferrari10/mediawiki/index.php/ColdBPM_EOI

HOM-BPMs at FLASH: Status



HOM-BPMs at FLASH: Status (2)

- Calibration
  - scan: ~30min for all modules
  - based on SVD
  - calibration procedure almost automatic

- Resolution
  - single bunch: 2-10 μm rms measured so far
  - potential to improve by changes in the LO oscillator

- Multi-bunch
  - capability demonstrated, with worse resolution

Profile monitors

- Second order: how to measure the size of the beam, tilts, correlations (banana) etc?
- This cannot (?) be done using internal wall currents.
- Must use a *probe* or interaction between the beam and *material/magnetic* field.
- Scanners/samplers vs Imagers
- a kind of ‘luminosity’ estimate
- ILC linac beam: 10 x 1 x 150
  - think of a flat noodle: 5 x 0.5 x 75 mm
- ILC damping ring beam 200 x 30 x 6000

- Bunch length / temporal structure is much, much, harder than transverse…
  - Microns & nanometers are the frontier & innovation is needed…

ILC Laserwires

Laserwires			
	IP	Laser	Detector
DR	3	3	3
RTML	22	4	6
Linac	20	6	20
BDS	18	6	6
	63	19	35

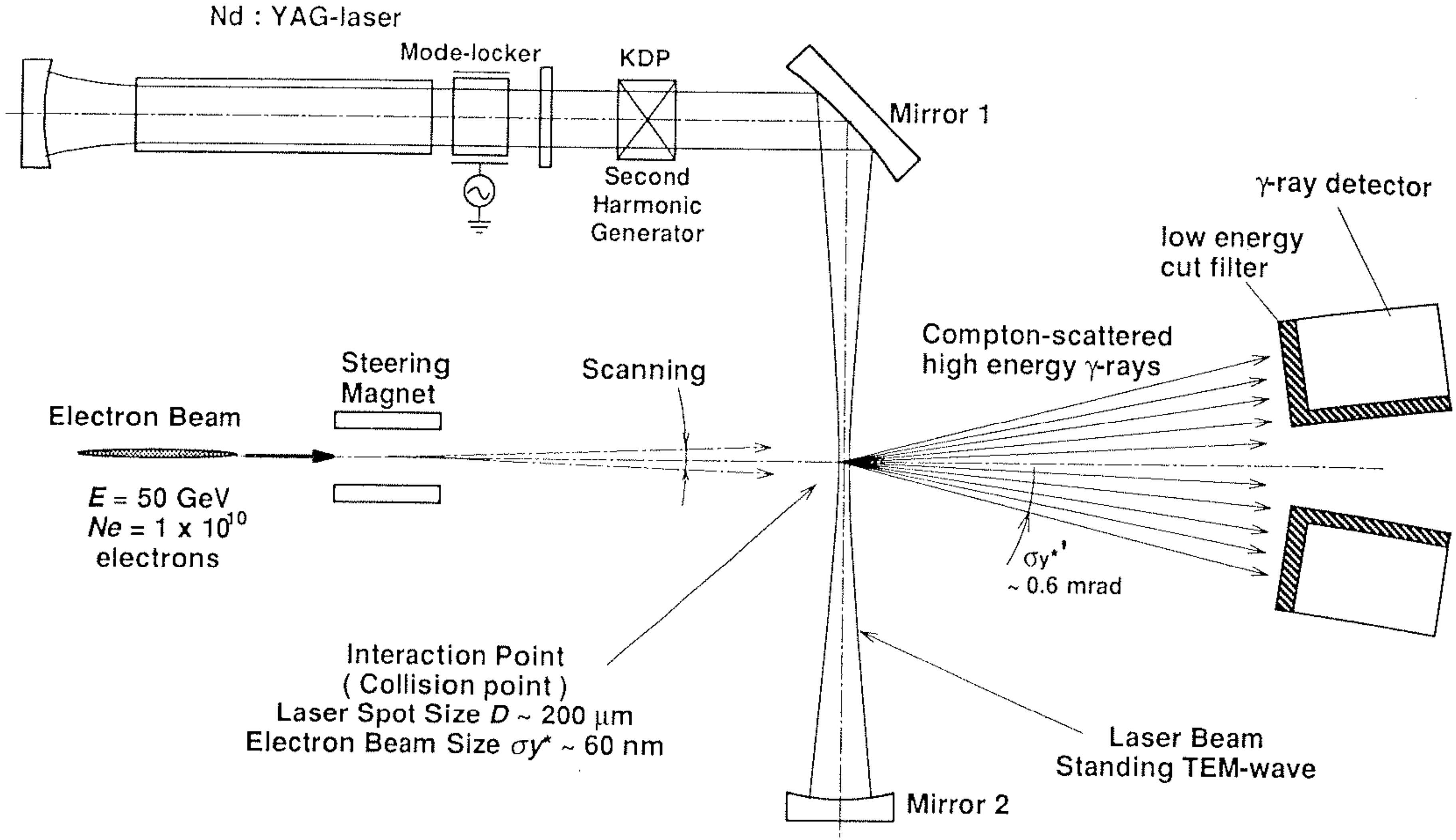
Laserwire basics:

1. Laser (one can feed many IP's)
2. Distribution
3. Deflector (scanner)
4. IP (multi-plane)
5. e/γ Separation
6. Detector

- High power light can fracture vacuum window
  - Likely a 'crack' not really a rupture
  - Must have a protection system near SCRF; technically feasible
- Optical power can increase 'tunnel radiation'
  - Like a wire, have to find the balance between signal and generated radiation
- Hard to integrate into cold system;
  - would need strong testing program to actually make it 'cold'

- No intrinsic MPS issues
- Ultra-fast scanning possible

Laserwire components



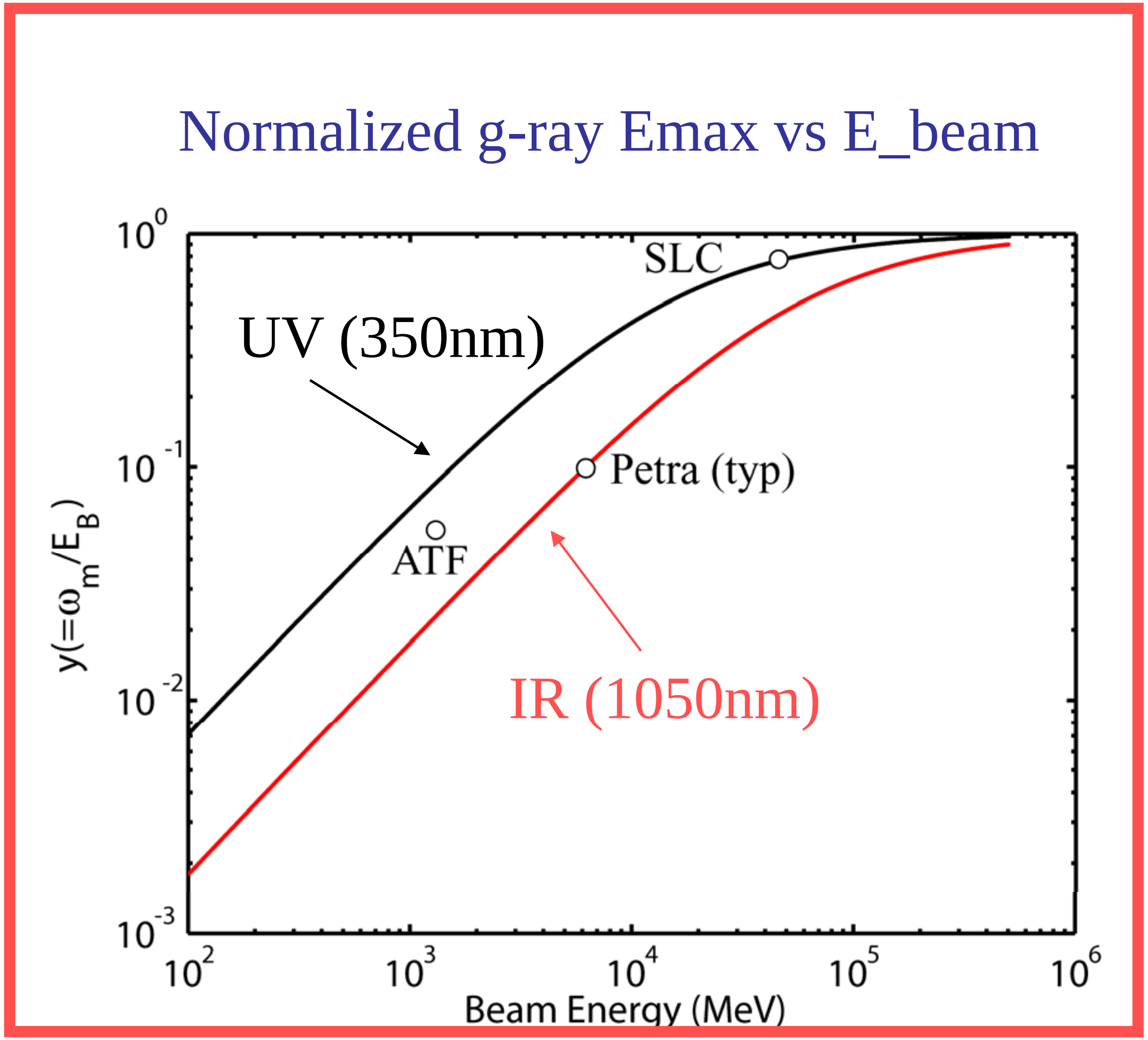
Compton scattering γ- ray Energy 'endpoint' for IR and UV lasers

Compton scattered γ-rays are much easier to detect at high energies. Degraded electrons also pushed cleanly outside machine E acceptance for E_beam>~ few GeV.

$$h\nu_{\max} = \frac{2E\varepsilon_1}{1+\varepsilon_1}$$

$$\varepsilon_1 = \frac{\gamma h\nu_0}{m_0 c^2}$$

Ref. 8



Bunch Length Monitors

- Time scales are so short:
  - ILC ~ 200um or 600 femtoseconds – ($c/2\pi\lambda$ ~ 0.24THz)
  - FEL ~ 10 um or 30 femtoseconds – (~ 5THz)
  - (too fast for most mixers)
- Use a strong RF deflection – time dependent sideways kick →
  - Kick the head of the beam one way & the tail the other
- Looks just like a normal warm RF structure – except slightly larger
  - Can also be done with cold RF
- We sense these dipole fields in the TESLA cavity – we drive them *hard* here…

Summary of bunch length monitors

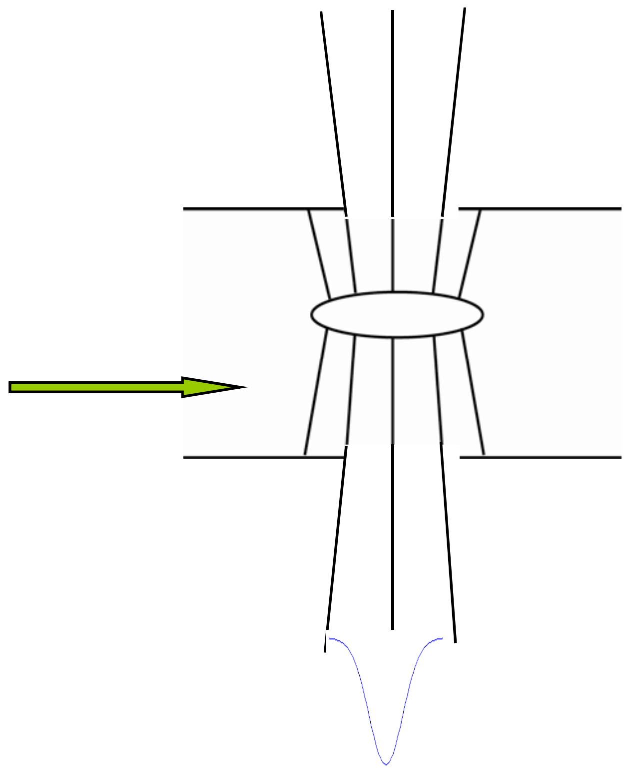
- Free electron lasers require very high peak current – this has pushed development of bunch length monitors

- deflecting structures
  - warm or cold
  - single bunch (warm) or full train (crab: cold)
  - require an imager
- infrared / mm wave detectors
  - diffraction radiation
  - coherent synchrotron radiation
  - simple ceramic gap
- electro-optic
  - use of non-linear optical materials
  - the material optical properties depend on the field of the beam; probed by a laser.

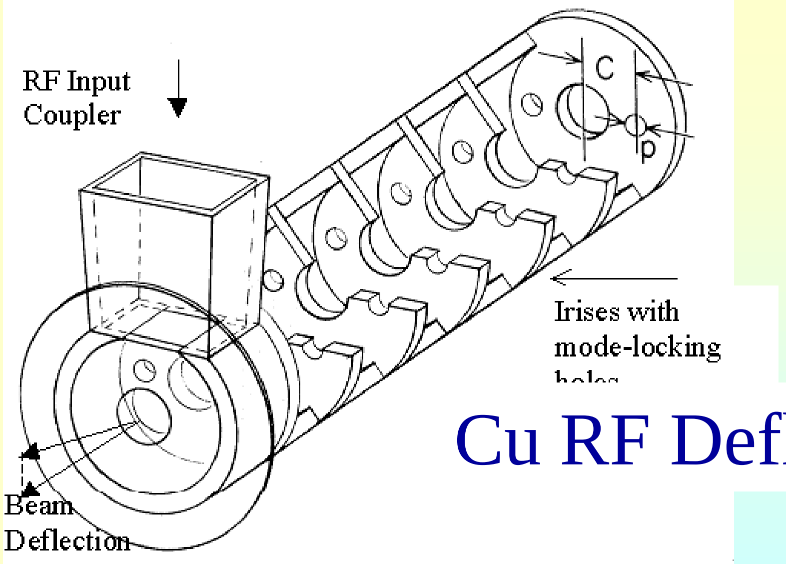
Gap monitor

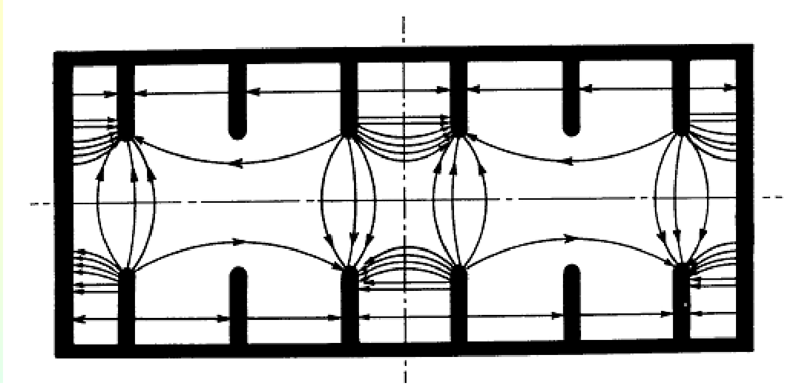
- simple ceramic gap in the beamline vacuum enclosure:

- detect the emitted field with a fast diode
  - frequencies ω~ sig_z
  - 200 um ~ 250 GHz (ILC)
- the diode has a bandwidth, several are needed to cover a reasonable range
- inexpensive, broad band, uncalibrated system

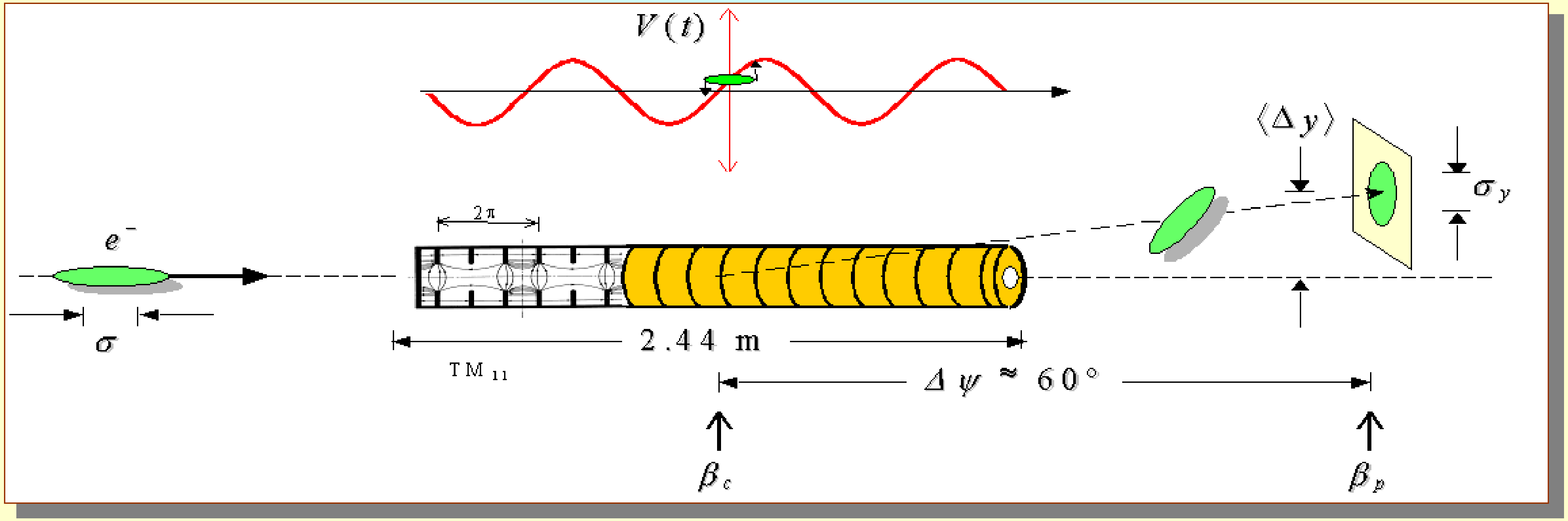


Cu RF Deflecting Structure and Profile Mon.

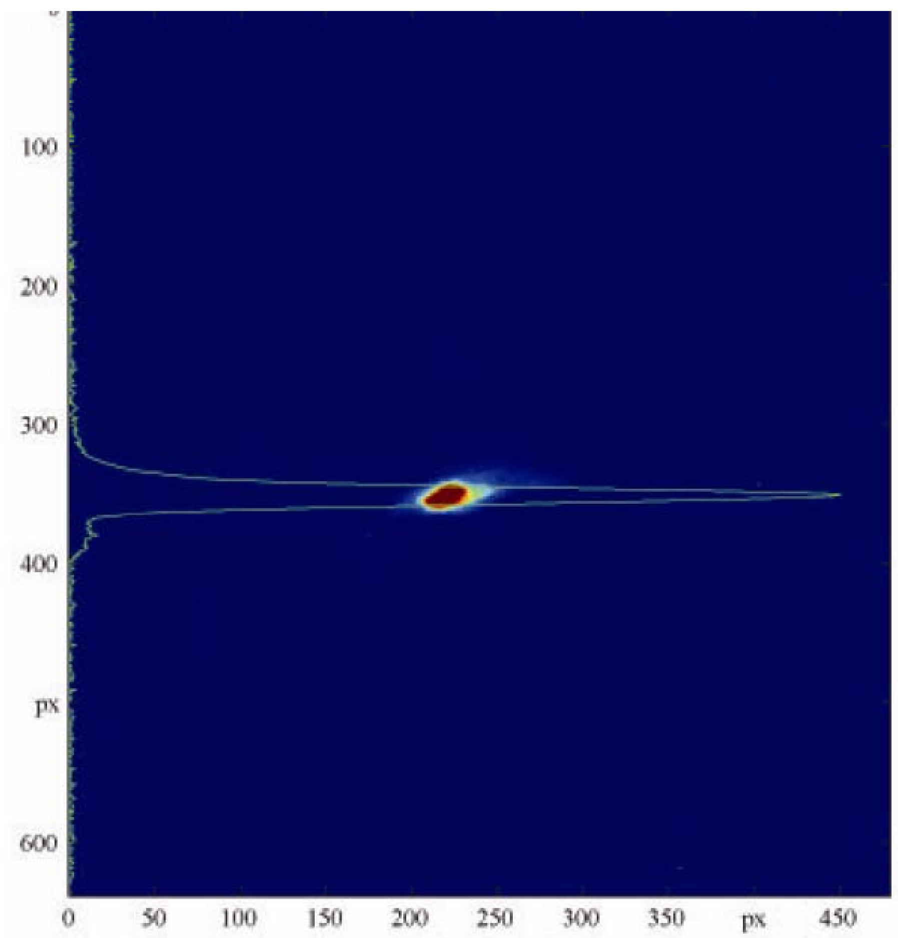


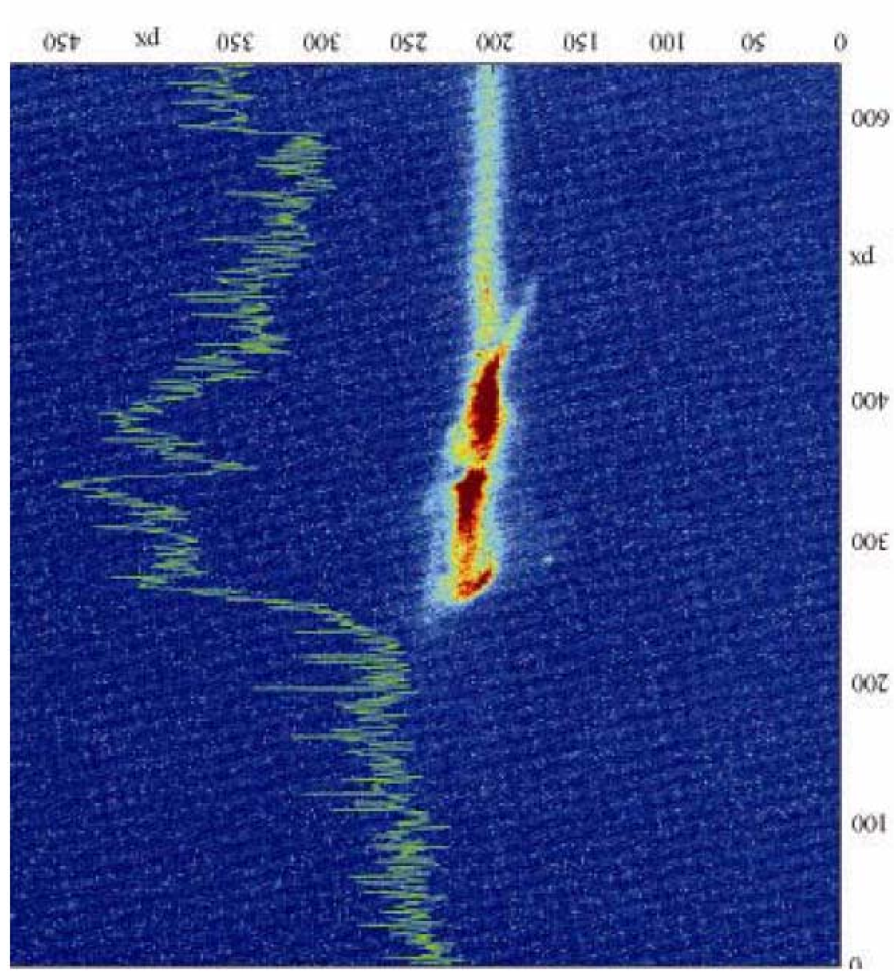


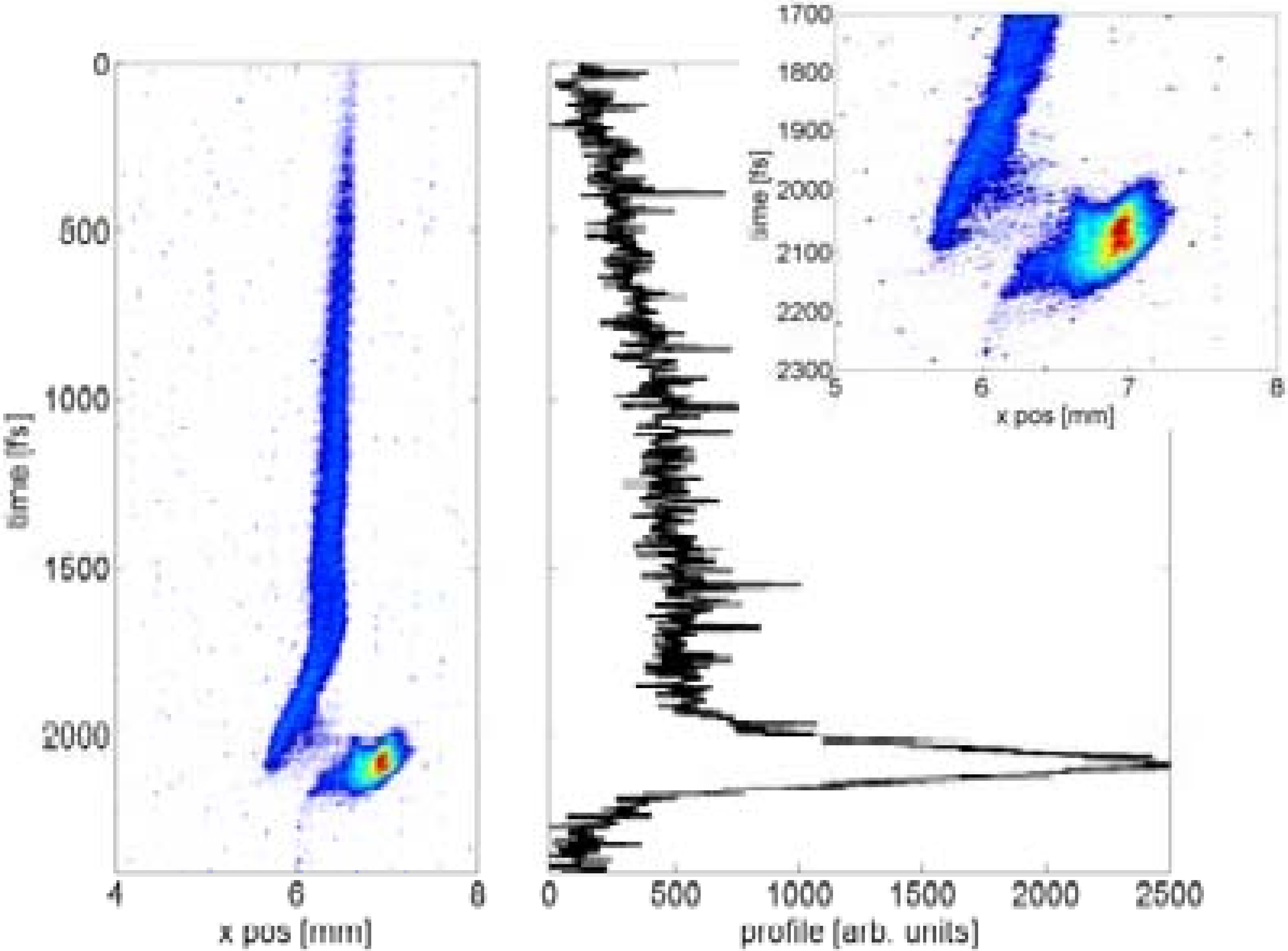
$$\text{bunch lenght}, \sigma_z \approx \frac{\lambda_{rf}}{2\pi}\frac{E_s}{|eV_0 \sin\Delta\psi \cos\varphi|}\sqrt{\frac{\left(\sigma_y^2-\sigma_{y0}^2\right)}{\beta_d\beta_s}}$$



Deflector on/off



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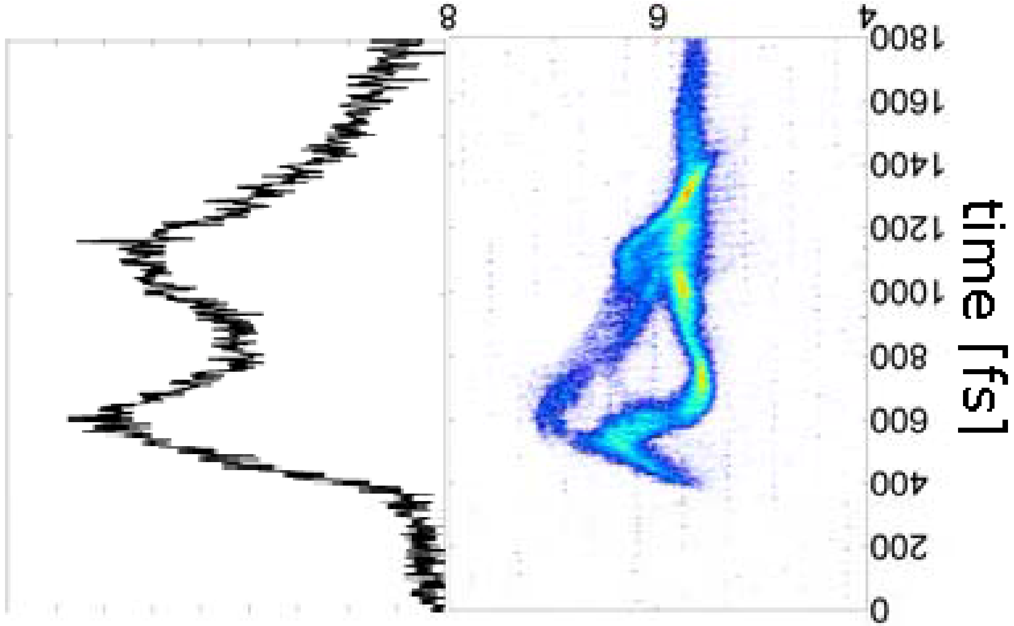

Deflector Images from ‘TTF – FLASH’