Beam Instrumentation

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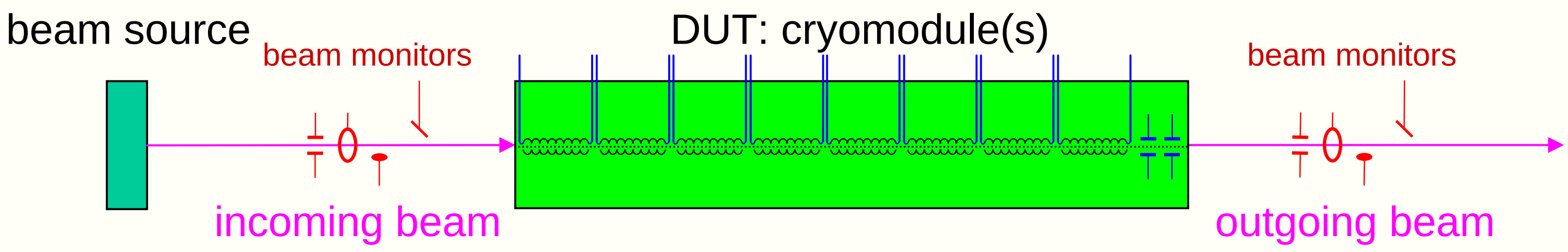
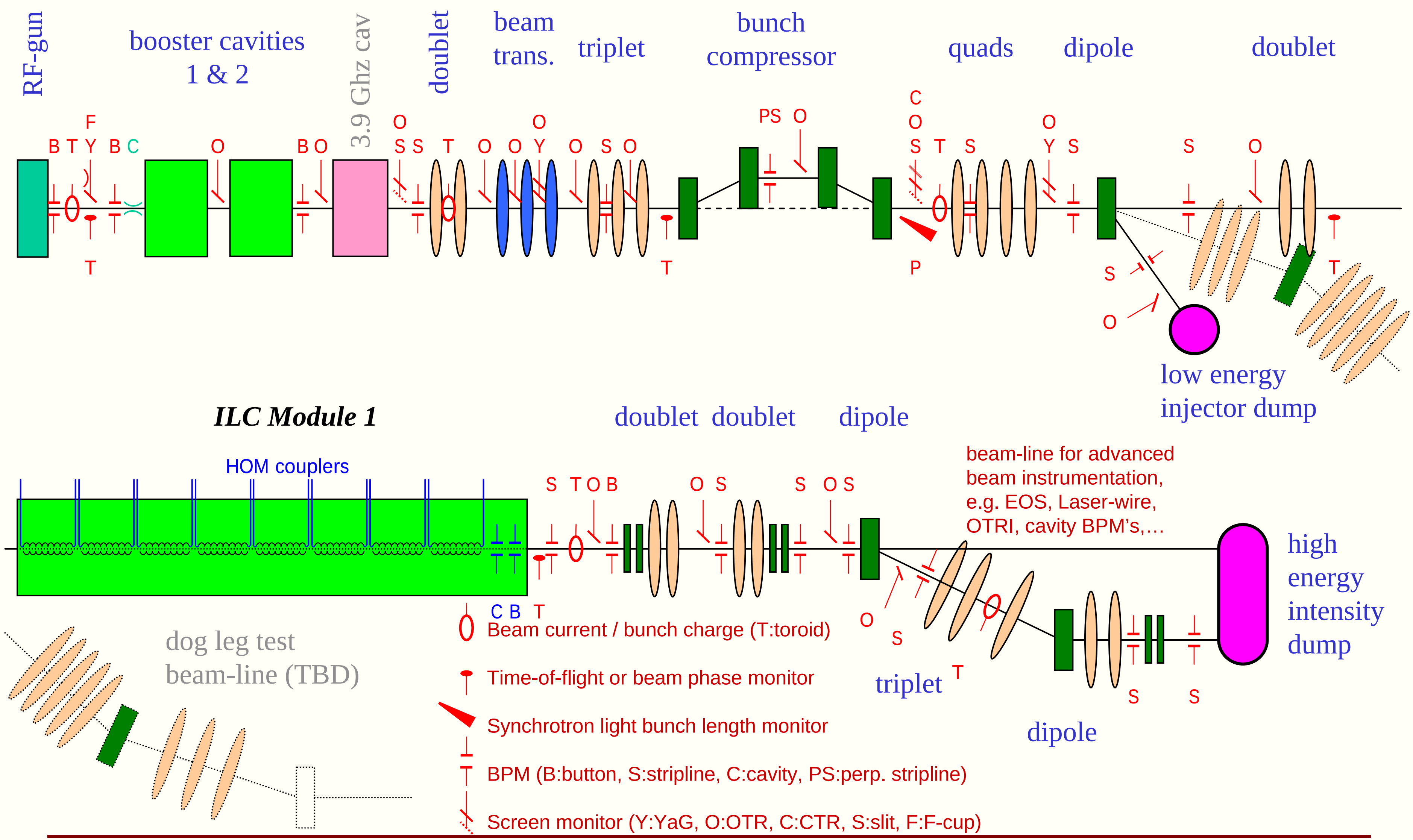
Motivation



- **Characterization of the SCRF cryomodule(s) under realistic ILC-like beam conditions:**
  - **Using the beam as a "test instrument".**
  - **Beam instrumentation is used to monitor and compare upstream and downstream beam conditions.**
  - **Additional beam monitoring uses HOM-coupler and cold-BPM signals of the cryomodule itself.**
- **Beam monitors are used to characterize the beam, e.g. orbit, bunch charge, emittance, bunch length, energy, jitter, phase, etc., in order to understand sources of RF-noise, cavity misalignment, phase mismatch, and other imperfections.**
- **The development of a cold cavity-BPM, which is part of the cryomodule, is essential for the low-emittance beam transport.**

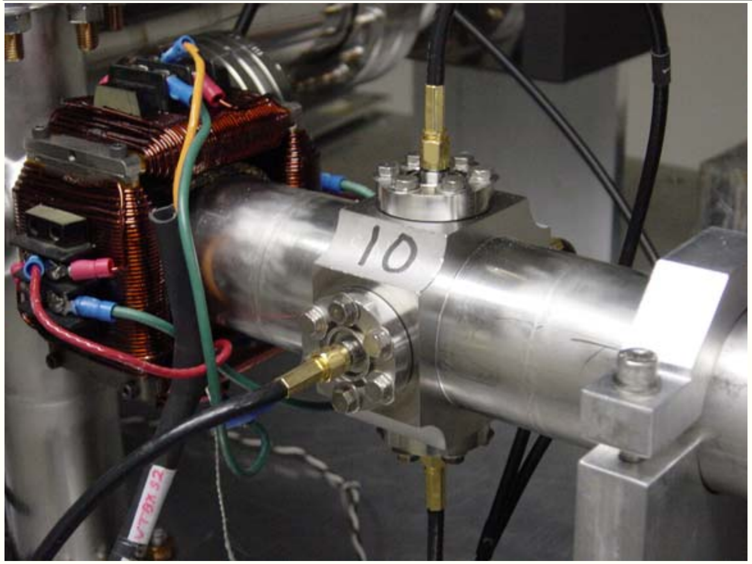
NML Beam Instrumentation



NML Beam Instrumentation (cont.)

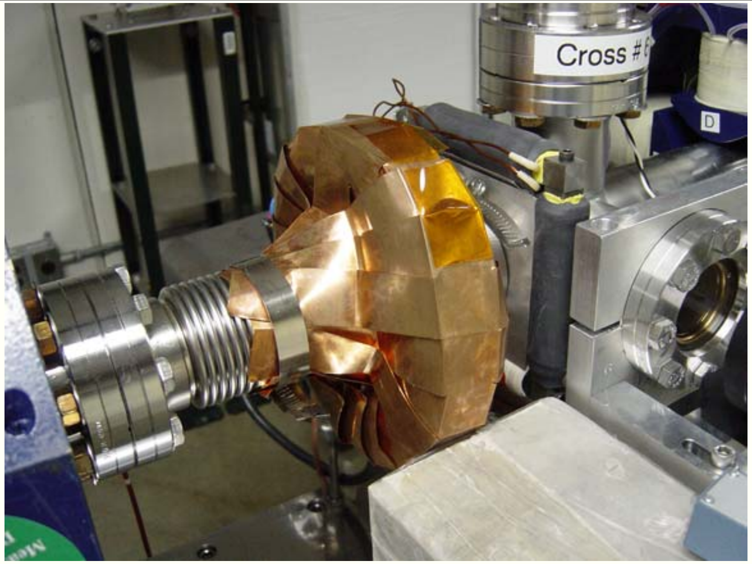
- **Preliminary list of required beam instrumentation:**
  - 5x toroids for bunch charge measurements.
  - ~ 20x BPM's for beam position / orbit measurements, also for beam (bunch) energy, optics and many other topics, including:
    - A cold cavity-BPM for the cryomodule (1 µm single bunch resolution)
    - A "perpendicular" stripline-BPM with EOM-based optical sampler read-out in the flat chamber of the bunch compressor (for bunch energy and horizontal position detection)
  - 4x time-of-flight (TOF) or phase monitors.
  - ~ 20x screen monitors for beam emittance, transverse particle distribution, dark current detection, etc. (OTR, YaG, slits,…).
  - Several beam monitors for bunch-length measurements (interferometer-based, RF-based, EOS-based,…).
  - HOM-coupler signal processing system.
  - A BLM-based machine protection system (MPS).
  - An ATCA-based read-out system for BPM's and toroids.
  - An EOS-based bunch-length monitor, and some other advanced beam monitors.
- **Most beam monitors need to time resolve single bunch information (< 300 ns measurement / integration time).**
- **Some beam monitor can be reused from the NICADD A0-Photoinjector project, but most needs to be designed and build.**

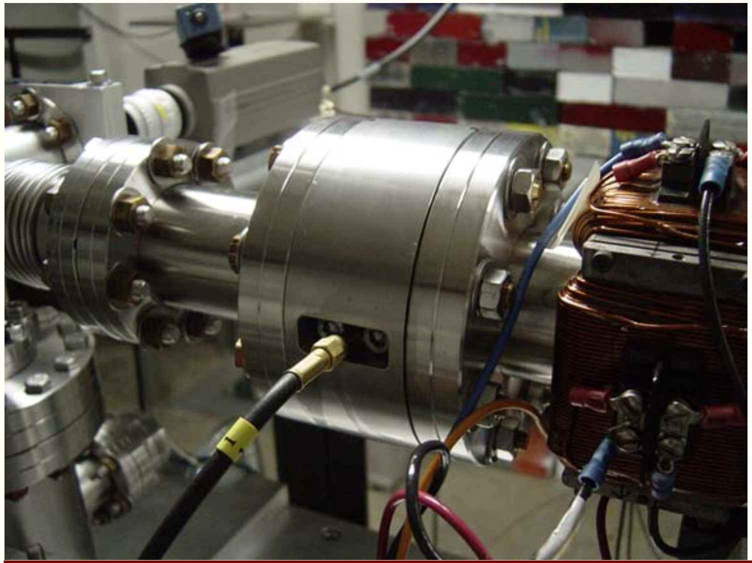
A0-Photoinjector Instrumentation



Button BPM ⇦

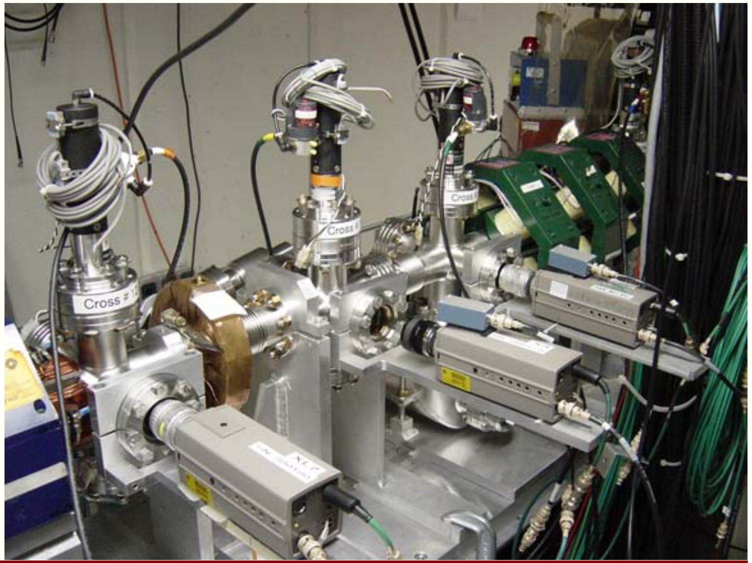
Toroid ⇨





Beam Phase Monitor ⇦

Screen Monitors ⇨



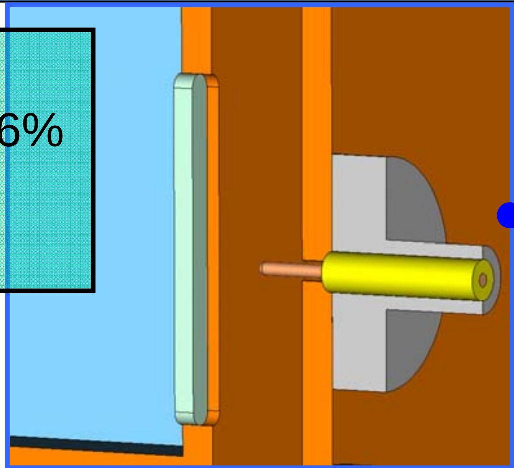
Example 1: Cold Cavity-BPM

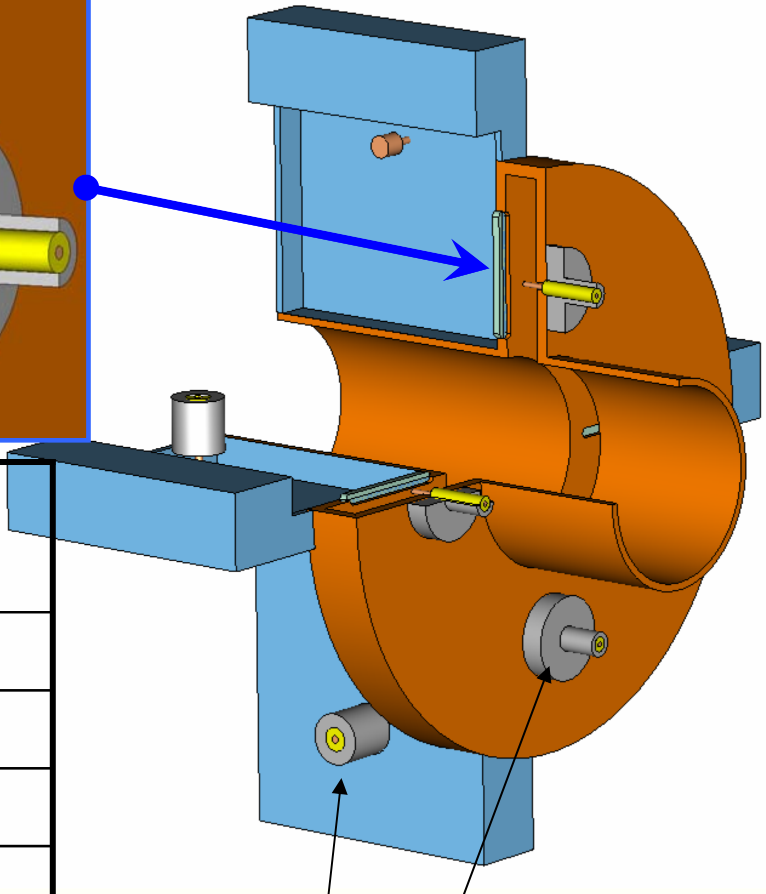
- **Requirements**
  - Real estate: ~ 170 mm length, 78 mm aperture.
  - Cryogenic environment (2…10 K).
  - Cleanroom class 100 certification.
  - UHV certification.
  - < 1 µm single bunch resolution (< 300 ns measurement time).
  - < 200 µm error between electrical BPM center and magnetic center of the quad.
- **Wavguide-loaded, "CM-free" cavity-BPM:**
  - Waveguide-loaded pillbox with slot coupling.
  - Dimensioning for f_{010} and f_{110} symmetric to f_{RF}, f_{RF} = 1.3 GHz, $f_{010} \approx$ 1.1 GHz, $f_{110} \approx$ 1.5 GHz.
  - Dipole- and monopole ports, no reference cavity for intensity signal normalization and signal phase (sign).
  - $Q_{load} \approx$ 600 (~ 10 % cross-talk at 300 ns bunch-to-bunch spacing).
  - Minimization of the X-Y cross-talk (dimple tuning).
  - Simple (cleanable) mechanics.

Cold Cavity-BPM: EM-Simulations

Fermilab

Window –
Ceramic brick of alumina 96%
♏ = 9.4
Size: 51x4x3 mm





Frequency, GHz, dipole **monopole**	**1.468** **1.125**
Loaded Q (both monopole and dipole)	**~ 600**
Beam pipe radius, mm	**39**
Cell radius, mm	**113**
Cell gap, mm	**15**
Waveguide, mm	**122x110x25**
Coupling slot, mm	**51x4x2**

N type receptacles,
50 Ohm,

Cold Cavity-BPM: Resolution Limit

$$V_{110}(x) = x \cdot \pi f_{110} \sqrt{Z_0 \left(\frac{1}{Q_\ell} - \frac{1}{Q_0} \right) \left(\frac{R_{sh}}{Q} \right)_{110}^{\delta x}} \frac{q}{\delta x}$$

$$V_{110}(x) = x \cdot 4.145 \cdot 10^3 \; V / nC$$

$$V_{110} \approx 4 \; mV / nC \; \mu m$$

with:

$$f_{110}(x) = 1.46 \, GHz$$

$$Z_0 = 50 \, \Omega$$

$$Q_\ell \approx 600$$

$$Q_0 \approx 2000$$

$$\left(\frac{R_{sh}}{Q} \right)_{110}^{\delta x = 1mm} = 14 \, \Omega$$

$$q = 1 \, nC$$

$$V_{ThermalNoise} = \sqrt{Z_0 \, k \, T \; BW} \approx 0.7 \; \mu V$$

with:

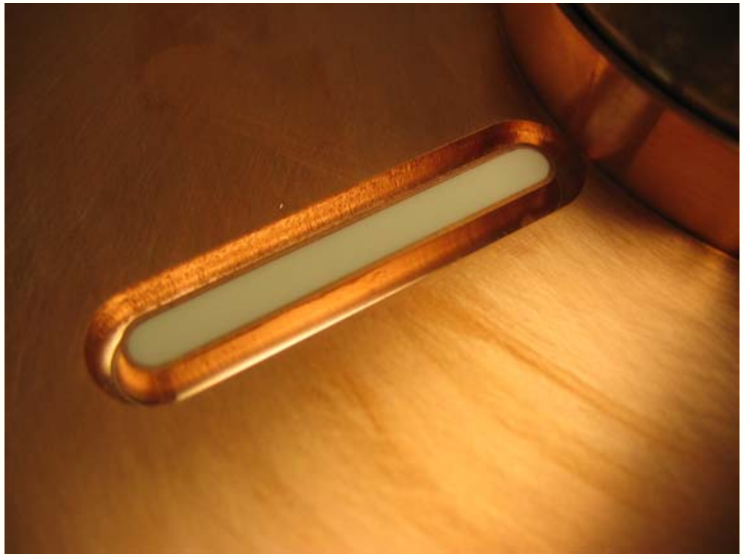
$$Z_0 = 50 \, \Omega$$

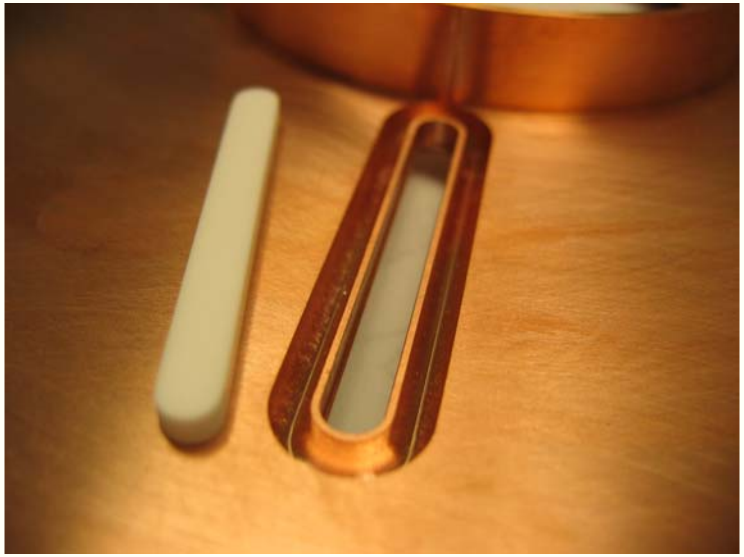
$$k = 1.38 \cdot 10^{-23} \; J / K$$

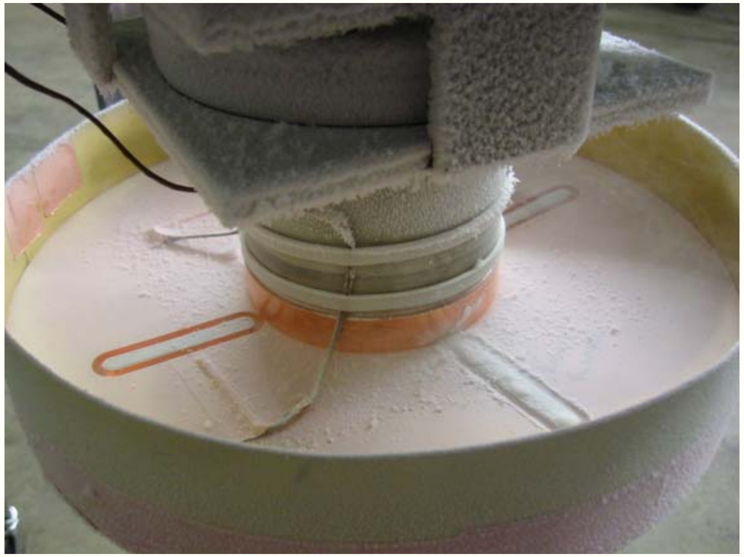
$$T \approx 300 \; K$$

$$BW = \frac{f_{110}}{Q_{\ell 110}} \approx 2.4 \; MHz$$

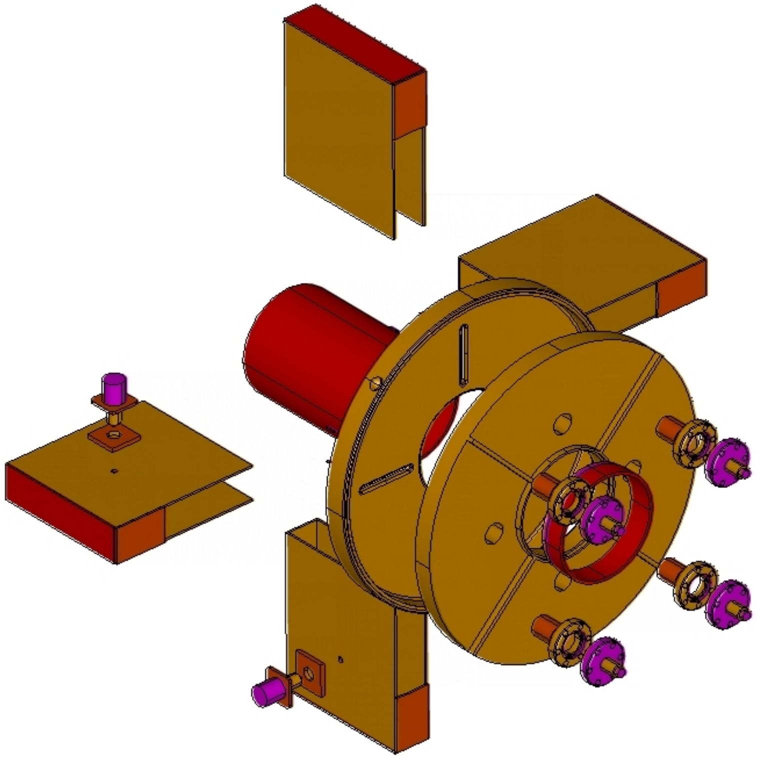
Cold Cavity-BPM: Brazing Tests

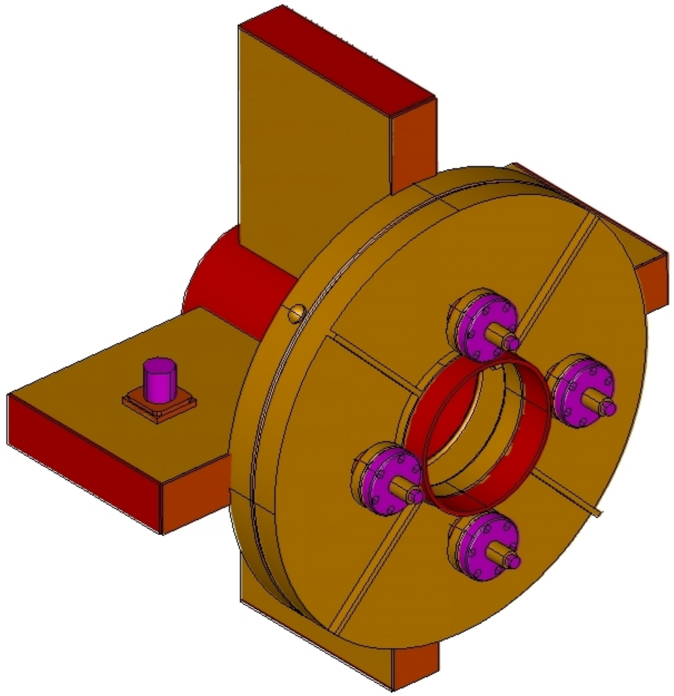




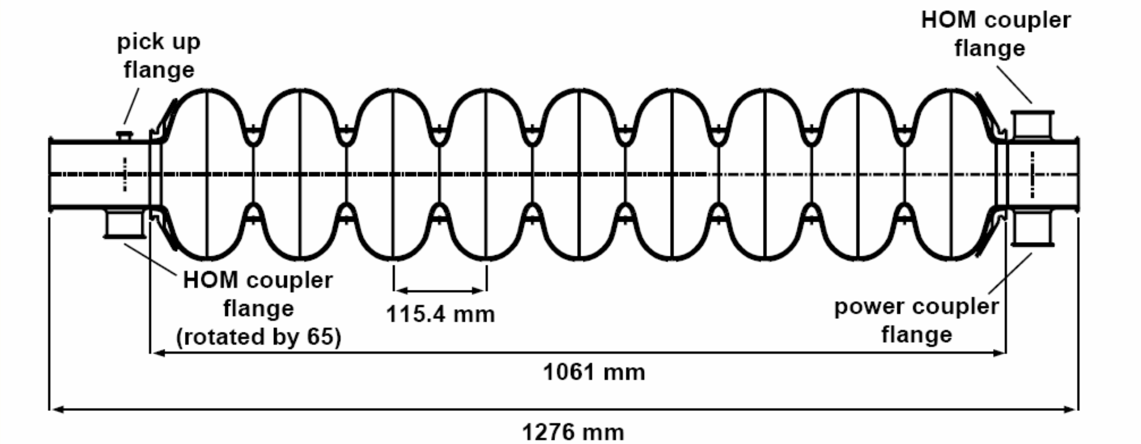


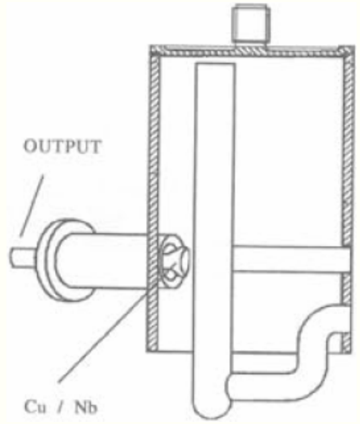
Cold Cavity-BPM Assembly





Example 2: HOM Coupler

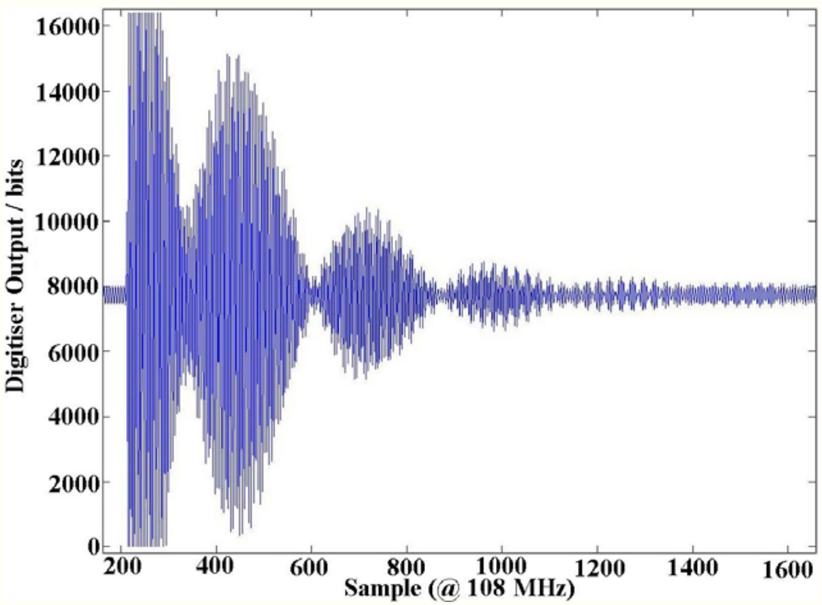


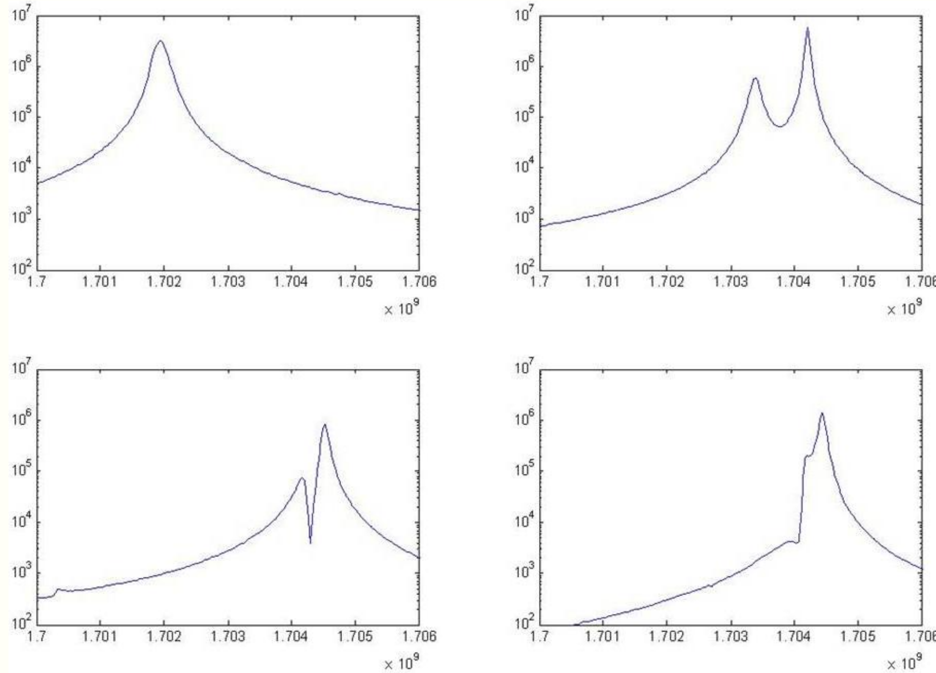


HOM coupler signals can be used for (narrowband):

- **Beam Position Monitoring**
  - **Dipole mode analysis of both polarizations.**
  - **Requires beam-based calibration data, to orthogonalize the polarization planes of the excited eigenmodes per SVD algorithm.**
- **Beam Phase Monitoring**
  - **Comparison of the leaking 1.3 GHz fundamental (TM_{010}) to the first monopole HOM (TM_{011}) on the same signal cable!**
  - **The method cannot resolve bunch-by-bunch phase information.**

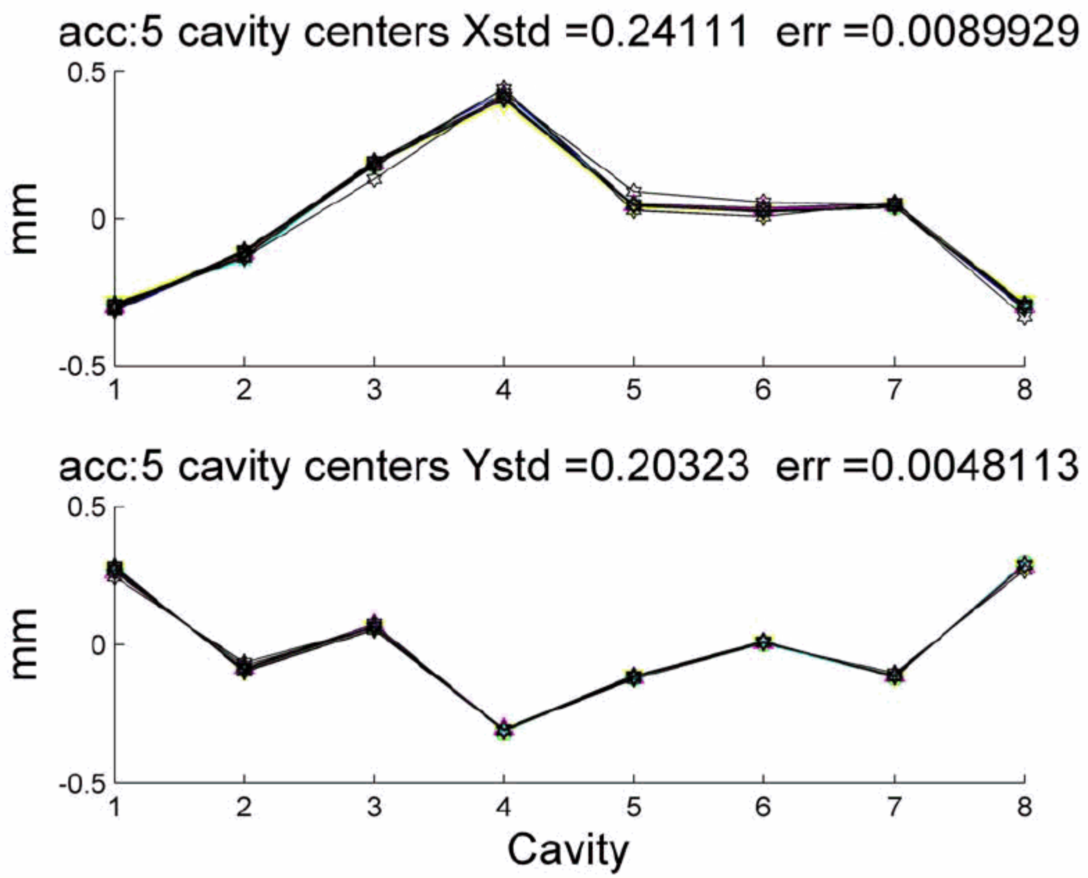
HOM Coupler: Signal Waveforms





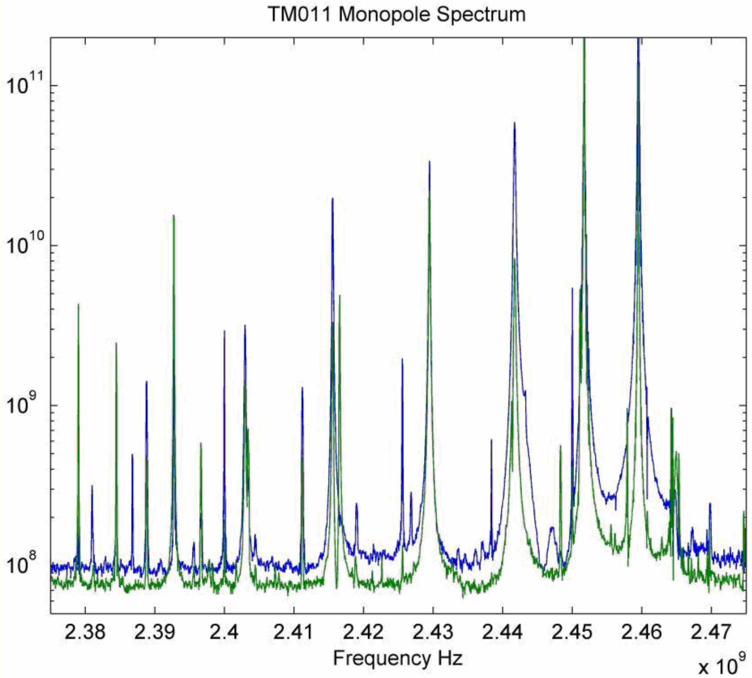
- HOM coupler waveforms of a dipole mode in time- and frequency domain.
- The polarization frequencies are not always well separated!
- The alignment of the polarization axes is due to cavity imperfections, coupler structures, etc. and may be even twisted.

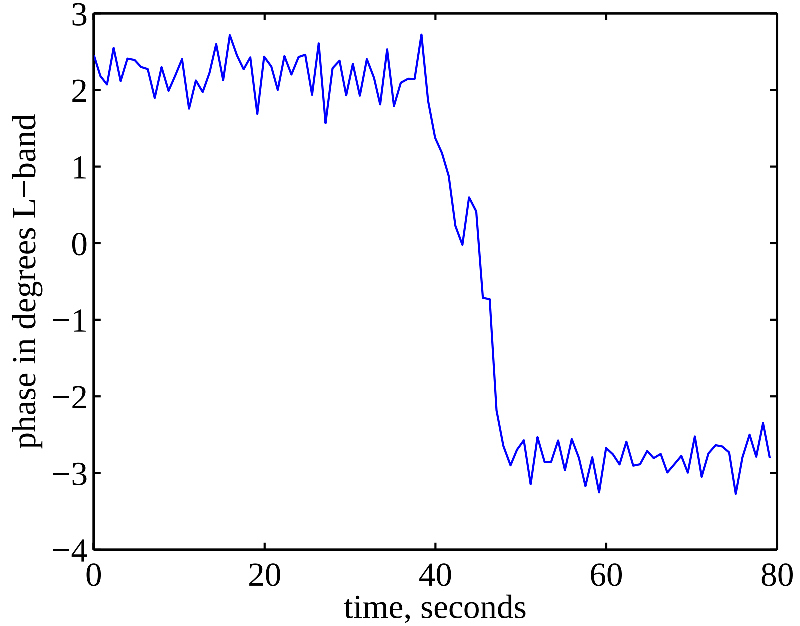
HOM Coupler: BPM



- **TTF results of ACC5 cavity alignment**
- **Narrowband read-out of the $TE_{111\text{-}6}$ mode**
- **Resolution: < 10 µm**

HOM Coupler: Phase Detection





Broadband HOM monopole measurements (TTF):

- **Broadband, oscilloscope-based (2.5 GHz) data acquisition.**
- **5 degree phase change set through the LLRF.**
- **Noise (~ 170 fs RMS) is equivalent to 0.08 degrees at 1.3 GHz.**

Collaborations

- Beam Instrumentation R&D traditionally includes strong collaboration efforts among laboratories and universities! Almost all instrumentation activities at NML will be based on collaborations.

- Improvements in the beam instrumentation and diagnostics go hand-in-hand with beam quality and stability.

- High quality, stable beam conditions at NML will generate new ideas, and open collaborations in other areas.

Cost Estimation

NML Beam Instrument	M&S (k$)	SWF (FTE)
Toroids	70	1.3
BPM's	315	3.5
TOF & Beam Phase (EOM-based)	120	2
Screen Monitors	125	1.5
HOM Signal Processing	70	1.5
BLM's	50	1
Read-out Electronics	180	1.5
Advanced Beam Monitor Dev., e.g. EOS	400	3
Tools (scope, software, RF equipment)	180	
Grand Total	**1510**	**15.3**

Cost Estimation (cont.)

- Beam monitors and instrumentation costs can be staged:
  - Start with basic monitors, i.e. toroids, BPM's, screens
  - Continue with more advanced beam monitors…
- Beam instrumentation always is under continuing development, more funds will be required in the long run!
- SCRF Instrumentation has to cover also other areas, e.g. test stands, HINS, protection systems, etc., therefore additional funds may be required!

Conclusions

- The beam instrumentation is used to test the performance of the SCRF accelerating structures, and related systems under realistic beam conditions.
- Precise, high resolution measurement methods will detect (also quantitatively) sources of imperfections, misalignments, errors, etc.
- A beam-based validation of the SCRF systems gives the final confidence and proof of quality and understanding of the entire project!

QUESTIONS