Cavity Beam Position Monitor (BPM) for future linear colliders such as CLIC.

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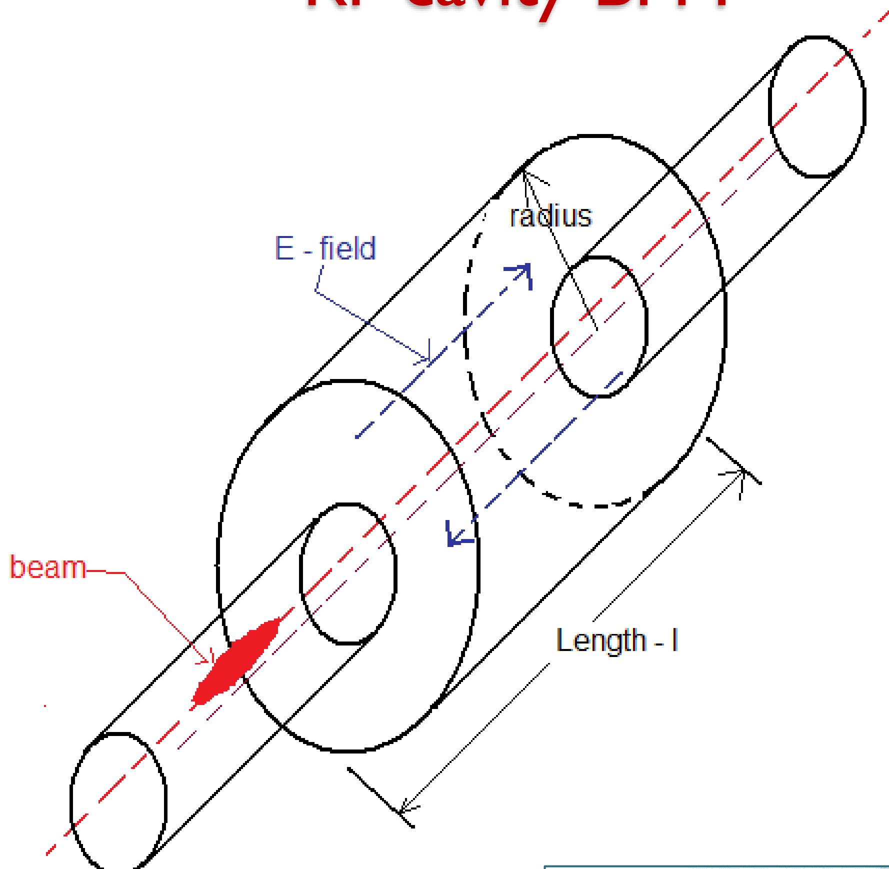
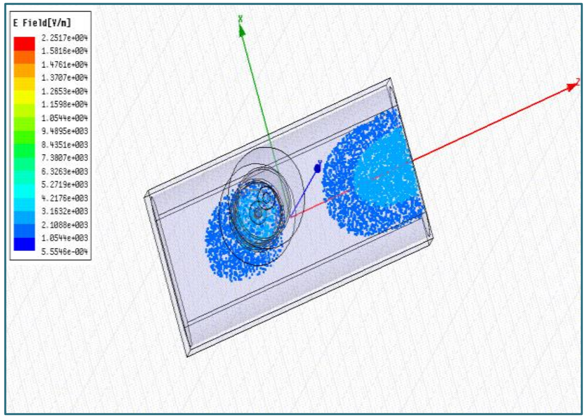
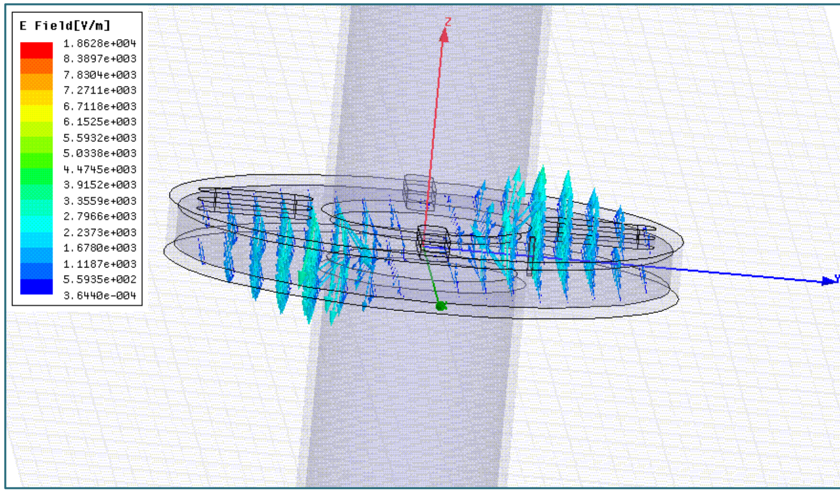
Outline

- Introduction to Cavity BPM system.
- Requirements for future linear collider, such as CLIC.
- Design and Electromagnetic simulation. (RHUL - NLS/DIAMOND)
- RF testing (RHUL - NLS/DIAMOND)
- Effect of temperature variation.
- Study of wake field in cavity BPM for CTF3
- BPM signal processing in single bunch mode and calibration. (RHUL-ATF)
- Signal overlaping from multi- bunches (RHUL-ATF).
- Conclusions and future work

RF cavity BPM







RF cavity BPM : Fundamental equations

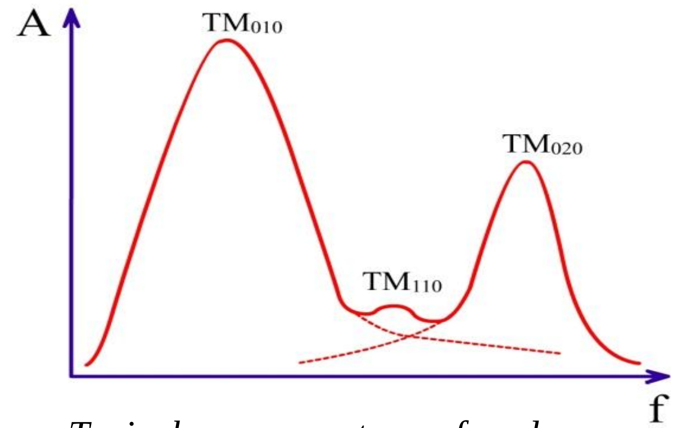
Transverse Resonance mode frequency:

$$\omega_{mn} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \left(\frac{j_{mn}}{R} \right)$$

Internal Quality factor: $Q_o = W / P_{loss}$

Loaded quality factor: $\frac{1}{Q_L} = \frac{1}{Q_o} + \frac{1}{Q_{ext}}$

Decay time constant: $\tau = Q_L / \omega$



Typical power spectrum of modes excited inside the resonance cavity.

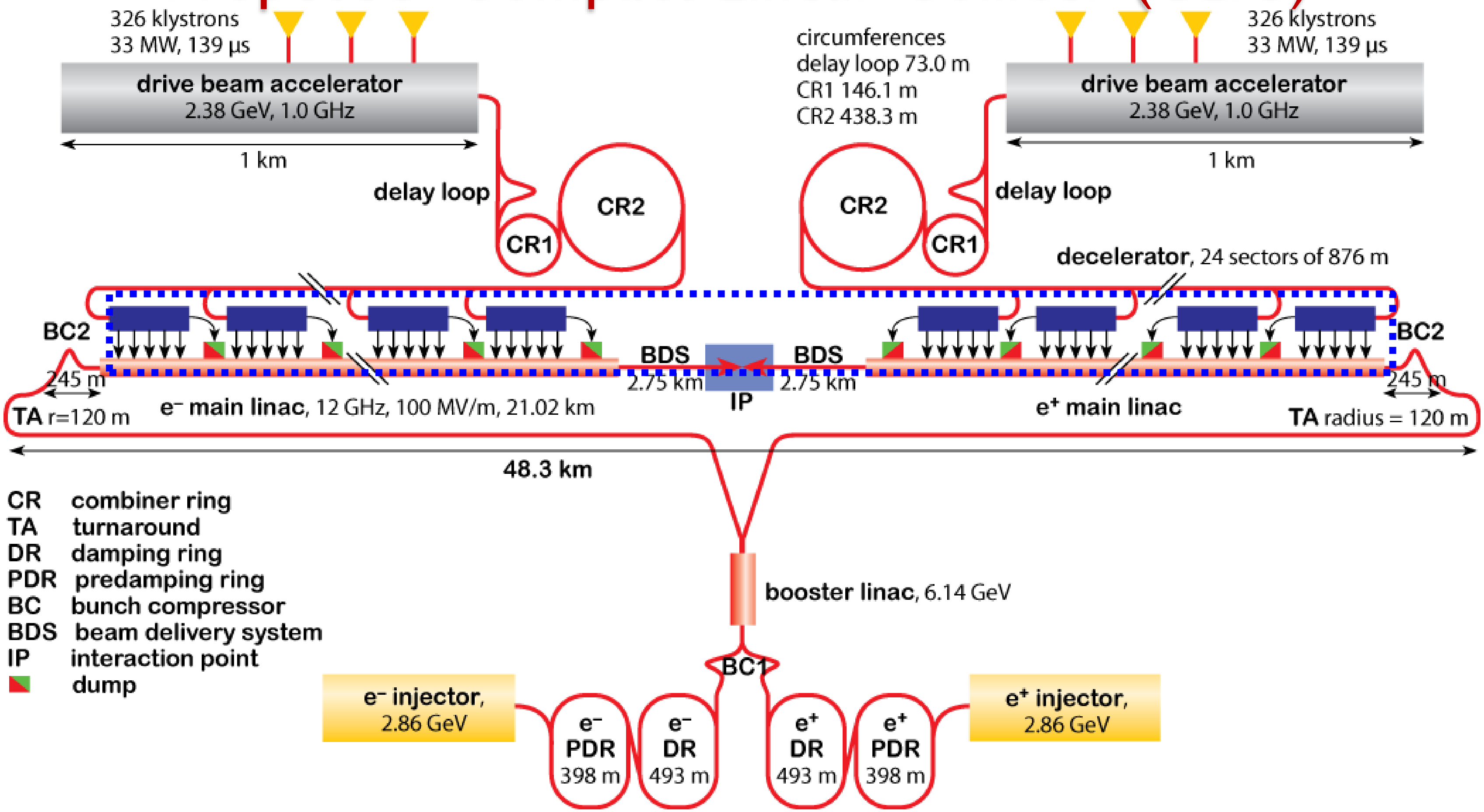
Normalized shunt impedance

$$\left(\frac{R}{Q} \right)_{11,x_0} = \frac{V_{11}^2}{\omega_{11} W_{11}} = \frac{(E_{x0} L)^2}{\omega_{11} \left(\frac{\varepsilon_0}{2} \oint_{Vcavity} |E|^2 dV \right)}$$

Voltage induced by position offset:

$$V_{1,out} = \frac{\omega_1}{2} \sqrt{\frac{Z}{Q_{1,ext}} \left(\frac{R}{Q} \right)_{1,0}} \, q \frac{x}{x_0} \cos\left(\frac{k\sigma_z}{2} \right)$$

Proposed Compact Linear Collider (CLIC)



Main linac Parameter			
Overall two linac length	48.4 km	I_{pulse}	1.5 A
Centre of mass energy	3 TeV	Number of bunches / pulse	312
Beam power	14 MW	Bunch separation	0.5 ns
Machine RF frequency	12 GHz	Bunch length	44 μm

Cavity BPM for CLIC

BPM requirements for CLIC main Linac		
Resolution	50 nm	
Drift tube diameter	8 mm	Upper limit on frequency
Measurement band width	20 MHz	Orbit bit correction for bunches at tail of bunch train.
Number of BPM required	~ 4776	

- Proposed total number of BPM in main linac: ~4776
  => Lower cost per cavity.
  => Simple design, without tuning to reduce vacuum failure as well as human labour cost.
  => Increase XY isolation by adequate asymmetry.

- Bunch separation = 0.5 ns ,
  => Signal overlapping between multi-bunches.
  => Lower the Q, less accurate cavity parameter measurements.

- Beam current = 1.5 A
  => Higher coupling, higher wall current, more heat , more wake for follwing bunches.

EM simulation codes

- Electromagnetic (EM) simulation codes.
  - Advanced Computational Electromagnetic-3P (ACE3P) suit, SLAC, USA.
    - Parallel, higher order, finite element based electro-magnetic code. I used following codes
      - Omega3P : Eigen mode solver to find normal modes of the cavity.
      - T3P : Time domain solver to calculate transient response.
      - S3P : S-parameter solver for transmission properties.
  - GdfidL :
    - 3D EM simulation code written in Fortran.
    - Finite difference time domain (FDTD) solver at core.
    - Uses orthogonal mesh to discretise the geometry.
    - Runs on serial and parallel machine.
    - Solvers:
      - Eigen-mode solver
      - Time domain solver

Cavity BPM project for NLS/DIAMOND light source at RAL, UK

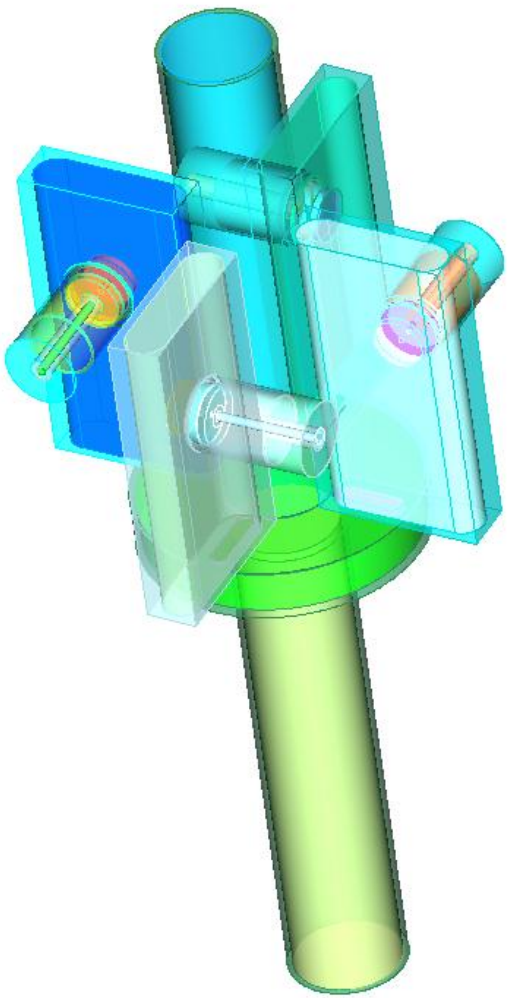
- Science disciplines utilizing DIAMOND light source.
  - Chemistry
  - Cultural heritage
  - Earth science
  - Engineering
  - Environmental science
  - Life science
  - Physics and material science

- Major parameters:
  - Accelerated particle : e^-
  - Particle energy : 3GeV
  - Circumference : 561.6 m
  - Beam current : 300 mA
  - Bunch repetition rate: 500kHz

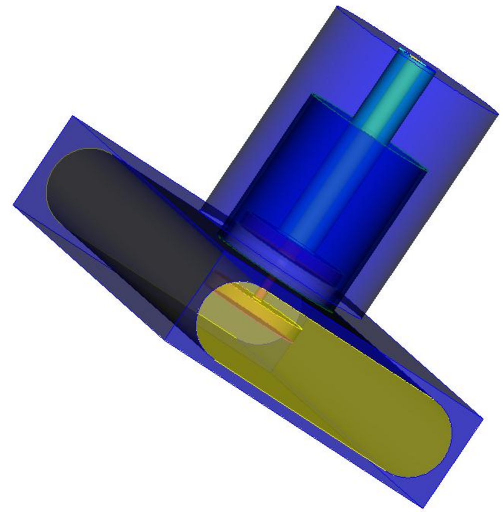
DIAMOND BPM: RF design and simulation

- BPM development project at DIAMOND[1]:

BPM cavity with beam pipe and coupler with feed-through



Waveguide coupler with feed-through

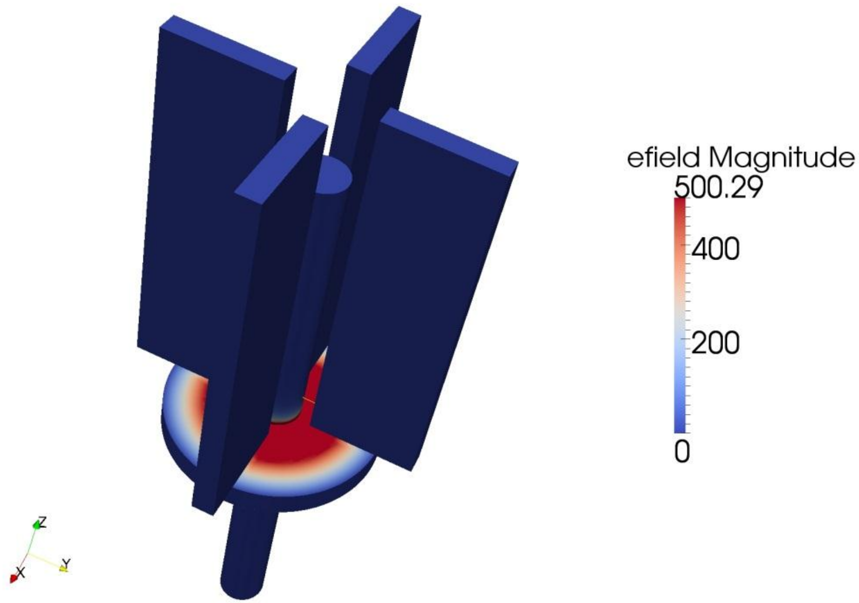


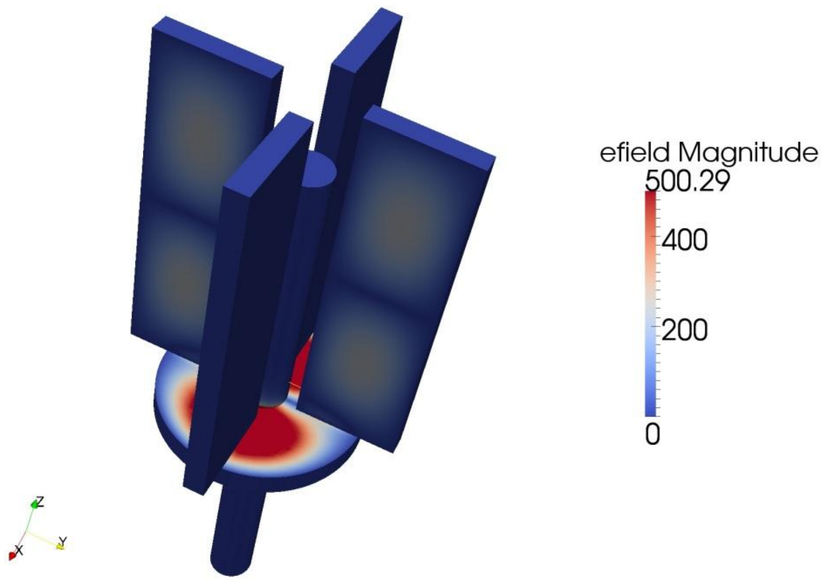
- Basic design considerations :
  - LO source synchronization and maximum IF frequency. (20 MHz)
  - There should be enough number of IF oscillations between two consecutive bunches.
  - Energy decay time of the cavity.
  - Vacuum compatibility of materials and shapes.

DIAMOND Cavity BPM: simulation

- Eigen mode solution : Monopole
  - Monopole frequency : 4.5 GHz
  - Monopole reduction by waveguide

$$f_{cut\text{-}off\,(Waveguide)} > f_{monopole\,(Cavity)}$$



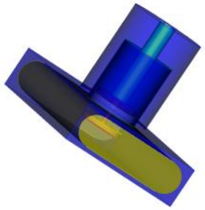


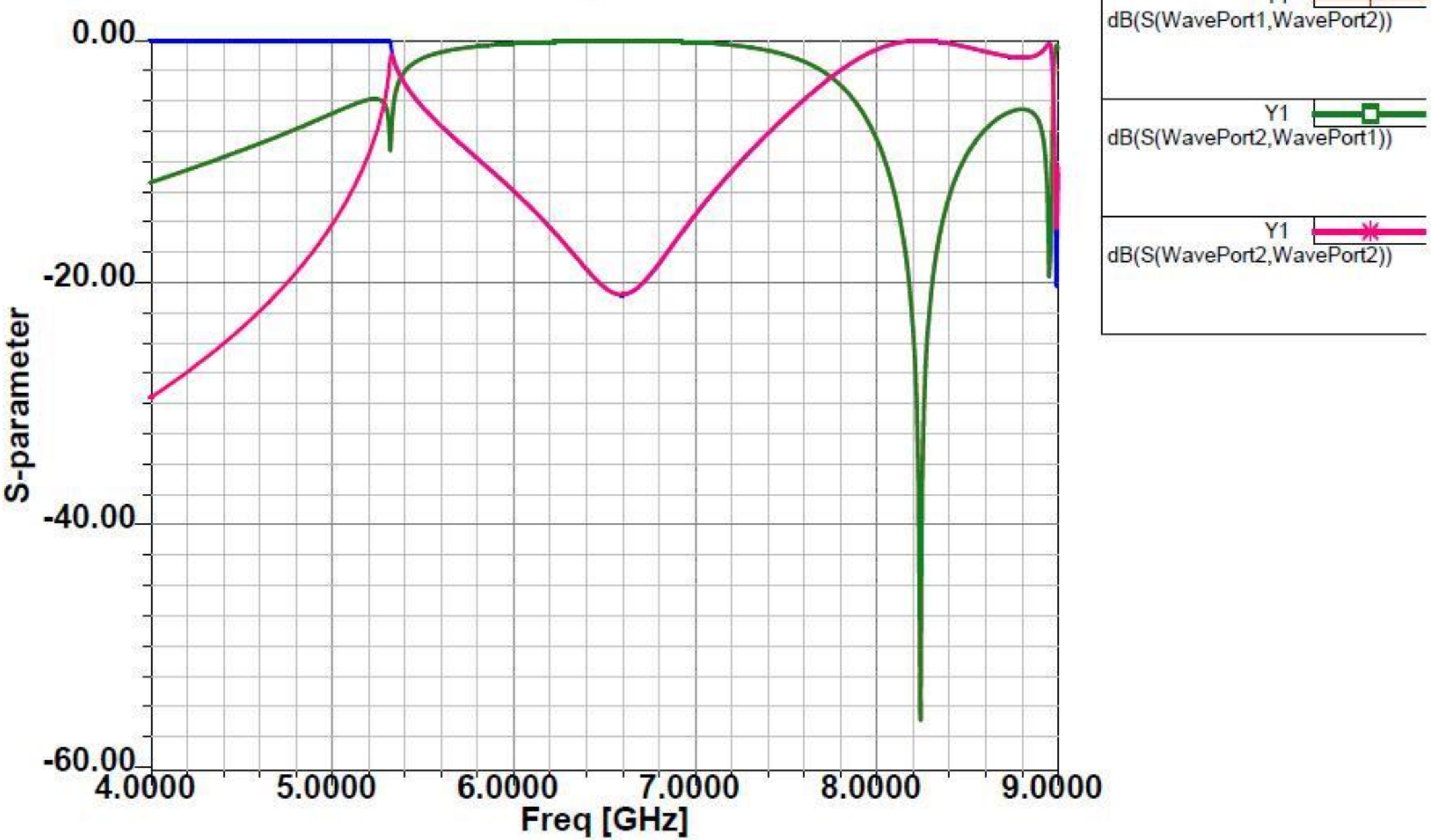
- Eigen mode solution : Dipole
  - Dipole frequency : 6.47 GHz
  - Dipole coupling into the waveguide

$$f_{cut\text{-}off\,(Waveguide)} < f_{dipole\,(Cavity)}$$

DIAMOND Cavity BPM: simulation

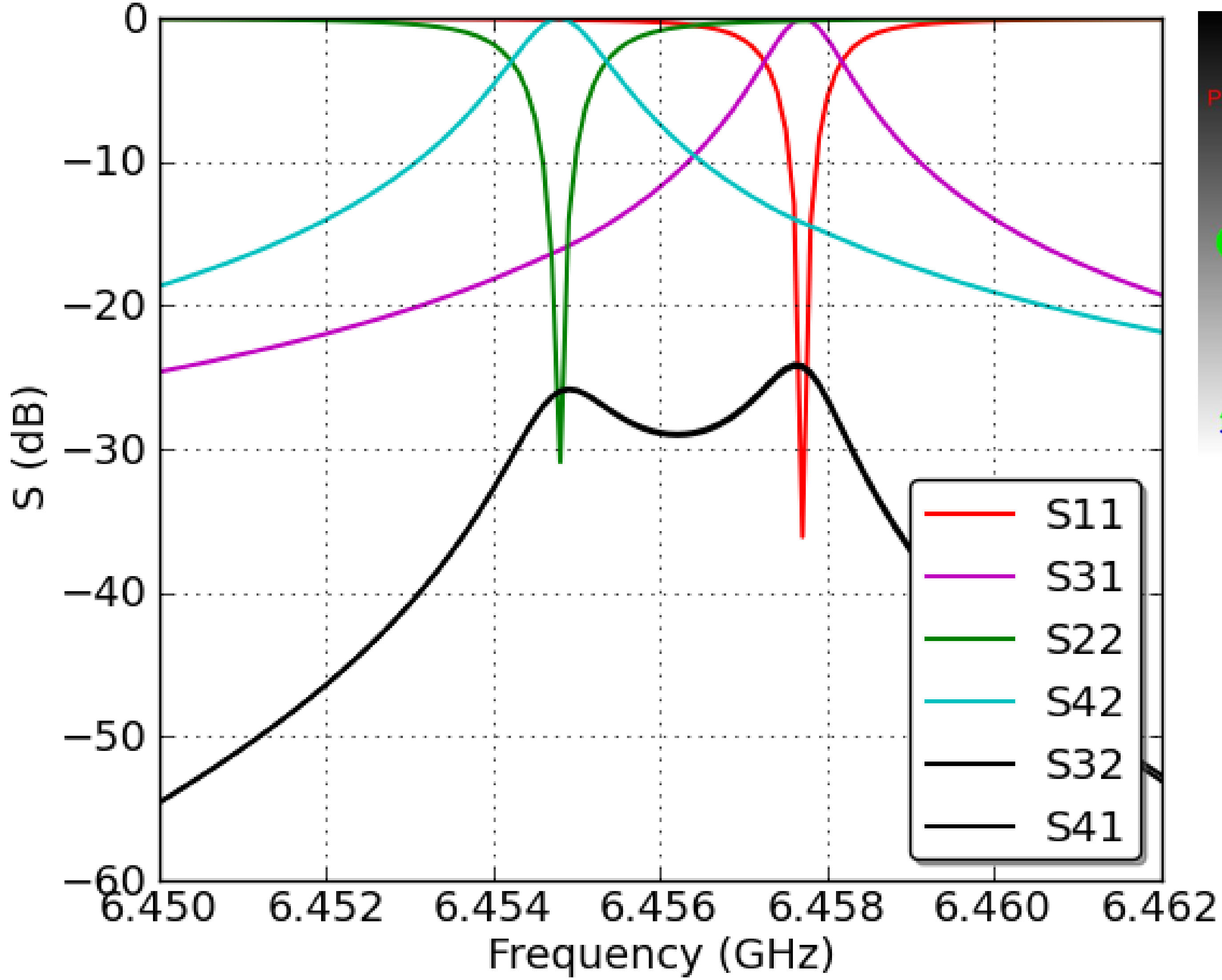
- Waveguide coupler

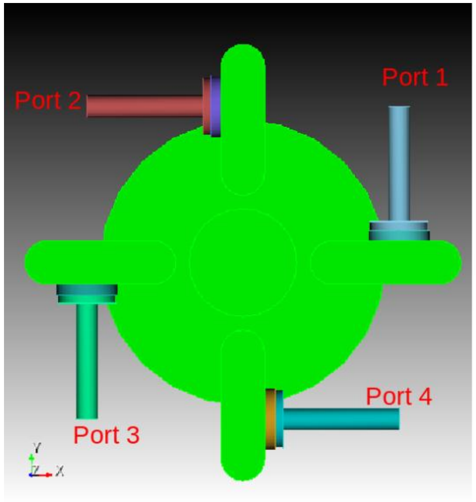




DIAMOND Cavity BPM: simulation

- S-parameter simulation



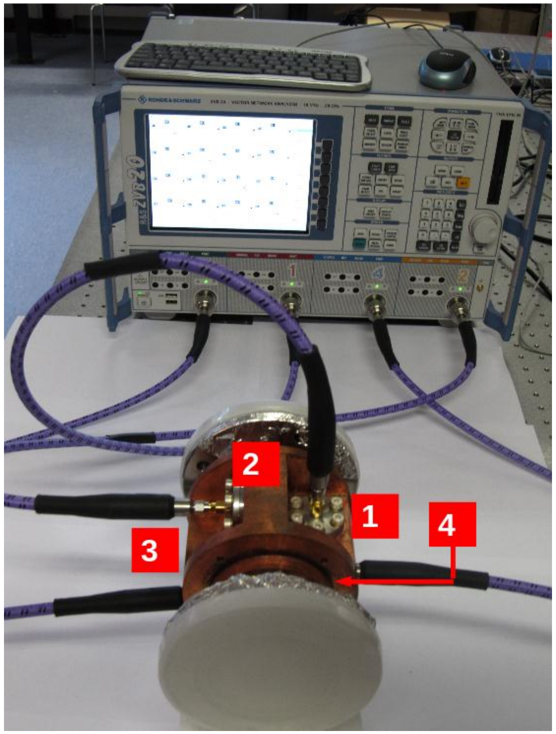


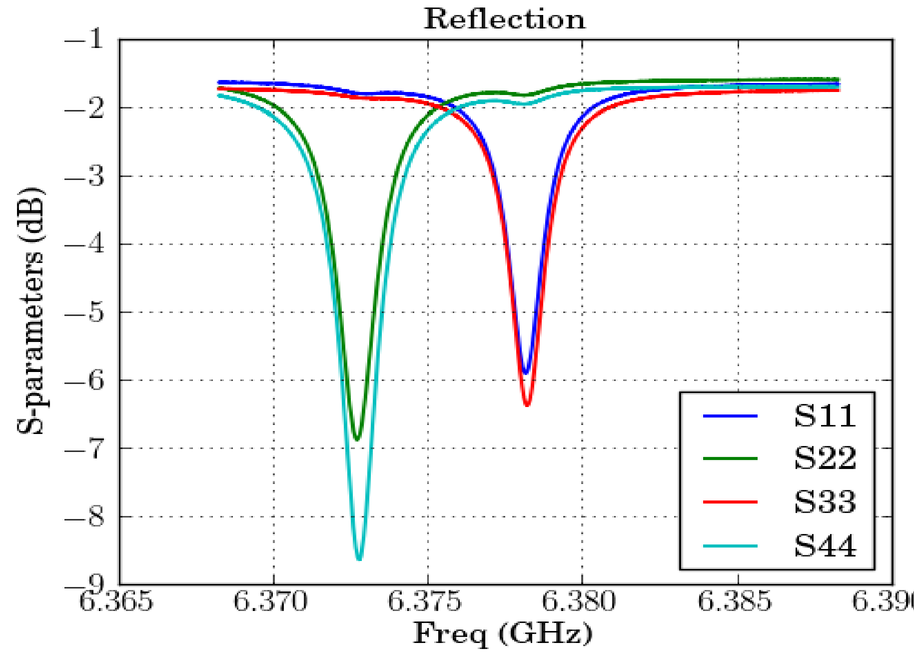
DIAMOND Cavity BPM: simulation

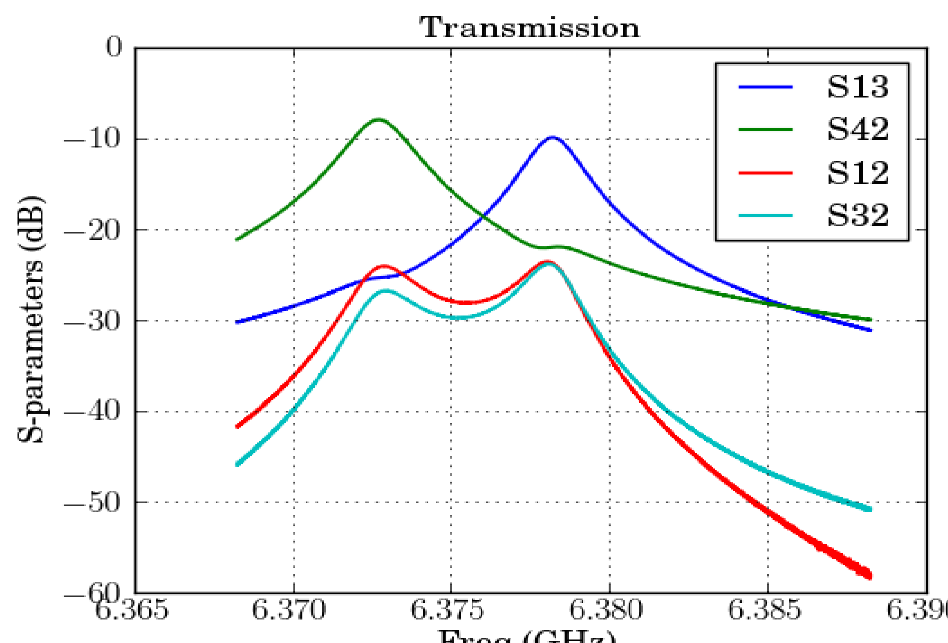
DIAMOND BPM simulation results	
Monopole frequency	4.5 GHz
Monopole suppression	< -55 dB
Dipole frequency	6.457 GHz
Frequency separation between X and Y position data	3 to 5 MHz
X and Y plane isolation	~ 25 dB
Q_L (or Decay time constant τ) Y-plane	~3000 (0.073 μs)
Amplitude pollution from previous bunch at 500Khz bunch repetition frequency	< 5 %

- Cavities were fabricated with FMB Berlin.

DIAMOND Cavity BPM: RF Measurements (S-Parameters)

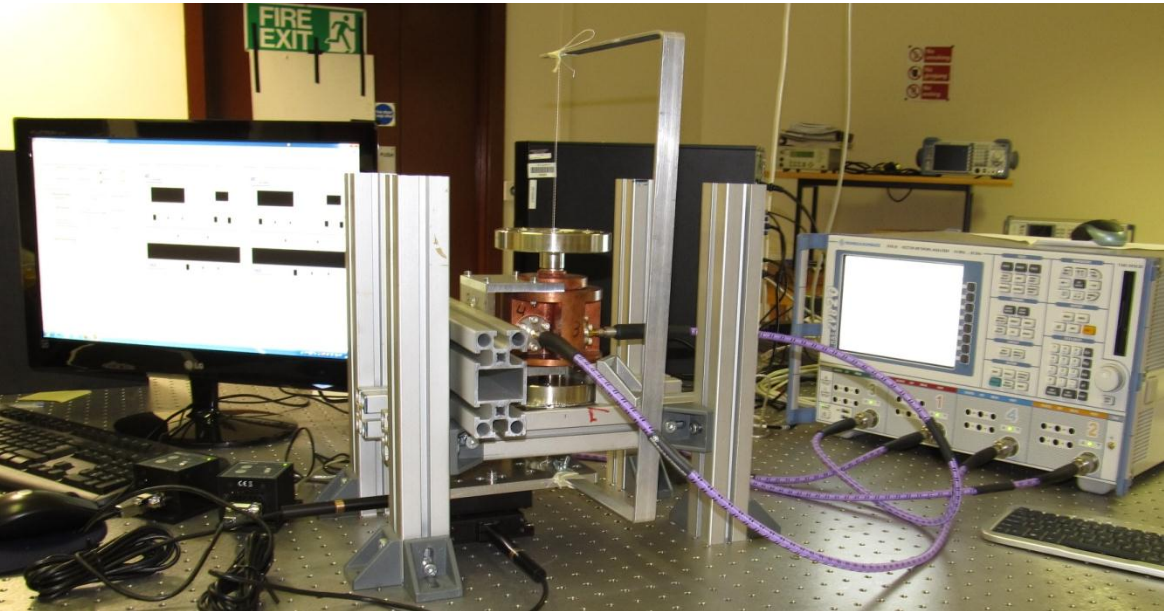






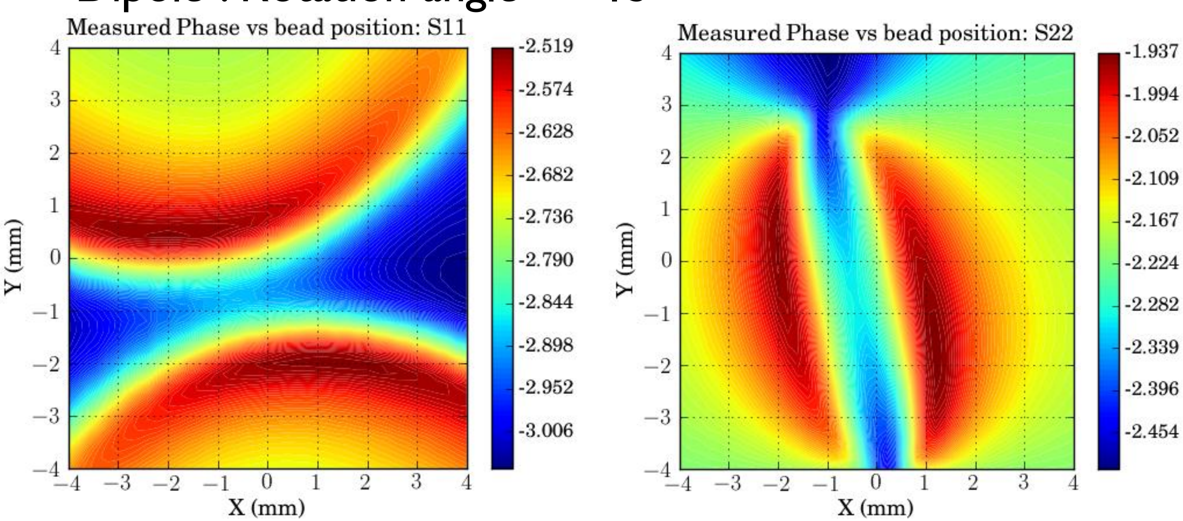
- Peak Frequency S11: 6.376GHz
- Peak Frequency S22: 6.371GHz
- Coupling loss: ~ -10 dB
- XY isolation : ~ -15 dB
- Monopole supresion: > - 55 dB
- Q_{load} : 2892

DIAMOND Cavity BPM: RF Measurements (Mode orientation)

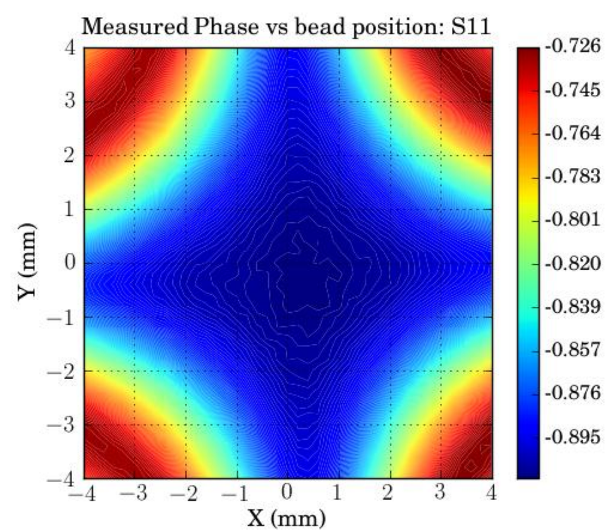


- +- (4 x 4 mm) scan with step size of 0.2 mm.
- Movers and VNA were remote controled and synchonised using USB and VISA over LAN.
- All S-parameters are recorded during single frequency sweep
- 6400 S-para files were processed in parallel mode on cluster.
- Rotation agrees with isolation.

Dipole : Rotation angle= ~13°

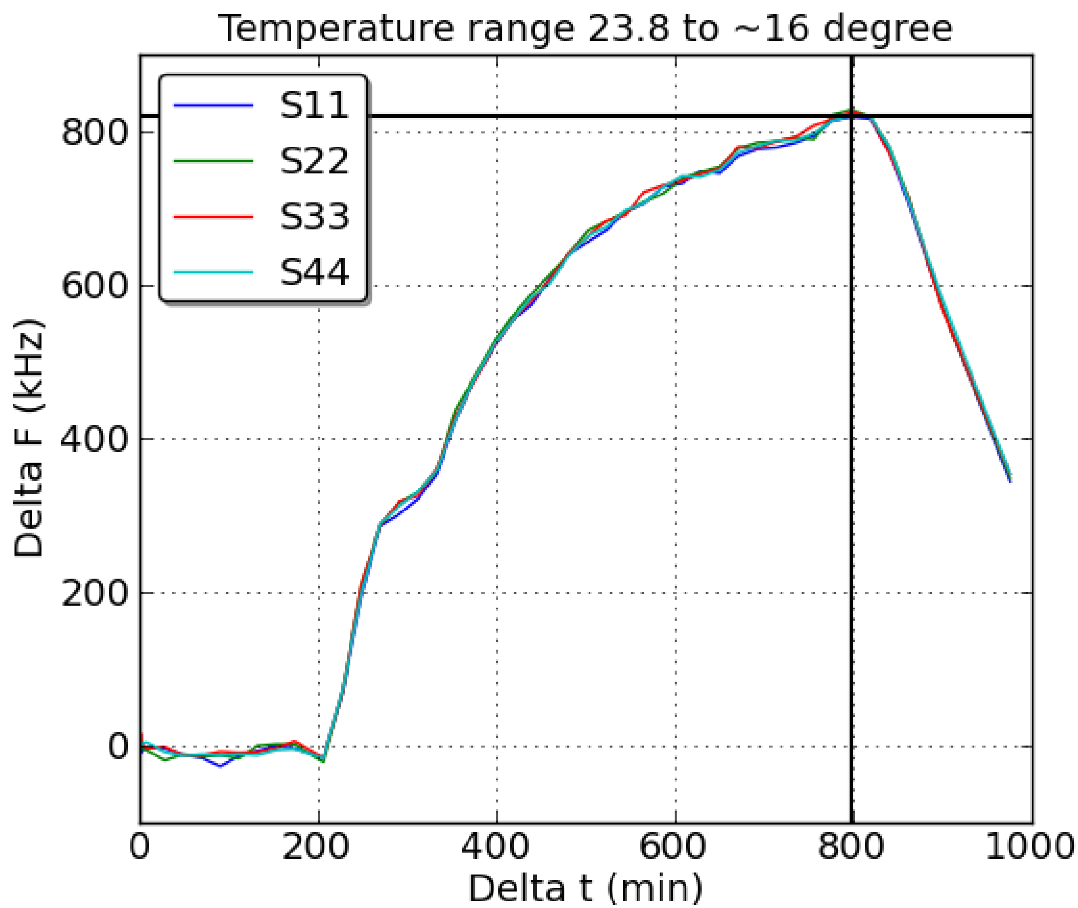


Quadrupole: Rotation angle: ~2°



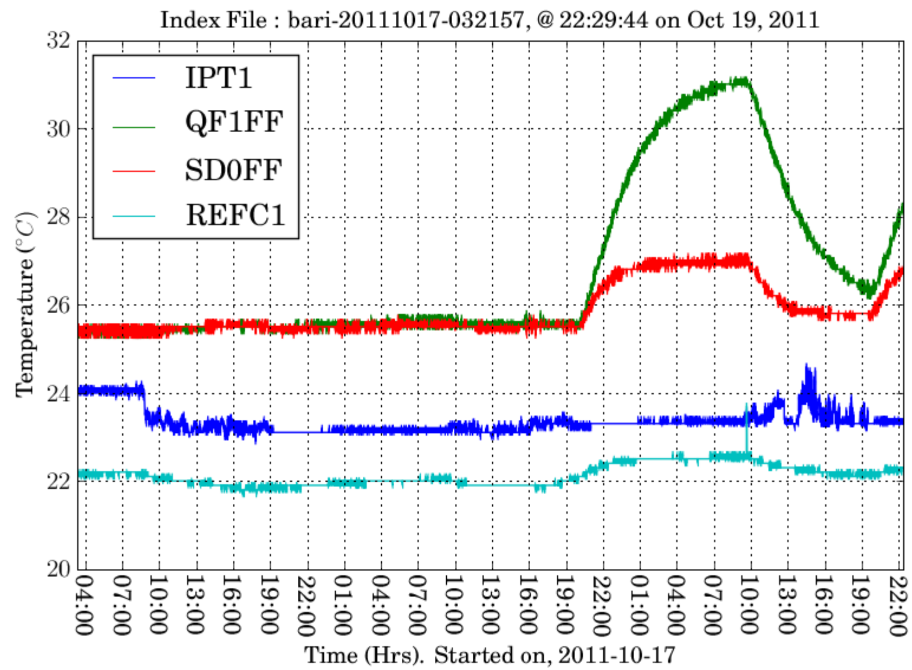
Effect of temperature variation

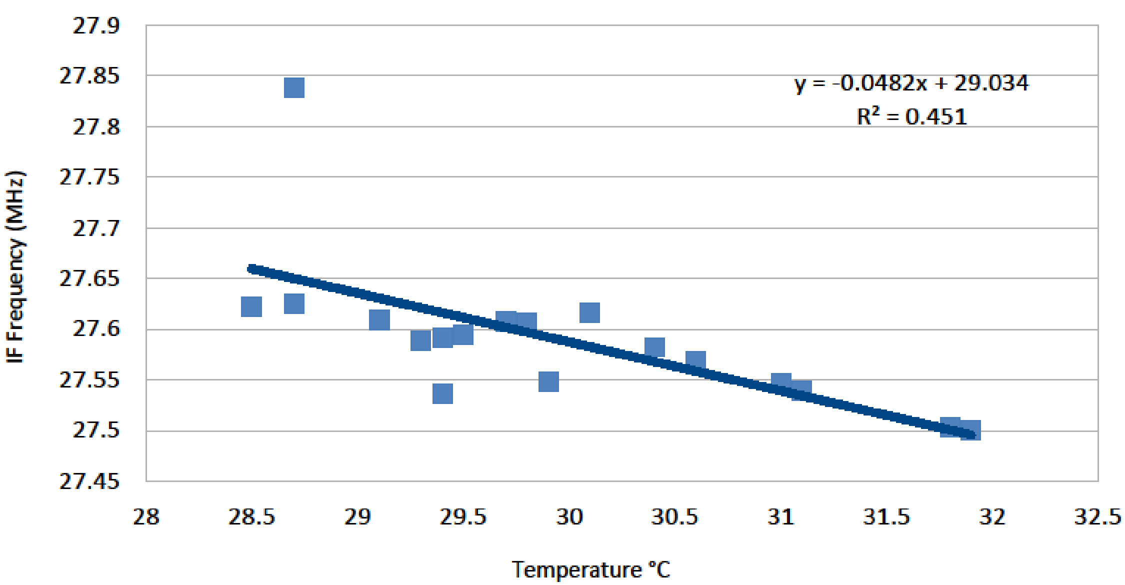
- Cavity frequency : ~ 6.376 GHz
- Change in peak frequency over night with time.
- AC was left on over night which cooled the room.
- Cavity resonance frequency increases due to shrinking by cooling.



Effect of temperature variation at ATF2

- Cavity MQF1FF frequency : ~ 2.888 GHz
- Cavity mounted at the end of the sextupole magnet with high current during operation.
- Temperature change: 7 °C.
- Temperature variation in all other cavities are less then 1 °C.

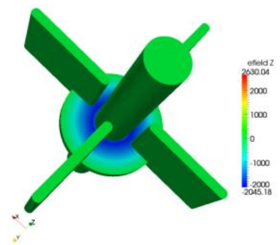




- Cavity frequency changes approximately by 48 kHz / °C

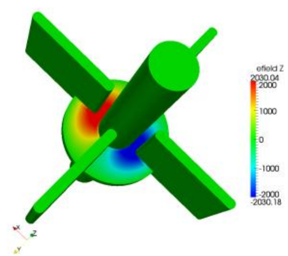
Cavity BPM for CTF3 and Wake field study.

- Cavity BPM designed and fabricated by Fermilab and CERN.
- Eigen mode simulation using Omega3P



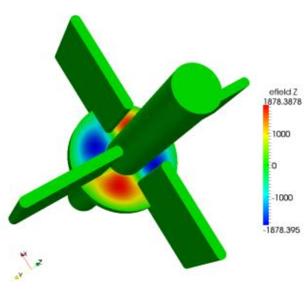
Monopole:

- Frequency : 11.14 GHz
- Q_0 : 421.96
- R/Q_{1mm} : 46.41 Ω



Dipole:

- Frequency : 14.988 GHz
- Q_0 : 517.89
- R/Q_{1mm} : 3.4 Ω



Quadrupole:

- Frequency : 20.34 GHz
- Q_0 : 572.62
- R/Q_{1mm} : 0.058 Ω

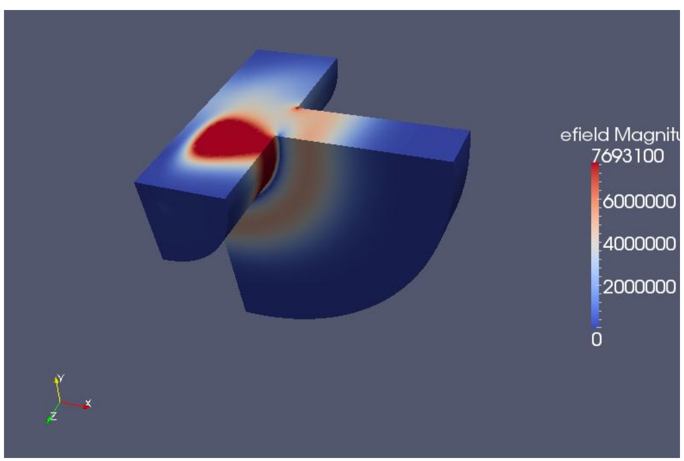
Cavity BPM for CTF3 and Wake field study.

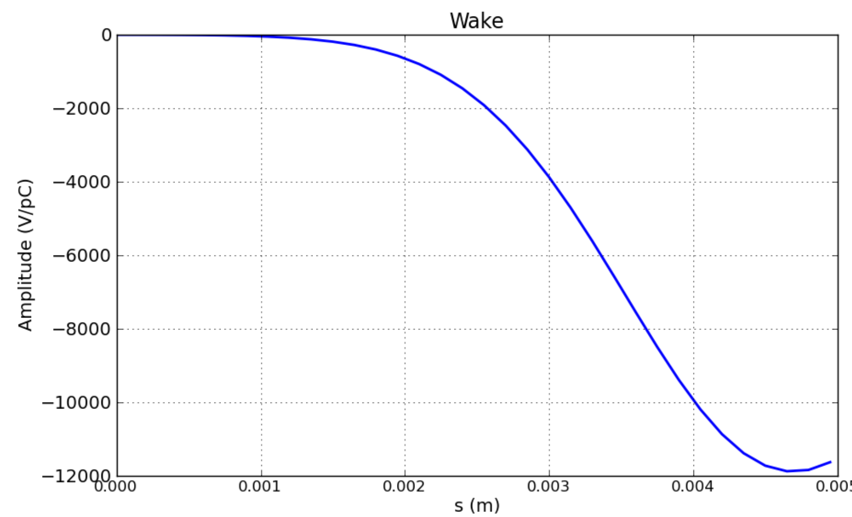
Bunch parameter:

- Bunch lenght σ = 1.0mm
- Effective length = 4 σ
- Bunch charge = 6.0 nC
- Field recording rate = 4ps

Postprocessing (Paraview)

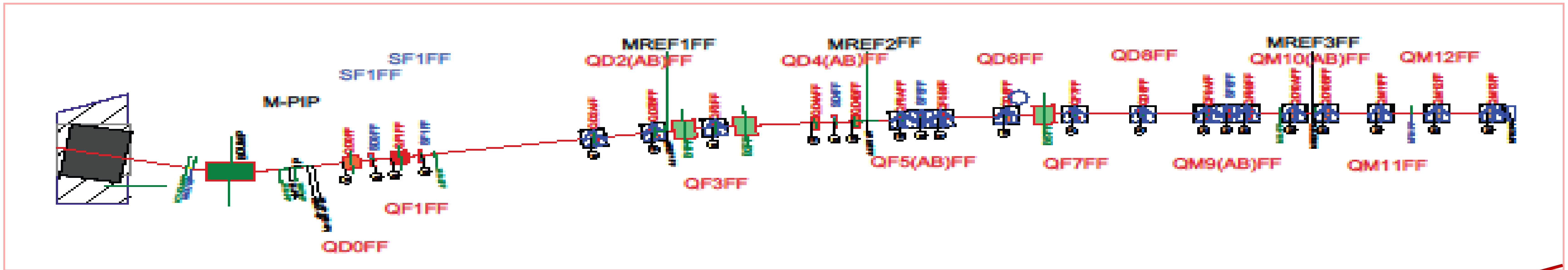
- Individial E and H components can be examined.

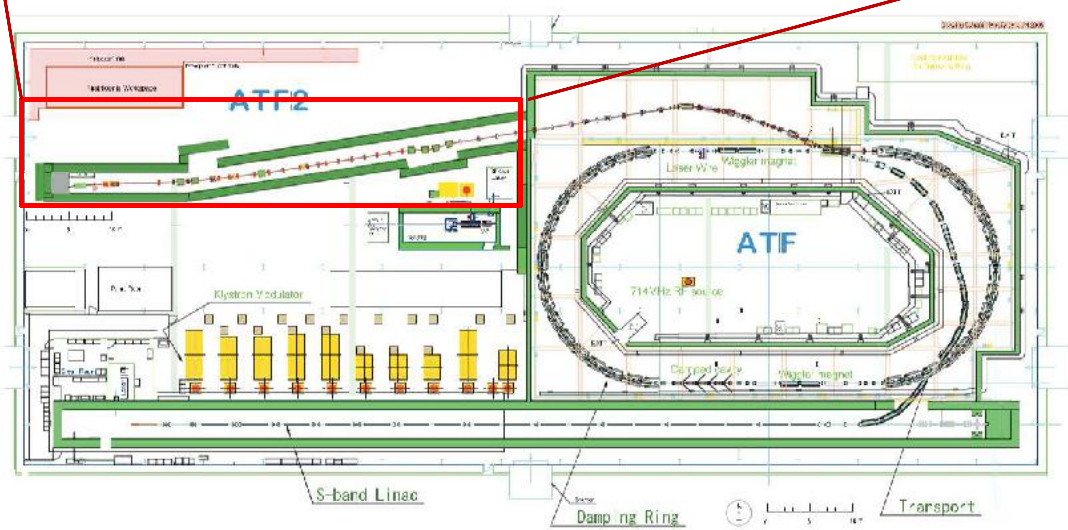




Data analysis and System calibration: ATF2, Japan

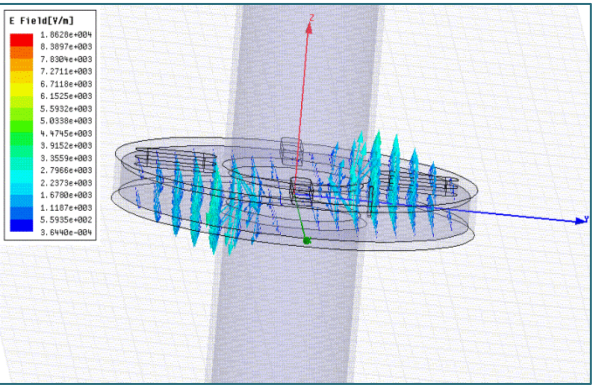
- ATF machine layout
  - 35 BPM at various places on ATF2 linac.

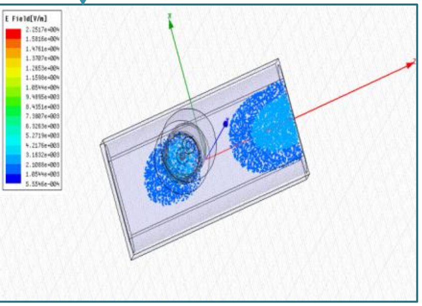




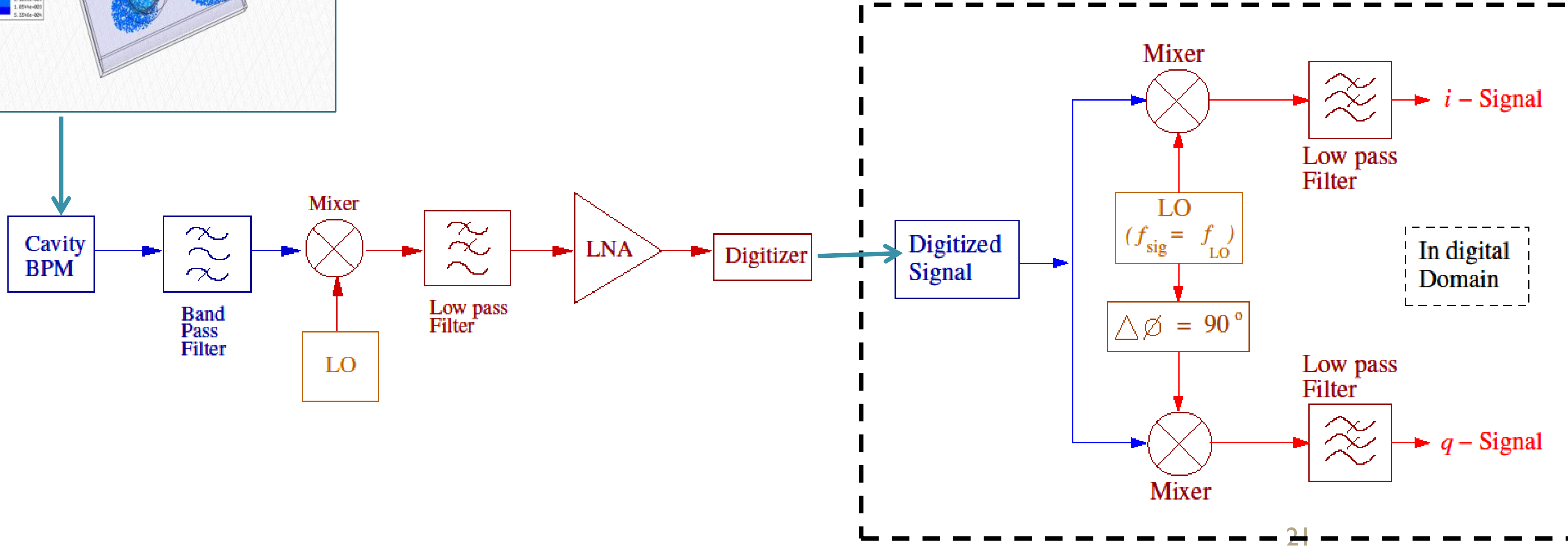
ATF in Multi-Bunch (train) Mode		
Parameter	**Value**	**Unit**
Number of bunches N_b	3	
Bunch separation t_b	154	ns
Linac (S-band)	1.3	GeV
Characteristic beam size	5 to 10	µm

ATF2 Cavity BPM system + DSP



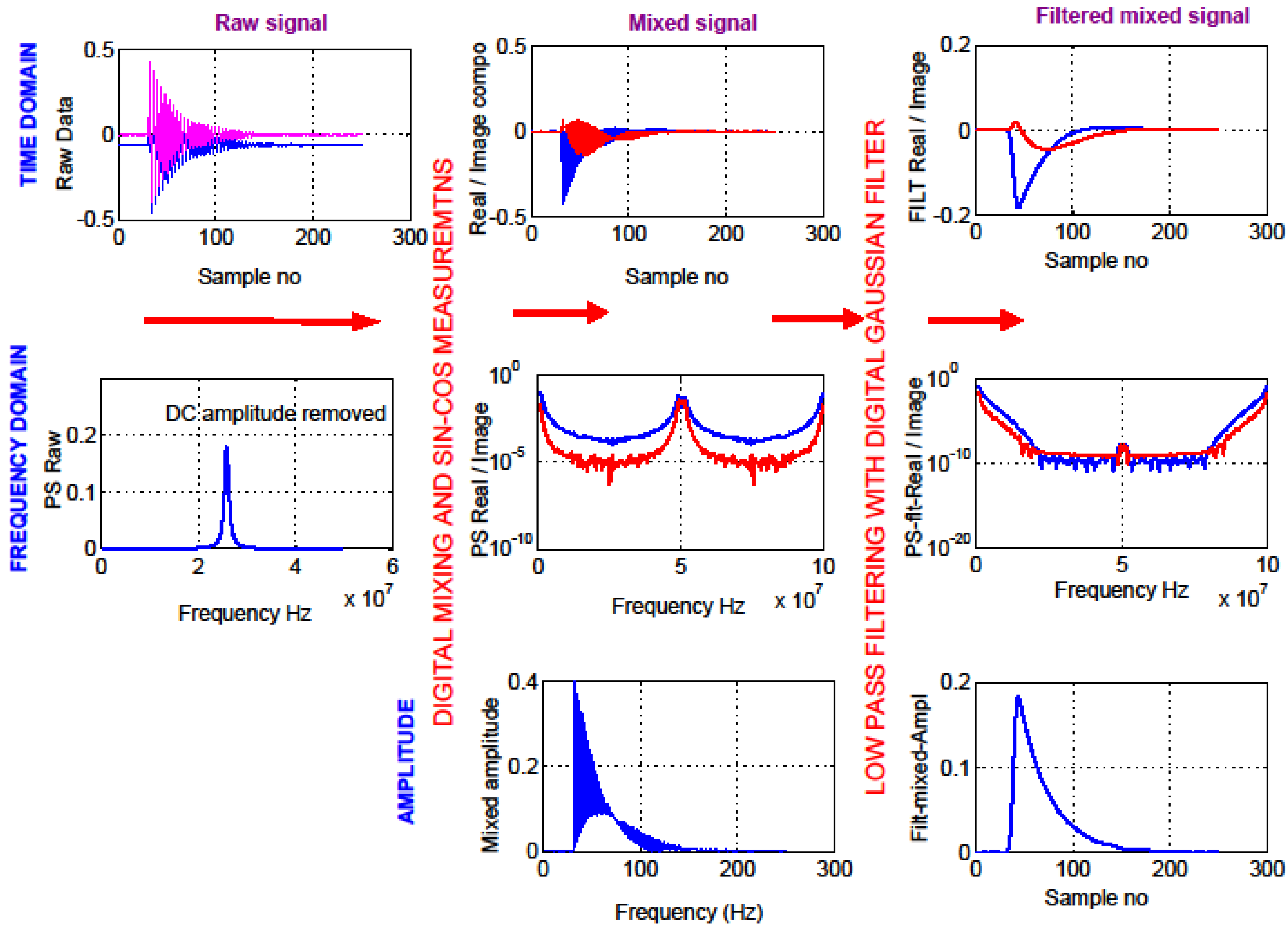


Dipole Cavity Parameters		
Parameter	Value	Unit
Number of position cavities	32 (+4)	C-Band (S-Band)
Number of reference cavities	4 (+ 1)	C-Band (S-Band)
Dipole frequency f	6.4235	GHz
Decay constant τ	151	Ns
Single bunch Resolution (with jitter)	5	µm



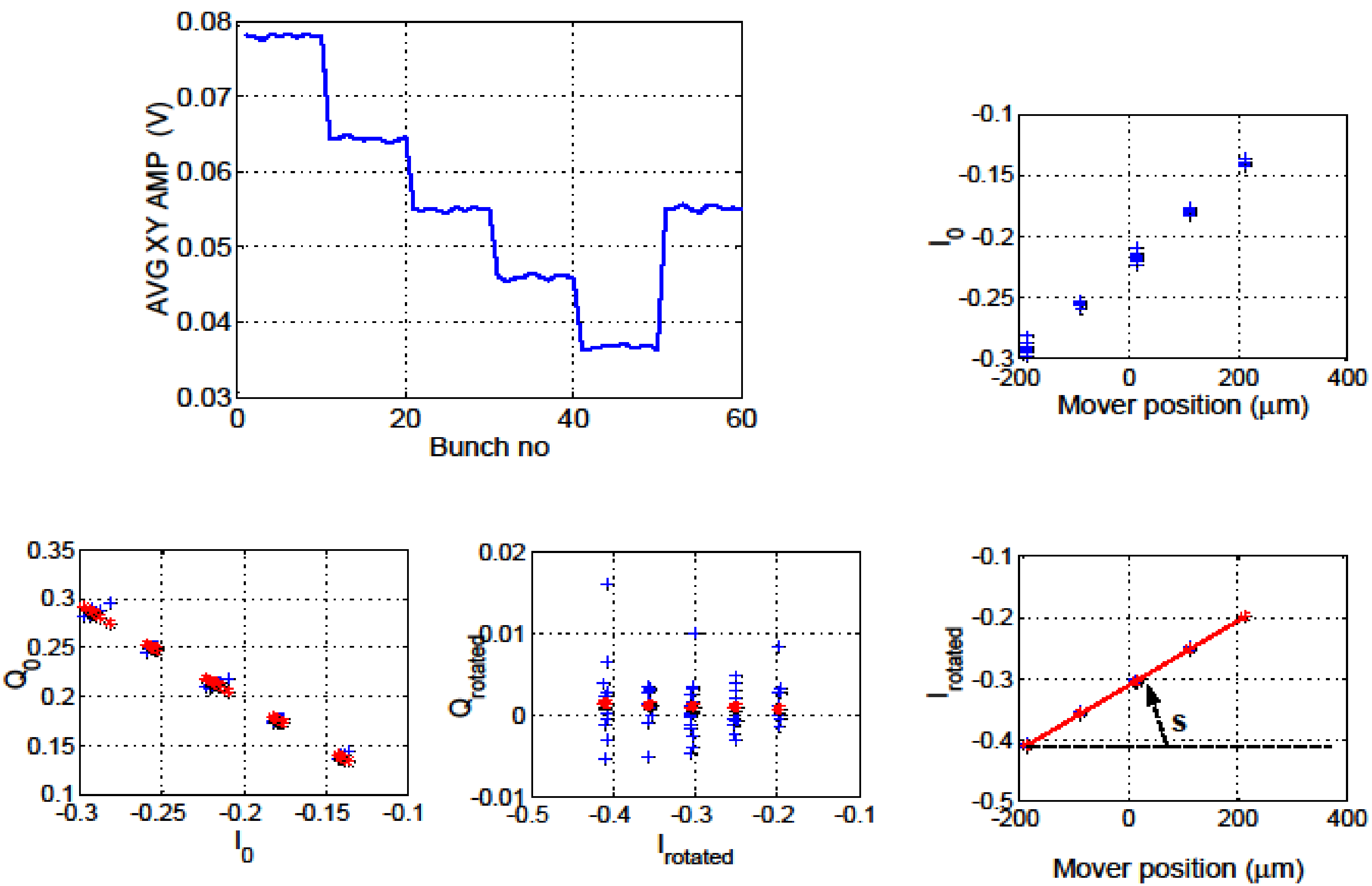
Data analysis and System calibration

- Digital signal processing

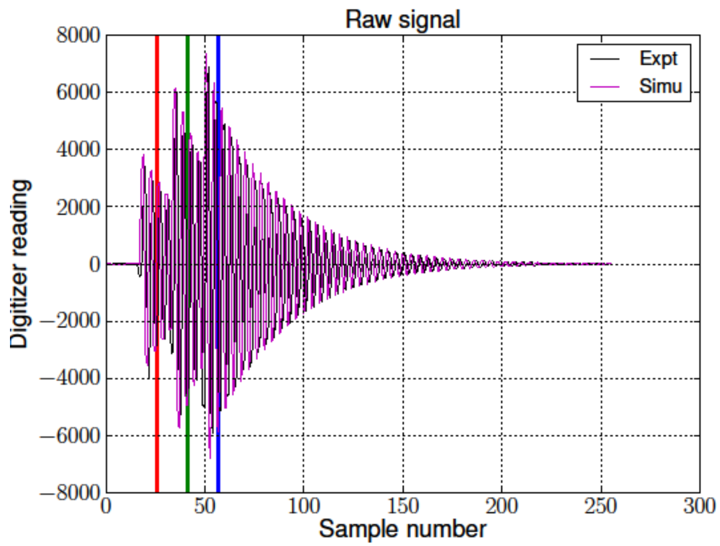


Data analysis and System calibration

- System calibration
  - BPM system resolution ~ 5 μm (with jitter).
  - After eliminating the noise due to beam jitter, position resolution of 25 nm is already been demonstrated.

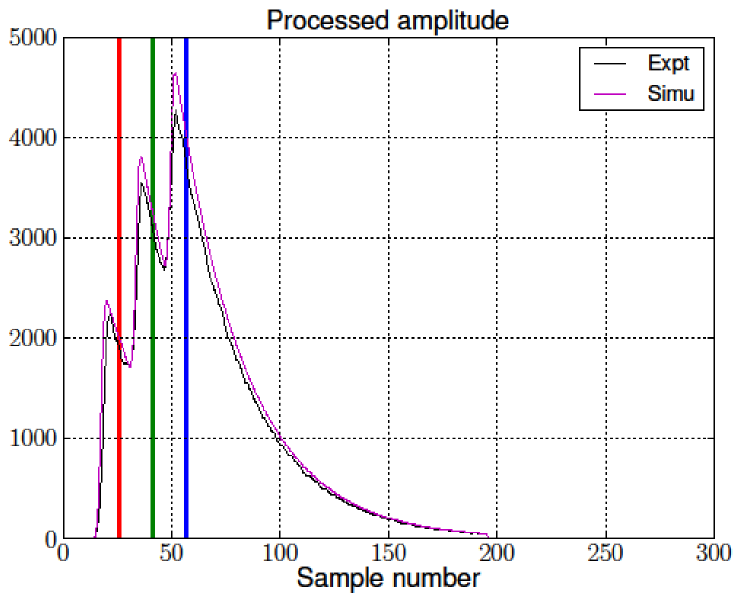


Multi-bunch analysis



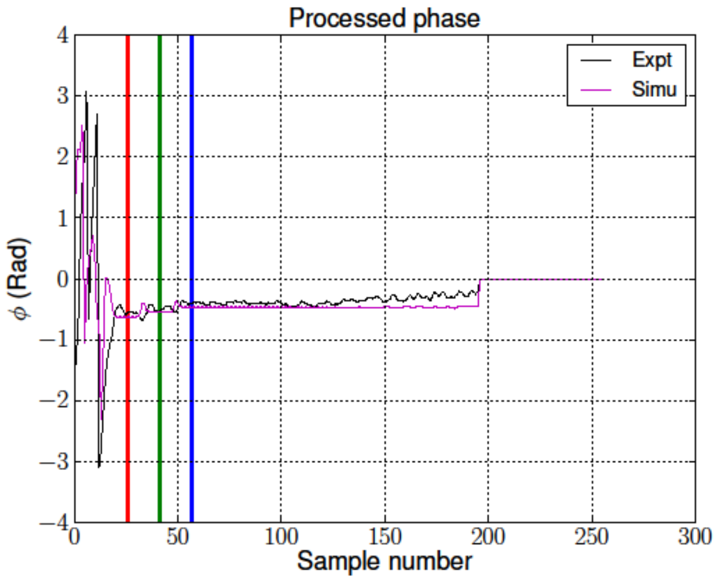
- In case of closely spaced bunches, next bunch arrives before the energy induced in cavity by previous bunches has decayed.
- Signal pollution due to overlap will give errornous measurements, hence should be subtraced using following equation.

$$A_j e^{i(\phi_j)} = \vec{V}_j - \vec{V}_{j-1}\, e^{-\frac{\Delta t_b}{\tau}}$$

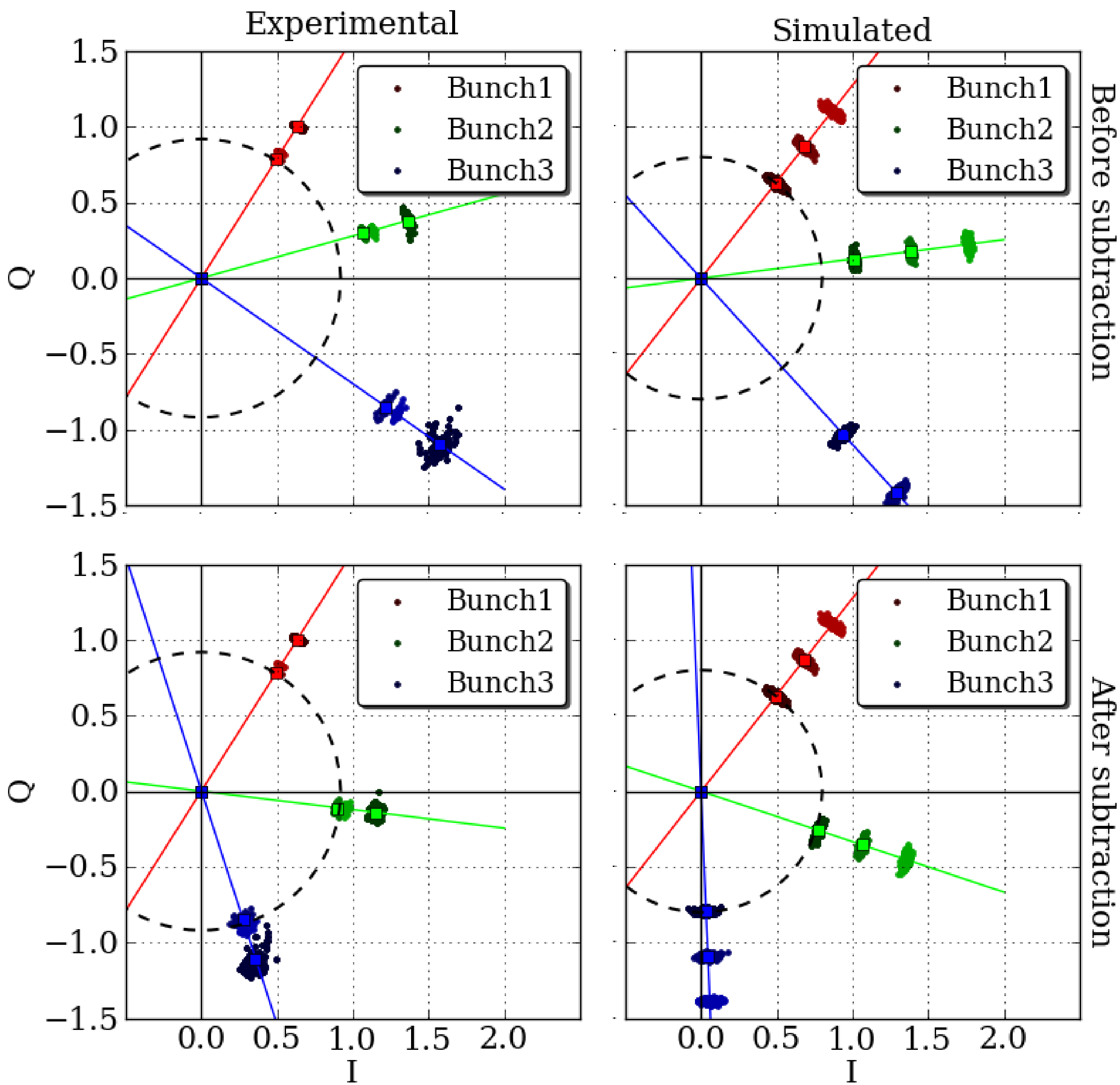


Colour convention

- Bunch 1: RED
- Bunch 2: Green
- Bunch 3: Blue



Multi-bunch analysis



- IQ Phasors:

$$I = \frac{A_d}{A_r}\cos(\theta_d - \theta_r)$$

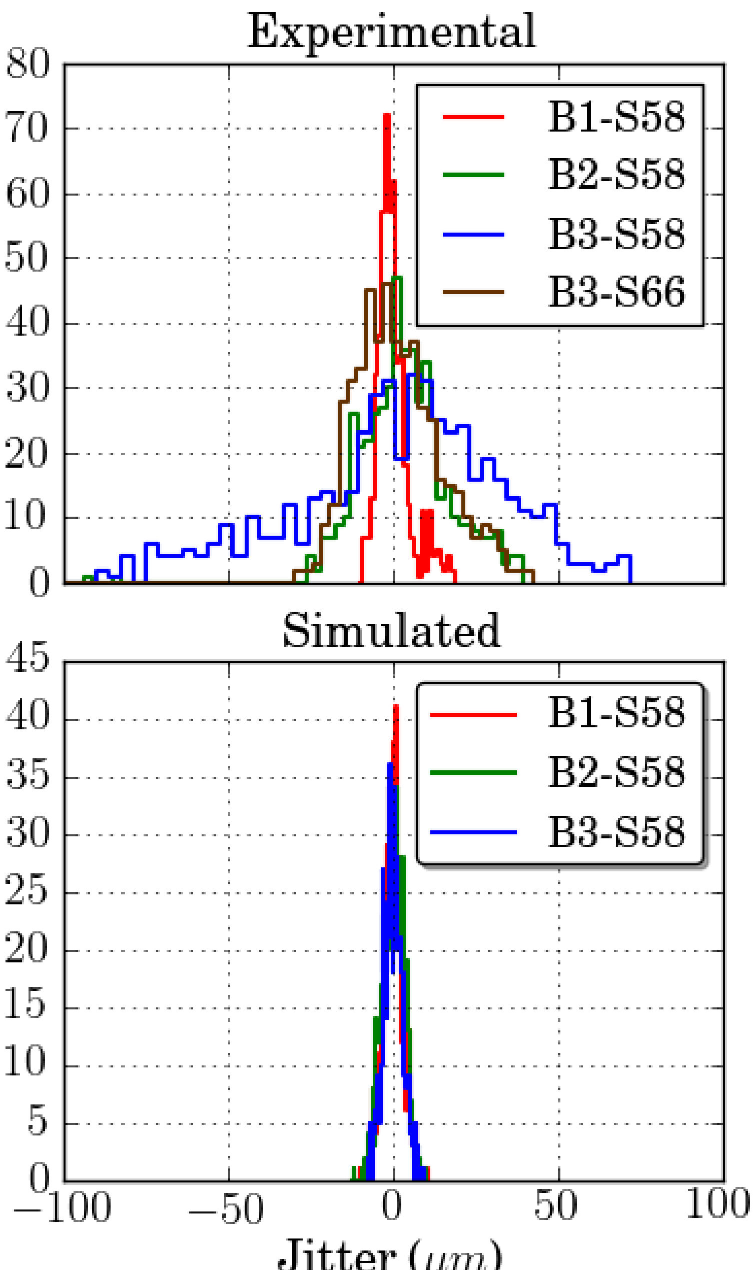
$$Q = \frac{A_d}{A_r}\sin(\theta_d - \theta_r)$$

After subtraction:

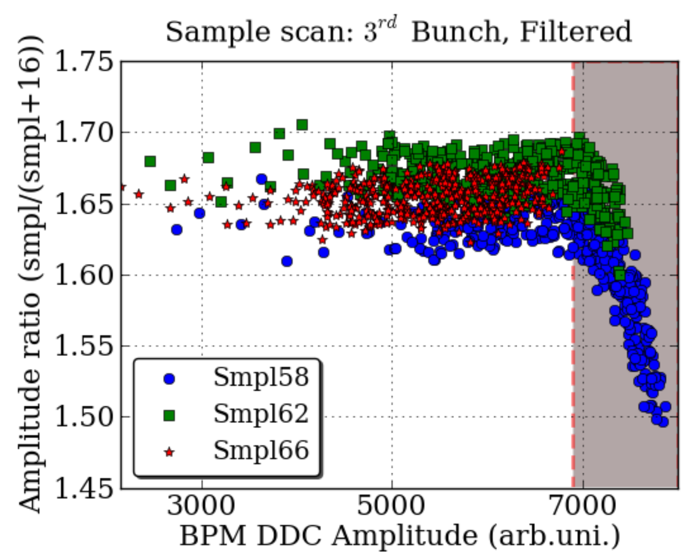
- Phasors for all three bunches have similar magnitude.
- Even phase differnce, due to frequency difference in dipole and reference cavity.

$$\Delta\theta = (\omega_d - \omega_r)\Delta t_b$$

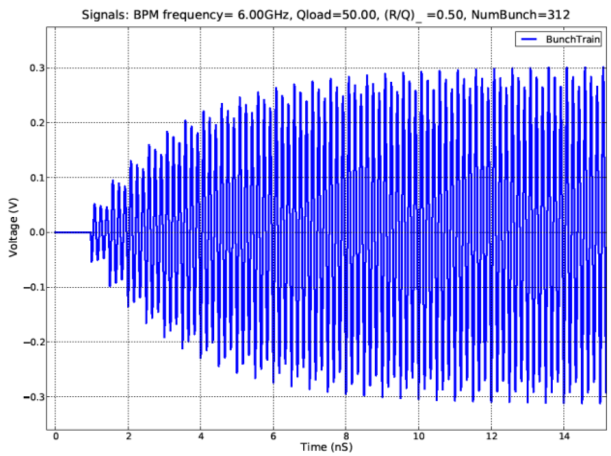
Multi-bunch analysis



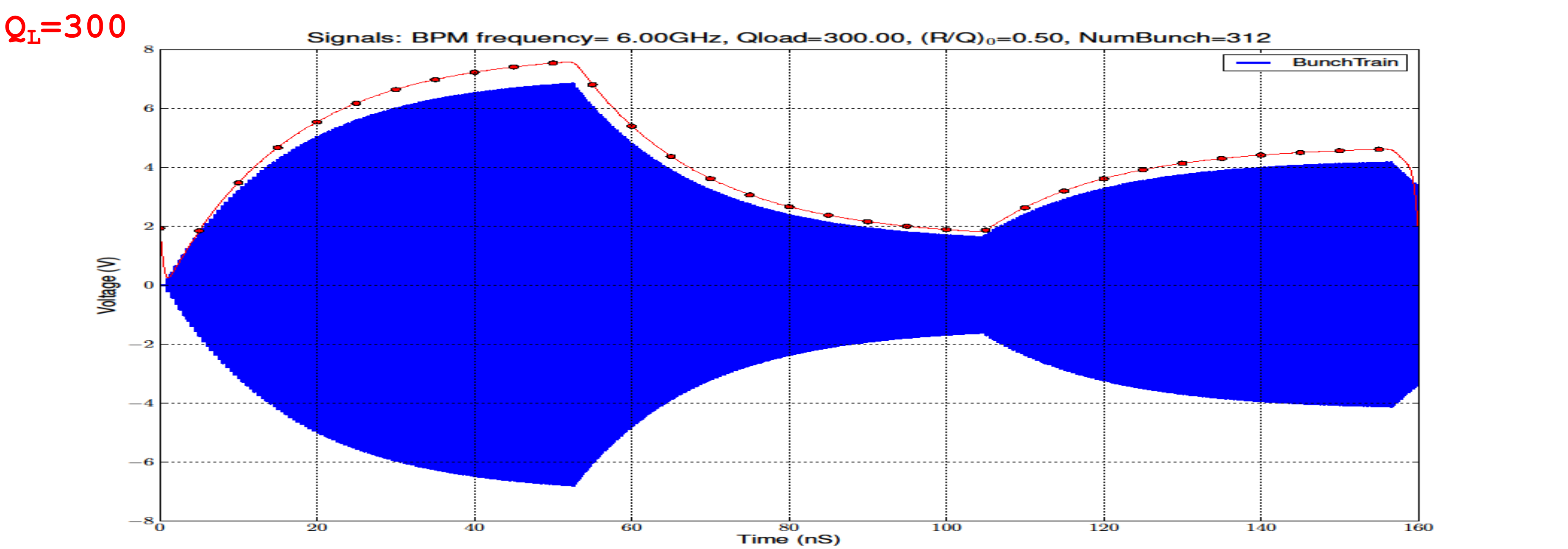
- The increase in jitter of third bunch after subtraction as due to saturation of electronics.
- Jitter spread could be less than that of the second bunch, that is 10 μm.
- Resolution in multibunch mode could not be reduced in to nano meter scale, as the beam jitter could not be subtracted effectively due to lack of strong correlation.



CLIC BPM: Signal simulation



- Multi bunch study is very important for as CLIC BPM would have to deal with signal overlap from several bunches, and signal may not be as clean as the fish shape bellow.



Conclusions and future work

- A cavity BPM has been designed , simulated for NLS/DIAMOND light source. RF characteristics and mode orientation were examined for the same, and the cavity is ready to be tested with beam during next few months.

- A method to remove signal pollution from closely spaced bunches is being develope and tested on beam data.

- Effect of temperature change on cavity has been studied..

- More data is needed for multibunch study, and temperature characteristics analysis which will be acquired soon.

Thank you