LHC Optics Measurement and Correction

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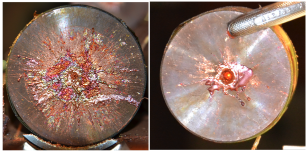
Overview of LHC optics measurements and corrections

Importance of Optics Commissioning

- **Machine protection**



Ph.D thesis of F.Burkhart

- **Machine performance**
  - **Optics errors can reduce delivered luminosity**
  - **Optics errors can create luminosity imbalance between experiments**
    critical for ATLAS and CMS
    aim for 1% level control of β^*
  - **High quality optics improves operational control**

Importance of Optics Commissioning

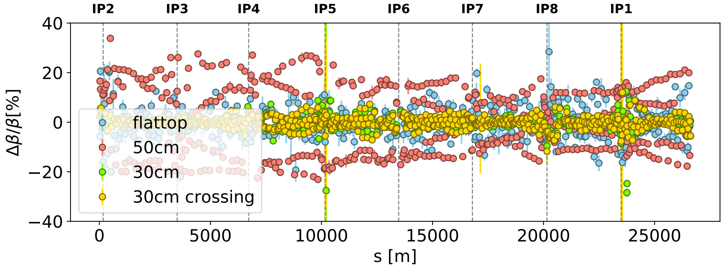
Optics studies make up a significant proportion of annual LHC commissioning with beam

We need to commission multiple machine configurations

$\rightarrow$ necessity of fast and reliable commissioning software

Many optics settings have to be (re-)commissioned

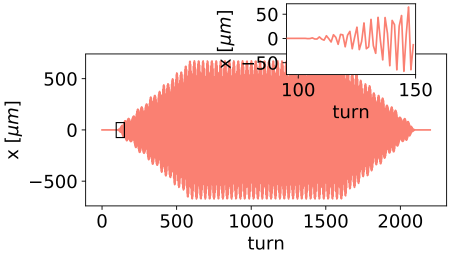
Injection, Low-β^* (several β^*-values), special optics (Ion, high-β^*, high β at injection, VdM

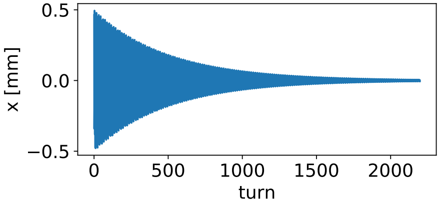


Optics measurements via AC-Dipole

Use AC-Dipole to drive coherent beam oscillation

- No decoherence
- No blow up due to adiabatic ramp-up/down

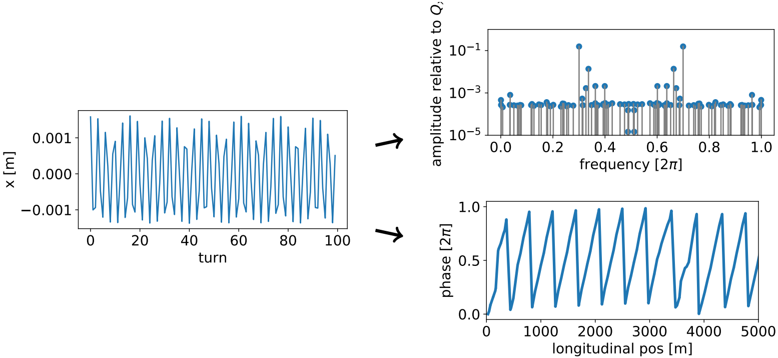




effect of driven motion has to be compensated

BPMs

- More than 500 dual plane beam position monitors record turn-by-turn betatron oscillation data during kicks
- Spectral analysis to obtain phase advances between BPMs
- Reconstruct β functions via N-BPM method



Beta Function

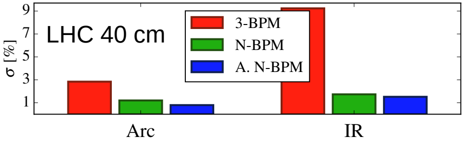
Beta from phase

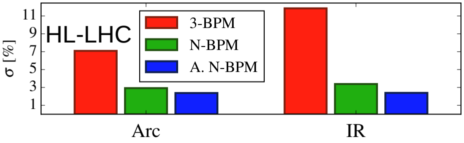
The β function can be calculated from the measured phase advances via:

$$\beta_i = \frac{\cot\varphi_{ij} - \cot\varphi_{ik}}{\cot\varphi_{ij}^{\text{model}} - \cot\varphi_{ik}^{\text{model}}} \beta_i^{\text{model}} \tag{1}$$

Improvements in β calculation

- Traditionally neighbouring BPMs
- improvement through averaging over several combinations, using error propagation to get correlations
- further improvement using analytical formula for error propagation

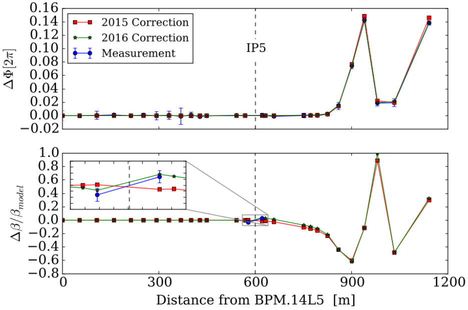




Local errors

First: apply corrections of large local errors

using phase beating = $\varphi_{\text{meas}} - \varphi_{\text{model}}$



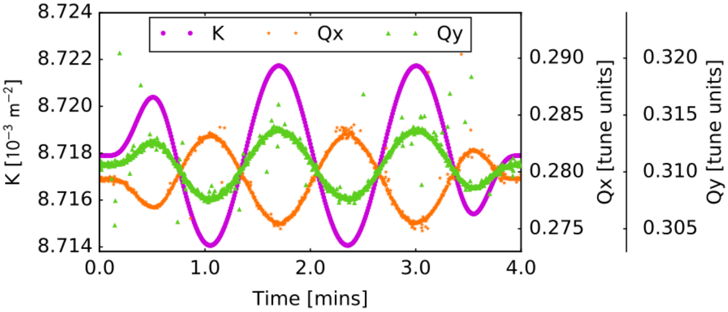
Phase beating corrected by 2015 and 2016 optics, but only 2016 also reproduces β beating.

Segment-by-segment technique

- Treat segment of ring as transfer line, propagate measured optics from entrance, then compare modelled phase propagation to measurement
- Use models to reproduce phase deviation and apply to real LHC

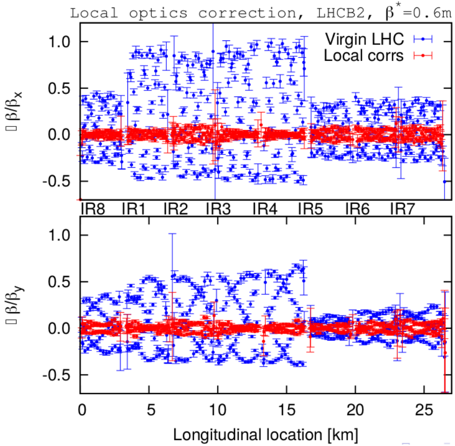
K-Modulation

Use K-Modulation to better constrain corrections in interaction region



After local corrections

Local corrections reduce β beating to a peak of $< 20\,\%$.
To reach lower β beating a global approach is needed.



Global Corrections

Response matrix approach is used to calculate global corrections

$$(\Delta\varphi_x, \Delta\varphi_y, \beta^*_x, \beta^*_y, \Delta\beta_x, \Delta\beta_y, \Delta ND_x, \Delta ND_y, \Delta Q_x, \Delta Q_y)^T = \mathbf{R} \cdot \Delta\vec{k}$$

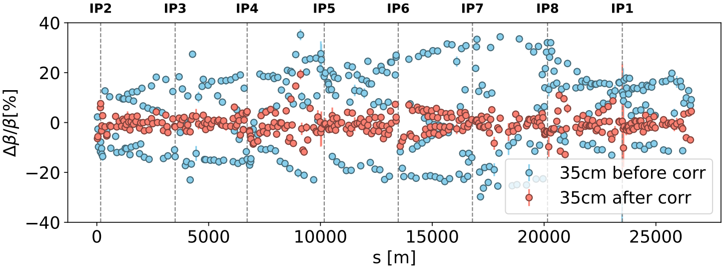
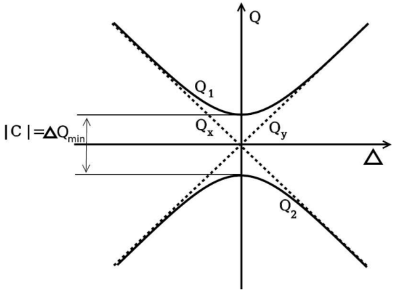


Figure: ATS optics MD. $\beta^* = 35\,\text{cm}$

Coupling correction

Correct linear transverse coupling



drives $Q_x - Q_y$ resonance relevant to

- working point
- dynamic aperture / lifetime
- amplitude dependent colsest tne approach
- Q-footprint distortion -> instabilities

correct by minimising strength of $Q_x - Q_y$ resonance

Overview of the software

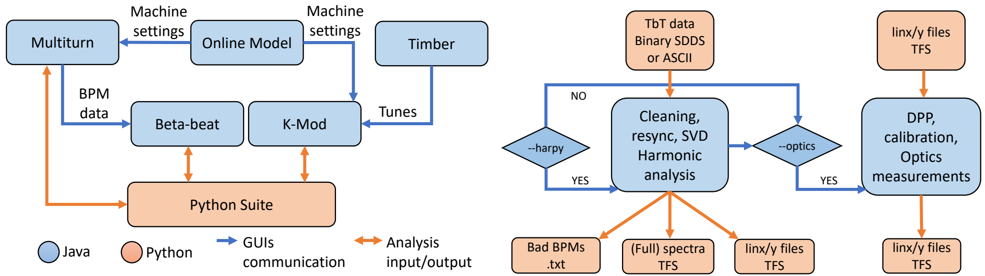


Figure: Flow chart of the OMC software suite. LEFT: included software parts. RIGHT: detailed view of the python suite performing harmonic analysis and optics calculations based on TbT measurements.

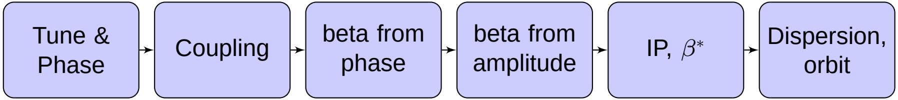
- GUIs and interface to machine / operation parameters: java.
- calculations: python.

Overview of the software

Collection of python scripts to calculate optics functions and corrections

Main considerations:

- keep maintainability and extensibility
- provide highest possible precision and accuracy
- have acceptable time efficiency for online analysis
- be independent of accelerator
  CERN has several accelerators, three of which routinely use our software (LHC, PSBooster, PS)



Local observable

Introduction

The aim is to locate error sources
need local observables, i.e. terms that only depend on lattice parameters and error sources in a localised region

Phase beating from quadrupolar RDTs

Betatron oscillation due to a quadrupolar field errors

$$\hat{x}_i = \mathcal{R}\left\{(1 - f^*_{2000,i})\sqrt{2I_x}e^{-i\left[2\pi N Q_x + \psi_{x,0}\right]}\right\} \quad (2)$$

(f_{2000} is generated by quadrupolar field errors δK_1)

$$f_{2000,i} = \frac{\sum \delta K_{1,w}\beta_w e^{-2i\varphi_{wi}}}{8(1 - e^{-4\pi Q_x})} \quad (3)$$

creates phase advance beating between elements:

$$\Delta\varphi_{ij} = -2h_{1100,ij} + 4\mathcal{R}\left\{f_{2000,j} - f_{2000,i}\right\} + O(f^2) \quad (4)$$

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Up to first order in f_{2000}, $|f_{2000}|$, $\mathcal{I}\left\{f_{2000}\right\}$, $\mathcal{R}\left\{f_{2000}\right\}$ and δK_1.

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global terms in red

Up to first order in f_{2000}, $|f_{2000}|$, $\mathcal{I}\{f_{2000}\}$, $\mathcal{R}\{f_{2000}\}$ and δK_1.

Elimination of global terms

$$\Delta\varphi_{ij} = -2h_{1100,ij} + 4\mathcal{R}\left\{f_{2000,j} - f_{2000,i}\right\} \quad (5)$$

$$= \bar{h}_{ij} - 8sin^2\varphi^{\mathrm{m}}_{ij}\mathcal{R}\left\{f_i\right\} - 8sin\varphi^{\mathrm{m}}_{ij}cos\varphi^{\mathrm{m}}_{ij}\mathcal{J}\left\{f_i\right\} \quad (6)$$

$$(7)$$

Eliminate $\mathcal{R}\left\{f_i\right\}$ by resummation:

$$\frac{\Delta\varphi_{ij}}{sin^2\varphi^{\mathrm{m}}_{ij}} - \frac{\Delta\varphi_{ik}}{sin^2\varphi^{\mathrm{m}}_{ik}} = \frac{\bar{h}_{ij}}{sin^2\varphi^{\mathrm{m}}_{ij}} - \frac{\bar{h}_{ik}}{sin^2\varphi^{\mathrm{m}}_{ik}} - 8\left(cot\varphi^{\mathrm{m}}_{ij} - cot\varphi^{\mathrm{m}}_{ik}\right)\mathcal{J}\left\{f_i\right\} \quad (8)$$

Repeat this method to eliminate $\mathcal{J}\left\{f_i\right\}$:

$$\frac{\frac{\Delta\varphi_{ij}}{\sin^2\varphi^{\mathrm{m}}_{ij}} - \frac{\Delta\varphi_{ik}}{\sin^2\varphi^{\mathrm{m}}_{ik}}}{\cot\varphi^{\mathrm{m}}_{ij} - \cot\varphi^{\mathrm{m}}_{ik}} - \frac{\frac{\Delta\varphi_{ij}}{\sin^2\varphi^{\mathrm{m}}_{ij}} - \frac{\Delta\varphi_{il}}{\sin^2\varphi^{\mathrm{m}}_{il}}}{\cot\varphi^{\mathrm{m}}_{ij} - \cot\varphi^{\mathrm{m}}_{il}} = \frac{\frac{\bar{h}_{ij}}{\sin^2\varphi^{\mathrm{m}}_{ij}} - \frac{\bar{h}_{ik}}{\sin^2\varphi^{\mathrm{m}}_{ik}}}{\cot\varphi^{\mathrm{m}}_{ij} - \cot\varphi^{\mathrm{m}}_{ik}} - \frac{\frac{\bar{h}_{ij}}{\sin^2\varphi^{\mathrm{m}}_{ij}} - \frac{\bar{h}_{il}}{\sin^2\varphi^{\mathrm{m}}_{il}}}{\cot\varphi^{\mathrm{m}}_{ij} - \cot\varphi^{\mathrm{m}}_{il}} \quad (9)$$

Elimination of global terms

$$\Delta\varphi_{ij} = -2h_{1100,ij} + 4\mathcal{R}\left\{f_{2000,j} - f_{2000,i}\right\} \tag{5}$$

$$= \bar{h}_{ij} - 8sin^2\varphi^{\mathrm{m}}_{ij}\mathcal{R}\left\{f_i\right\} - 8sin\varphi^{\mathrm{m}}_{ij}cos\varphi^{\mathrm{m}}_{ij}\mathcal{J}\left\{f_i\right\} \tag{6}$$

(7)

Eliminate $\mathcal{R}\left\{f_i\right\}$ by resummation:

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Repeat this method to eliminate $\mathcal{J}\left\{f_i\right\}$:

$$\Phi^{\mathrm{meas}}_{ijkl} = \Phi^{\mathrm{model}}_{ijkl} \tag{9}$$

Elimination of global terms

$$\Delta\varphi_{ij} = -2h_{1100,ij} + 4\mathcal{R}\left\{f_{2000,j} - f_{2000,i}\right\} \tag{5}$$

$$= \bar{h}_{ij} - 8sin^2\varphi^{\mathrm{m}}_{ij}\mathcal{R}\left\{f_i\right\} - 8sin\varphi^{\mathrm{m}}_{ij}cos\varphi^{\mathrm{m}}_{ij}\mathcal{I}\left\{f_i\right\} \tag{6}$$

(7)

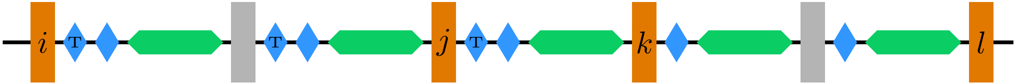
Special case: model phase advances of $n\pi$:

$$\Delta\varphi_{ij} = \bar{h}_{ij} \tag{8}$$

$$\frac{\frac{\Delta\varphi_{ij}}{\sin^2\varphi^{\mathrm{m}}_{ij}}-\frac{\Delta\varphi_{ik}}{\sin^2\varphi^{\mathrm{m}}_{ik}}}{\cot\varphi^{\mathrm{m}}_{ij}-\cot\varphi^{\mathrm{m}}_{ik}}-\frac{\frac{\Delta\varphi_{ij}}{\sin^2\varphi^{\mathrm{m}}_{ij}}-\frac{\Delta\varphi_{il}}{\sin^2\varphi^{\mathrm{m}}_{il}}}{\cot\varphi^{\mathrm{m}}_{ij}-\cot\varphi^{\mathrm{m}}_{il}}=\frac{\frac{\bar{h}_{ij}}{\sin^2\varphi^{\mathrm{m}}_{ij}}-\frac{\bar{h}_{ik}}{\sin^2\varphi^{\mathrm{m}}_{ik}}}{\cot\varphi^{\mathrm{m}}_{ij}-\cot\varphi^{\mathrm{m}}_{ik}}-\frac{\frac{\bar{h}_{ij}}{\sin^2\varphi^{\mathrm{m}}_{ij}}-\frac{\bar{h}_{il}}{\sin^2\varphi^{\mathrm{m}}_{il}}}{\cot\varphi^{\mathrm{m}}_{ij}-\cot\varphi^{\mathrm{m}}_{il}} \tag{9}$$

Local error sources:

$$\bar{h}_{ij}=\frac{1}{2}\sum_{w\in I}\beta^{\mathrm{m}}_{w}\delta K_{w,1}sin^2\varphi^{\mathrm{m}}_{wj} \tag{10}$$



Simulation with LHC design field errors

Simulating the LHC with a set of field errors that are to be expected after local and coupling corrections

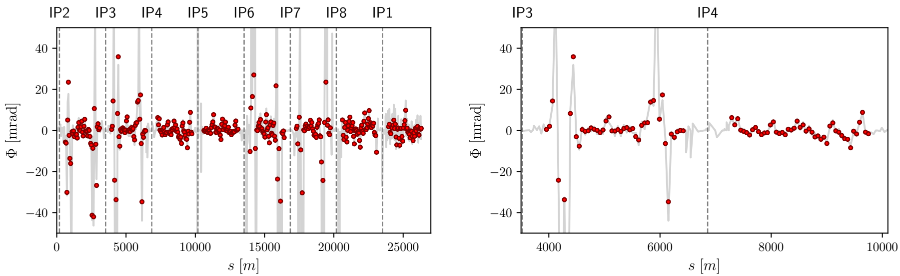


Figure: local observable for combination 45-45-45. LEFT: whole ring, RIGHT: zoom into the arcs around IP4

good agreement between simulation and formula

noise

Adding noise to the simulations:

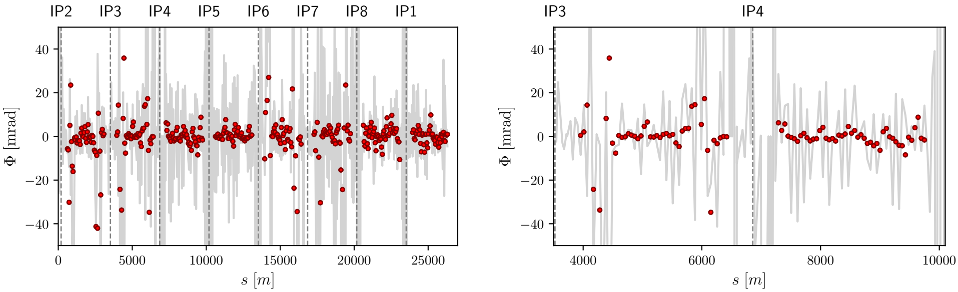


Figure: local observable for combination 45-45-45. LEFT: whole ring, RIGHT: zoom into the arcs around IP4

noise distorts the agreement

π phase advances

Testing the case $\varphi_{ij}^{\mathrm{m}} = n\pi$

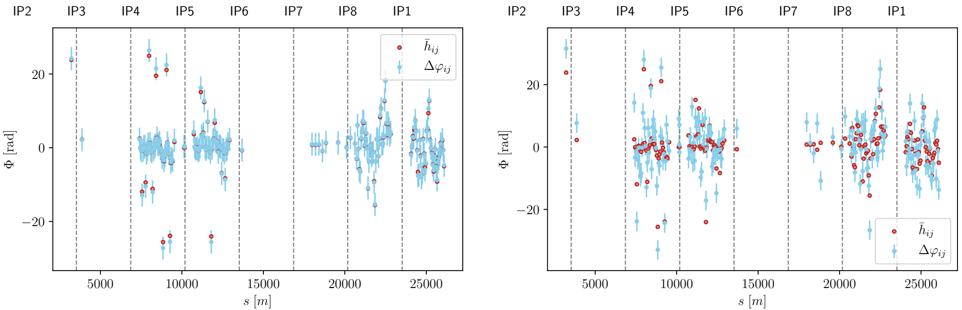


Figure: π model phase advances. LEFT: without noise, RIGHT: with noise

Overall better agreement than in the general case. Noise also affects agreement, but less stringly.

measurements

LEFT: Local observable, RIGHT: π model phase advances

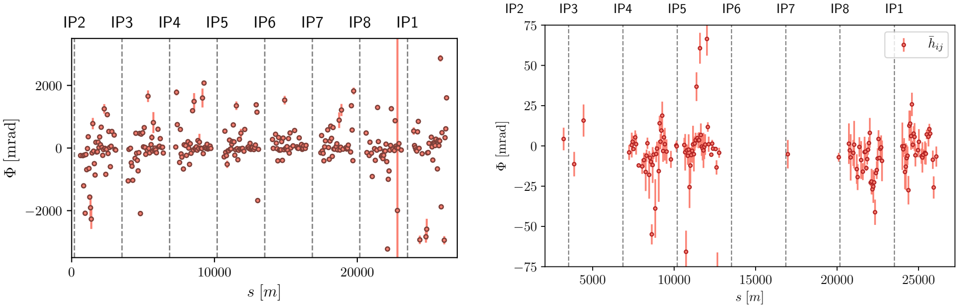


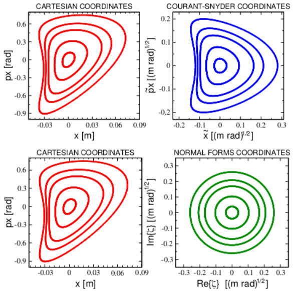
Figure: LHC machine development study with flat beams. LEFT: combination 45-45-45, RIGHT: π phase advances.

Conclusions and Outlook

Conclusions

- Up to first order a local observable for linear perturbations exist
- It can be shown that second order is not possible (i.e. not local)
- Noise is still an issue (can be mitigated by better instruments, more turns for FFT)

Backup Slides


CARTESIAN COORDINATES
px [rad]
x [m]
COURANT-SNYDER COORDINATES
p̃x [(m rad)^1/2]
x̃ [(m rad)^1/2]
CARTESIAN COORDINATES
px [rad]
x [m]
NORMAL FORMS COORDINATES
Im{ζ} [(m rad)^1/2]
Re{ζ} [(m rad)^1/2]

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Betatron oscillation due to quadrupolar field error

$$\hat{x}_i = \mathcal{R}\left\{\left(1 - f^*_{2000,i}\right)\sqrt{2I_x}e^{-i\left[2\pi N Q_x + \psi_{x,0}\right]}\right\} \tag{11}$$

Phase distortion from $f_{2000,i}$

$$\begin{aligned}\Delta\varphi_{2000,i} &= arg\left\{1 - 4i f^*_{2000,i}\right\}\\ &\approx -4\mathcal{R}\left\{f_{2000,i}\right\}\end{aligned} \tag{12}$$

and tune shift

$$\Delta Q = -\frac{\partial\langle H\rangle_\varphi}{\partial J_x} = \frac{\partial 2J_x h_{1100}}{\partial J_x} = -2h_{1100} \tag{13}$$

together give **phase beating**

$$\Delta\varphi_i = -2h_{1100,i} + 4\mathcal{R}\left\{f_{2000,j}\right\} \tag{14}$$

Phase advance beating

Some intermediate results:

$$h_{1100,ij} = -\frac{sgn(j-i)}{4}\sum_{w\in I}\beta_w \delta K_{w,1} + O(\delta K_1^2) \quad (15)$$

$$f_{2000,j} = sgn(j-i)\frac{1}{8}\sum_{w\in I}\beta_w \delta K_{w,1} e^{2i\varphi_{wj}} + f_{2000,i} e^{2i\varphi_{ij}} \quad (16)$$

Can be combined to

$$\Delta\varphi_{ij} = -2h_{1100,ij} + 4\mathcal{R}\left\{f_{2000,j} - f_{2000,i}\right\} \quad (17)$$