NHT Code Status

S. ANTIPOV

HSC SECTION MEETING 17.02.2020

MANY THANKS

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Physics

1. Impedance: Single-bunch + couple-bunch modes
2. Chromaticity
3. Damper feedback system: both resistive and reactive
4. Landau damping by nonlinearities
5. Beam-beam interaction (not tested, outside the scope)

RF well, Imp, Damp, CB

$$\frac{\Delta\omega}{\omega_s} X = \boxed{SX} - \boxed{iZX} - \boxed{igFX} + \boxed{CX},$$

Key Assumptions: 2017

1. Weak space charge: SC tune shift is negligible compared to the synchrotron tune
2. Dipolar impedance only
3. Flat intra-bunch and beam-beam wakes
4. Equidistant bunches
5. Gaussian longitudinal distribution
6. Independent modes and weak head-tail approximation (for Landau damping)
7. Stability diagram approach based on predefined linear detuning coefficients and using only the most unstable mode

Key Assumptions: 2020

1. Weak space charge: SC tune shift is negligible compared to the synchrotron tune
   - Landau damping by SC can be treated in a linear model (Métral, Ruggiero ’04)
2. Dipolar impedance only
3. Flat intra-bunch and beam-beam wakes
   - High frequency HOMs can also be treated
4. ~~Equidistant bunches~~
5. ~~Gaussian longitudinal distribution~~
6. Independent modes and weak head-tail approximation (for Landau damping)
7. Stability diagram approach based on predefined linear detuning coefficients and using only the most unstable mode

Running on Lxplus

>>> ssh –Y lxplus

>>> mathematica[1]

Compatible with Mathematica 10 or higher (current lxplus version is 12)

Parallelized computation utilizing up to 10 cores

Include only the physics you need, run only the scans you need

Input files - all are optional:

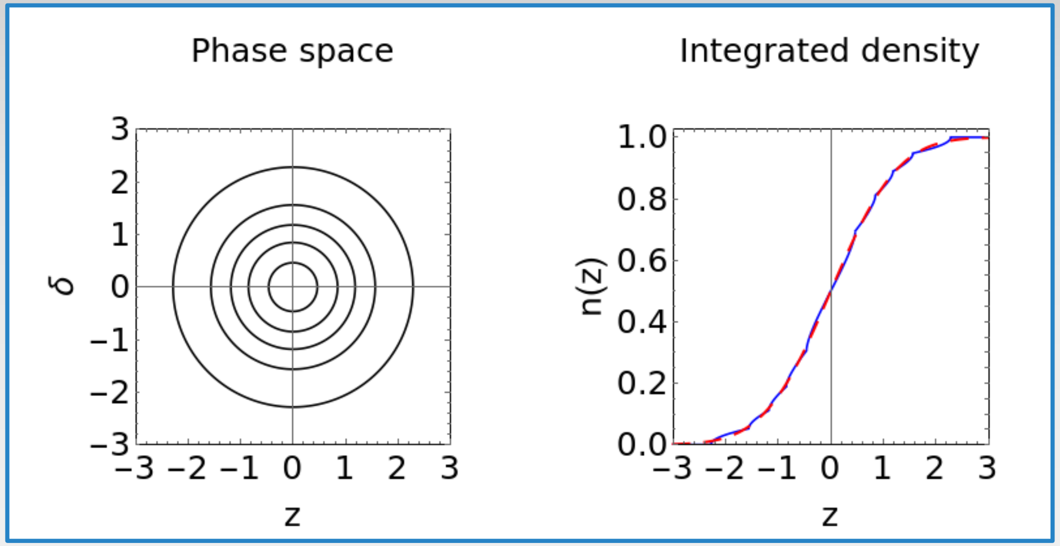
- Dipolar impedance (smooth, well defined)
- Dipolar wake (1 bunch spacing …)
- Filling pattern

Computation steps:

1. Precompute Impedance and Wake Matrices (~ 1 h, once)
   - For given Z, W, Q', and long. distribution
2. Solve eigenvalue problem (< 1 sec)
   - Can vary damper gain, phase, N_b
   - Can choose Q'
   - Can chooze SB or CB problem

[1] Thanks O. Berrig for showing how to run mathematica on lxplus

Longitudinal Basis



Numer of rings: $2\pi f \Delta\tau << 1$

4 Longitudinal distributions are supported at the moment:

- Gaussian
- q–Gaussian
- Uniform
- Air-Bag (Gaussian with 1 radial ring)

Other distributions can be added easily if needed

Single bunch problem

Eigenvalue problem:

RF well, Imp, Damp, CB

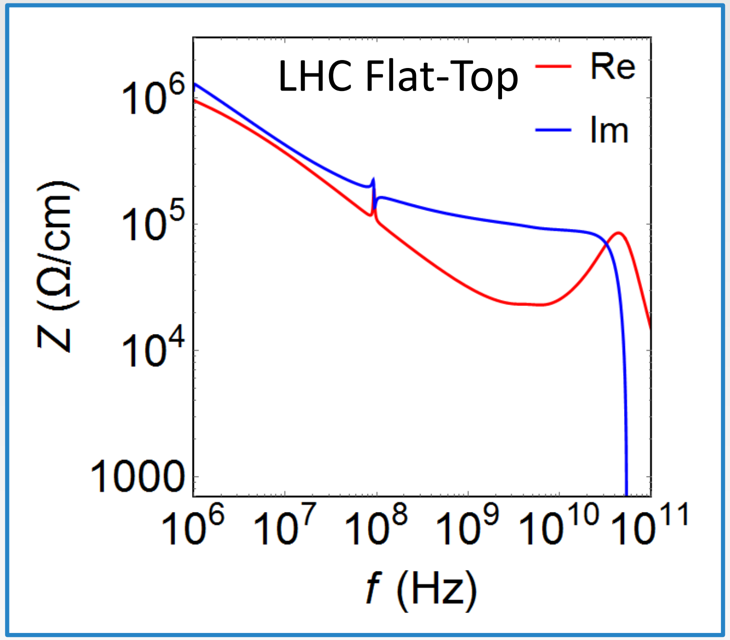
$$\frac{\Delta\omega}{\omega_s}X = \boxed{SX} - \boxed{iZX} - \boxed{igFX} + \boxed{CX},$$

Compute impedance integrals:

$$Z = i^{l-m}\frac{\kappa}{n_r}\int_{-\infty}^{+\infty} Z_1^{\perp}(\omega')J_l(\chi'_\alpha)J_m(\chi'_\beta)d\omega'.$$

Easily parallelized – up to x10 speedup on lxplus

Impedance has to be a smooth function of frequency for better numerical convergence of the integrals



Coupled bunch problem: equidistant bunches

Eigenvalue problem:

RF well, Imp, Damp, CB

$$\frac{\Delta\omega}{\omega_s} X = \boxed{SX} - \boxed{iZX} - \boxed{igFX} + \boxed{CX},$$

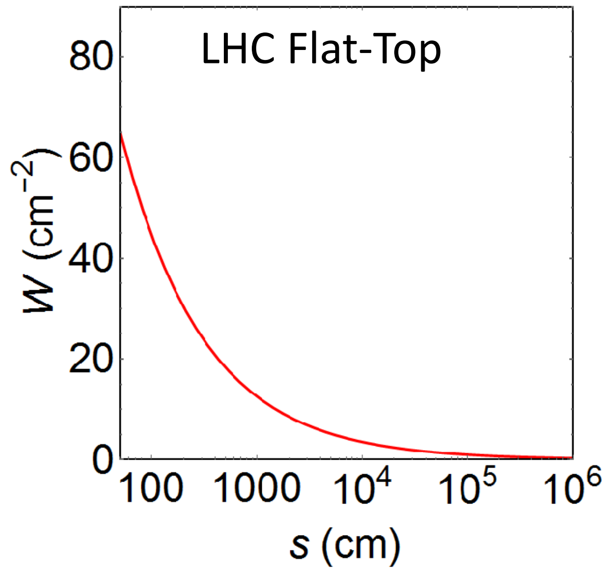
Flat wake approximation:

$$C^{\mu}_{lm\alpha\beta} = W^{\mu} F_{lm\alpha\beta}$$

$$F = \frac{i^{m-l}}{n_r} J_l(\chi_\alpha) J_m(\chi_\beta)$$

Equidistant bunches:

$$W^{\mu} = 2\pi\kappa \sum_{k=1}^{\infty} W(-ks_0)\exp(2\pi i \nu_{k\mu}) \qquad \mu = 0, \ldots M-1, \qquad \nu_{k\mu} = k(\mu+\nu)/M$$

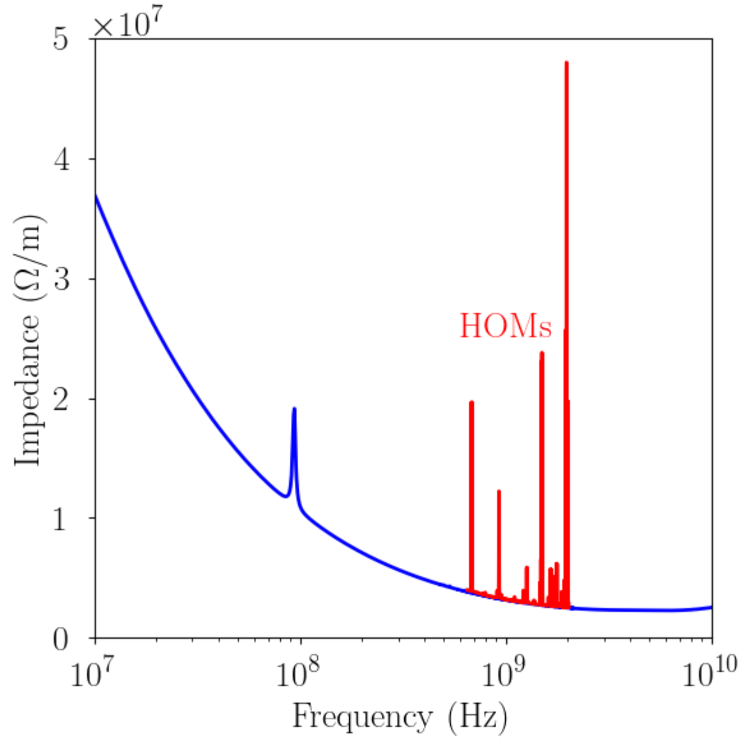


Coupled bunch problem: HOM

Can add a couple (preferably just one) most critical HOM

~~Flat wake approximation~~

$$W^{\mu} = 2\pi\kappa \sum_{k=1}^{\infty} W(-ks_0)\exp(2\pi i \nu_{k\mu}) \qquad \mu = 0, \ldots M-1, \quad \nu_{k\mu} = k(\mu+\nu)/M$$



Details in S. Antipov *et al.*, *PRAB* 22, 054401 (2019)

Coupled bunch problem: realistic pattern

Eigenvalue problem:

$$\frac{\Delta\omega}{\omega_s} X = \underbrace{SX}_{\text{RF well}} - \underbrace{iZX}_{\text{Imp}} - \underbrace{igFX}_{\text{Damp}} + \underbrace{CX}_{\text{CB}},$$

Flat wake approximation:

$$C^{\mu}_{lm\alpha\beta} = W^{\mu} F_{lm\alpha\beta}$$

$$F = \frac{i^{m-l}}{n_r} J_l(\chi_\alpha) J_m(\chi_\beta)$$

Need to solve for couple-bunch eigenmodes:

$$w^{\mu} Y^{\mu} = (W - igG) Y^{\mu}$$

- Adding up conventional and damper wakes
- If the feedback is ideal – last term is a diagonal matrix and can be taken out

$$W^{\mu} - ig \rightarrow w^{\mu}$$

Coupled bunch problem

$$w^{\mu} Y^{\mu} = (W - igG) Y^{\mu}$$

Since bunch patters are, in general, pretty regular many intra-bunch wakes are the same.

- Wake need to be computed only once – significant time saving

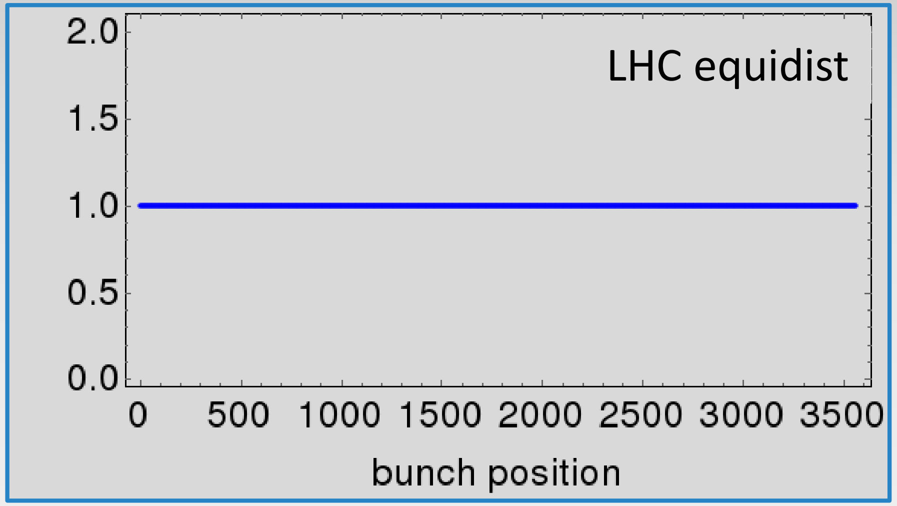
By default computes a handful of most unstable and most stable modes

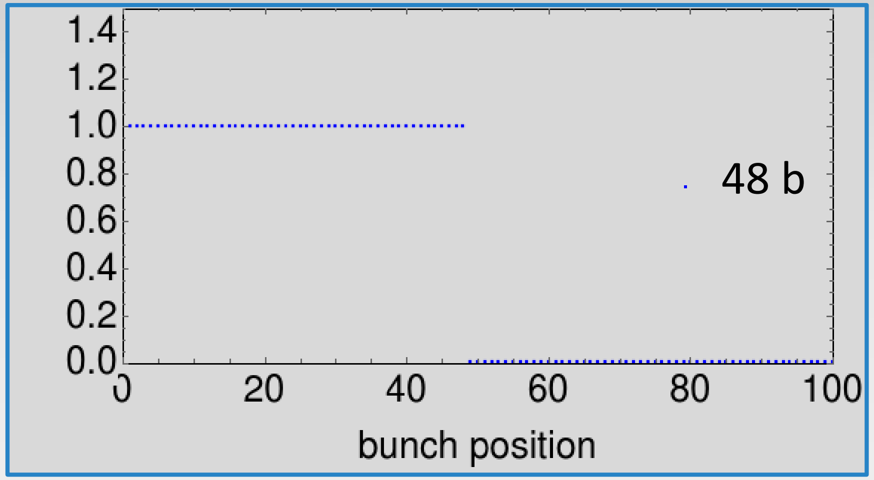
- Originally - guessing the CB numbers based on the knowledge of the wake
- Iterative Arnoldi solver, which ulilizes the sparness of the matrix
- Approximate solution using a lower rank approximation (see Halko *et al.* '11)

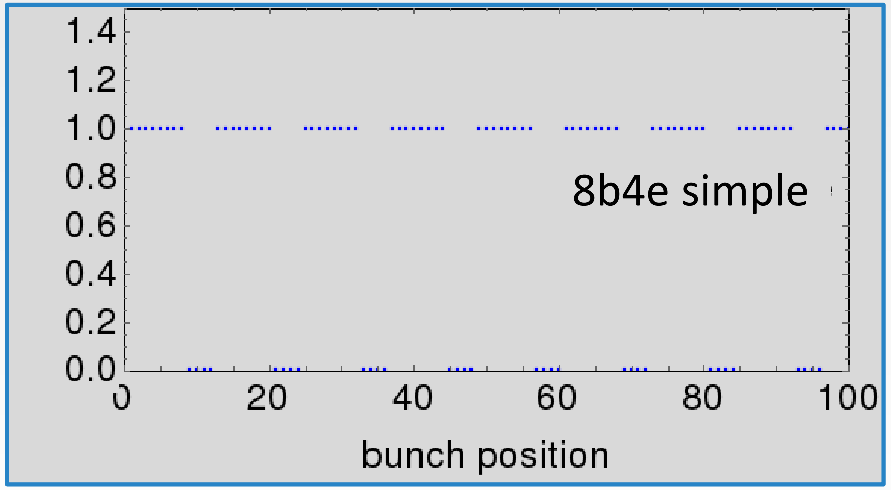
One can also explicitly ask it to compute all the CB modes

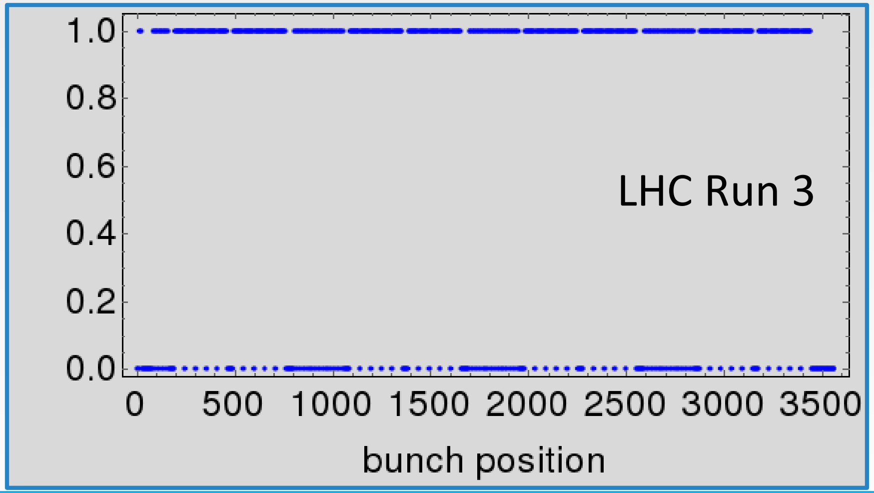
- Works in a reasonable time even for a system as large as FCC (circa 10000 CB modes)
- Used for benchmarking

Filling patterns









Damper

Eigen value problem:

RF well, Imp, Damp, CB

$$\frac{\Delta\omega}{\omega_s}X = \underbrace{SX}_{\text{RF well}} - \underbrace{iZX}_{\text{Imp}} - \underbrace{igFX}_{\text{Damp}} + \underbrace{CX}_{\text{CB}},$$

By default an ideal feedback is assumed (damper matrix **G** = *g* **E**)

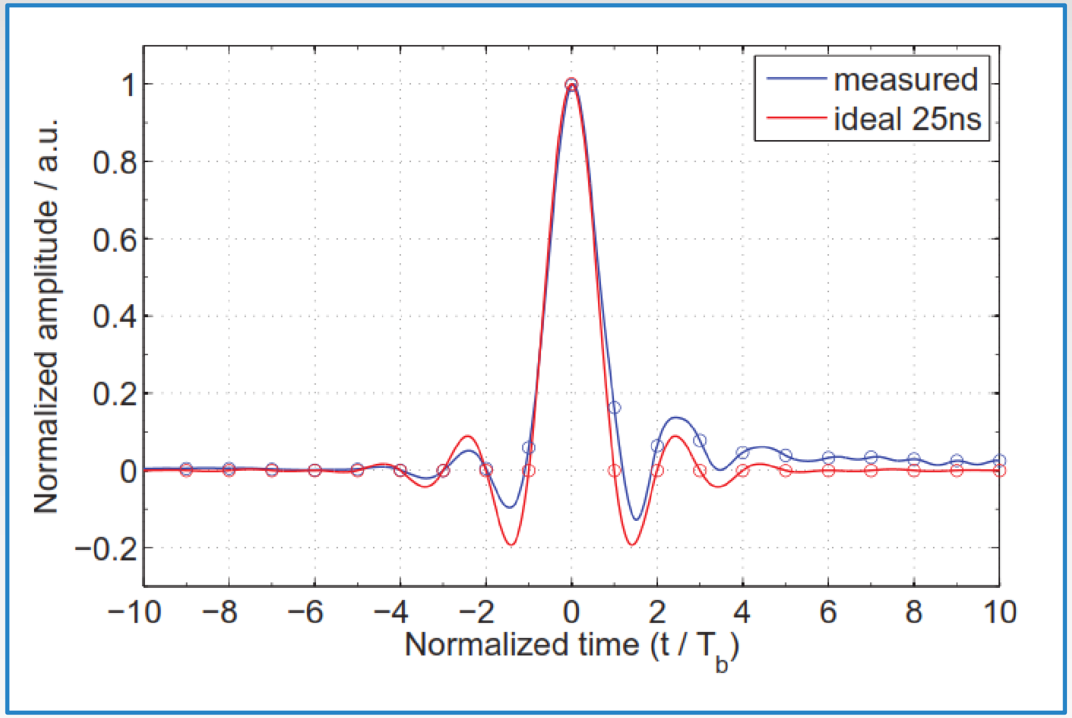
Unideal feedback - need to solve for couple-bunch eigenmodes:

$$w^{\mu}Y^{\mu} = (W - igG)Y^{\mu}$$

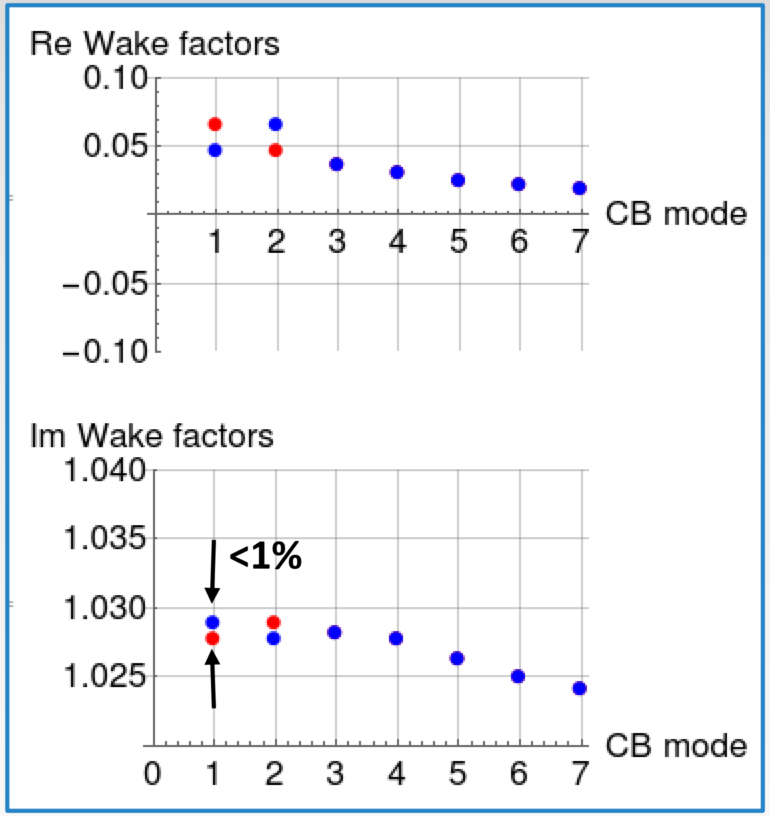
- Straightforward – matrix **G** can be readily filled from data
- Can no longer vary damper strength – affects the CB modes

Damper: Realistic LHC

Feedback **kick leaks** into
the bunches **behind** and in the **front**



W. Hofle *et al., IPAC'13*



In a practical case of LHC no significant difference has been found

Running a Test Case

Set up Physics

- Impedance (SB problem)
- CB Wakes
- Damper
- HOM (if any)

Choose Parameters

- Chromaticity
- Damper gain and phase (if applicable)
- Intensity

Running a Test Case

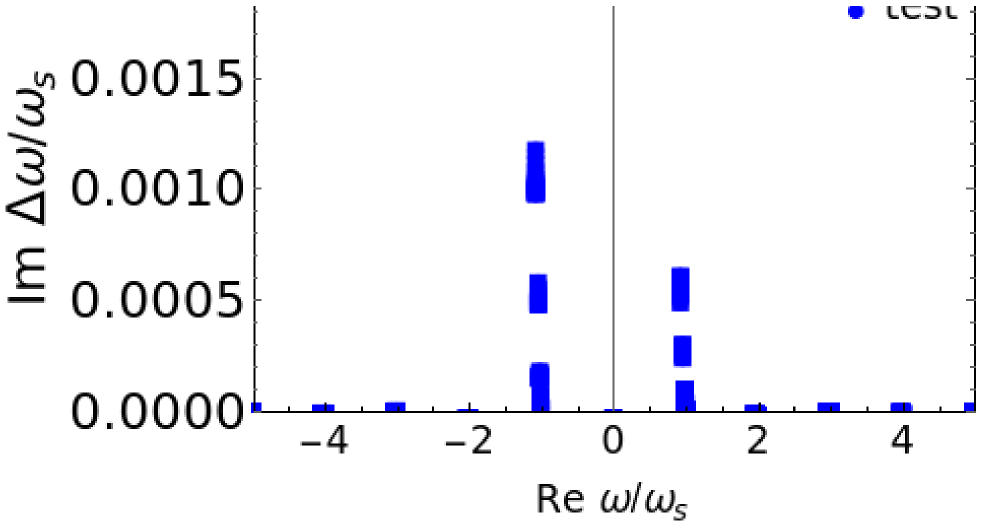
Set up Physics

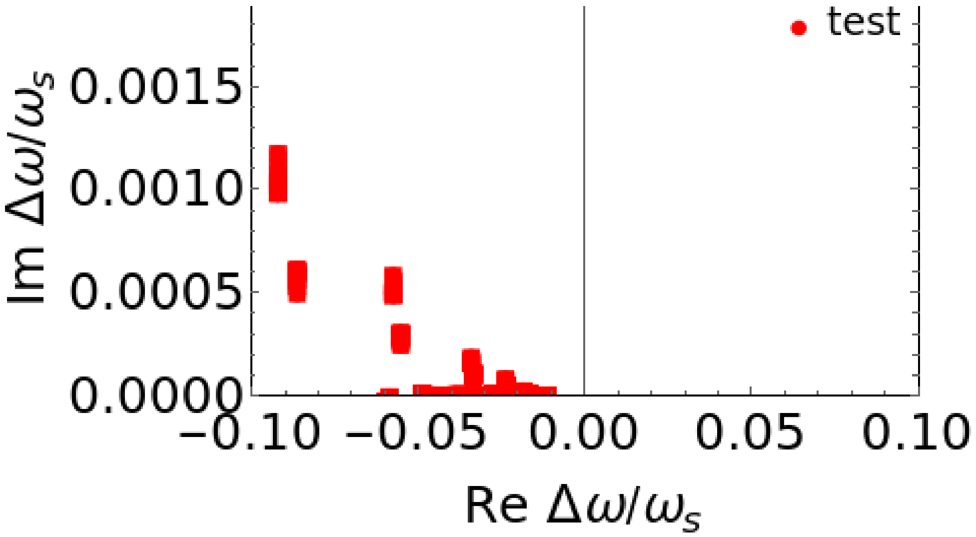
- Impedance (SB problem)
- CB Wakes
- Damper
- HOM (if any)

Choose Parameters

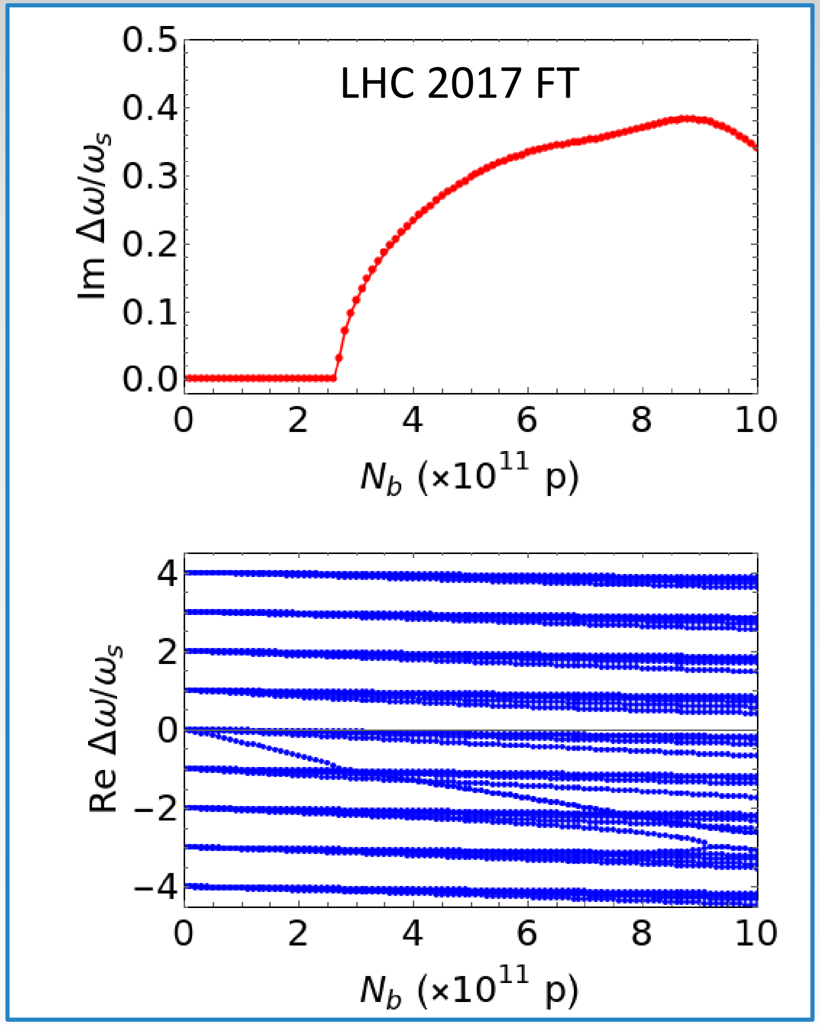
- Chromaticity
- Damper gain and phase (if applicable)
- Intensity

Output – Eigenmodes. Eigenvectors are computed but not stored by default





1D Scan – TMCI Search



Multiparametric Scans

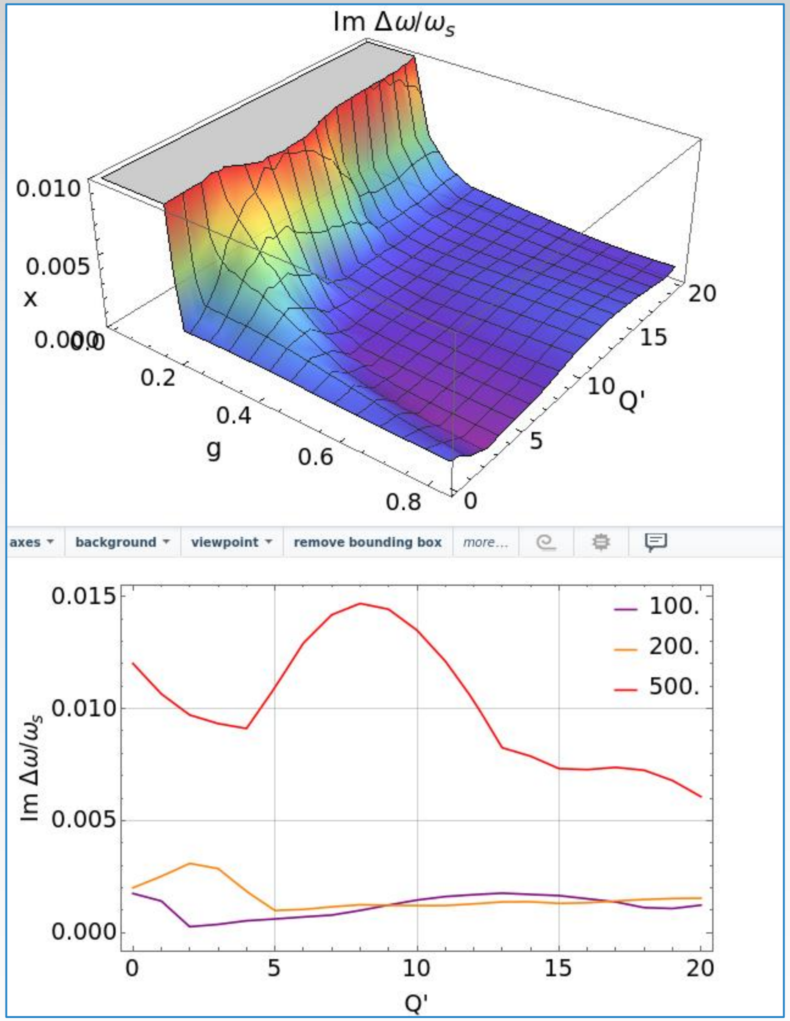
2 Parameters:

- Chroma & Damper
- Intensity & Damper
- Intensity & Chroma
- Damper Gain & Phase

Can scan arbitrary number of parameters at once

- Complete problem – 1 sec/case/core

Fully parallelized within one node on lxplus



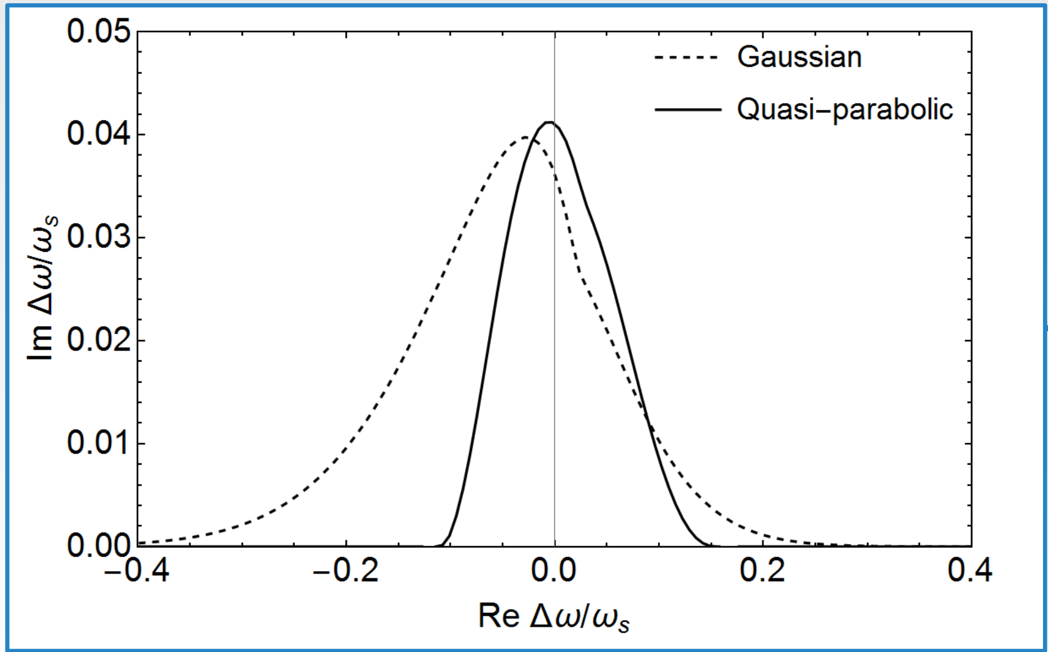
Landau damping

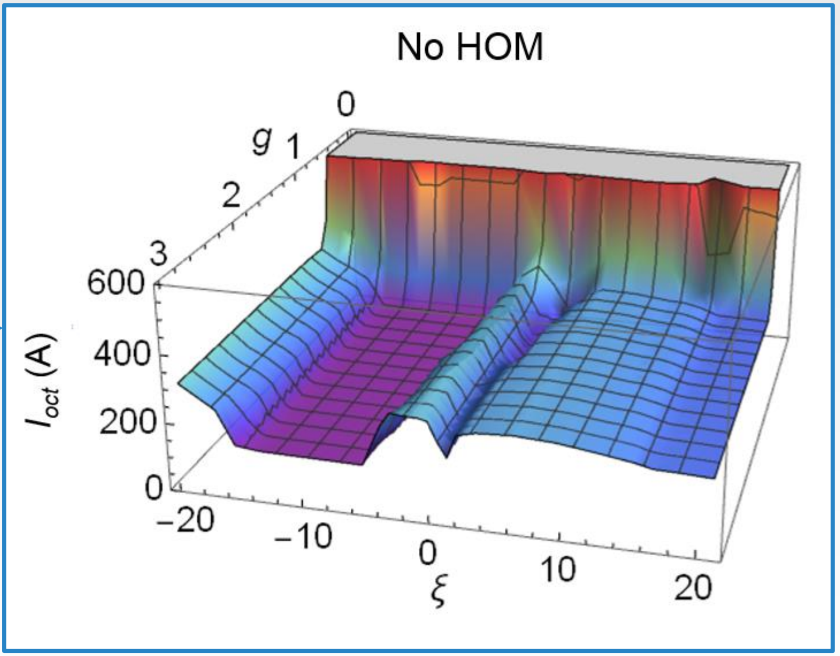
Stability diagram approach

- Only the most ustable mode, can extend to all modes
- Gaussian or Quasi-Parabolic transverse distribution

Hard-coded detuning coefficients

- Coupling can be introduced as a change in detuning coefs.



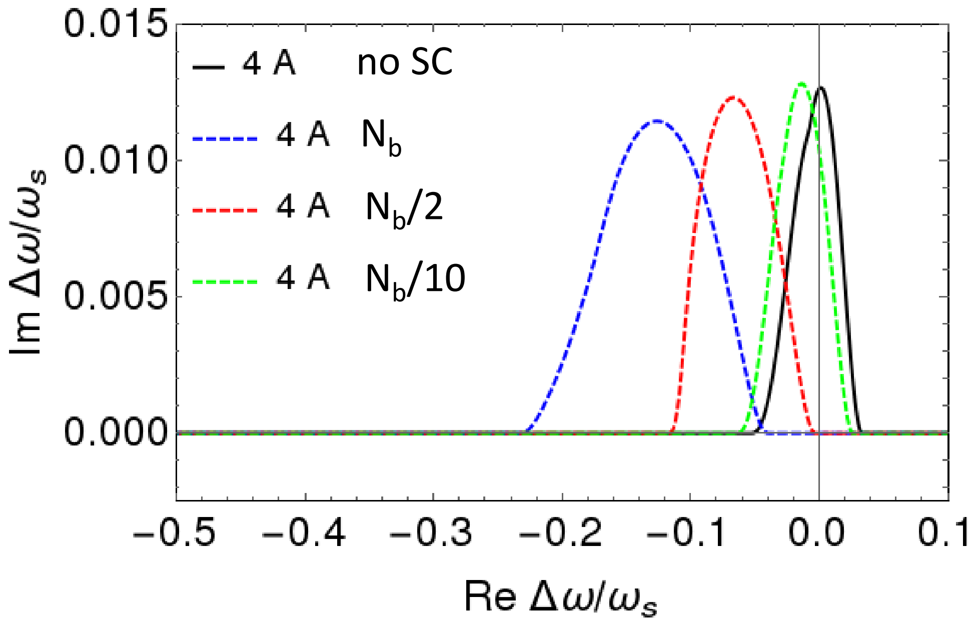


Landau damping: Accounting for space charge

Simplified coasting beam model:

- E. Métral and F. Ruggiero, CERN-AB-2004-025-ABP
- Quasi-parabolic transverse distribution
- Linear space charge
- Use with great care!

Space charge shifts the maximum of the SD



LHC injecton, E = 450 GeV
Bunch intensity: $N_b = 1.15 \times 10^{11}$ p
Linear SC param.: $\Delta_0 = -1.1 \times 10^{-3}$

Benchmarks

S. Antipov, 112nd HSC, 26.07.2017	Analytical formulas, DELPHI	SPS (Broadband)
S. Antipov *et al.*, *PRAB* 22, 054401 (2019)	PyHT	HLLHC (Crab Cav)
N. Klinkenberg, 155th HSC, 24.09.2018	DELPHI	FCC-hh
D. Amorim *et al.*, *ICFA Beam Dyn. News.* 72 (2017)	DELPHI, BIB-BIM	HE-LHC
D. Amorim, 180th HSC, 17.06.2019	PyHT, DELPHI	LHC
N. Mounet, 181st HSC, 01.07.2019	DELPHI	HLLHC (Crab Cav)
C. Zannini, 180th HSC, 17.06.2019	PyHT	SPS (HOM)

What next?

Sample notebooks created for some CERN machines:

- LHC
- HL-LHC
- SPS
- Anything else?

Possible further development

- Major issue – lack of automatic convergence check
  - Need be able to expand matrices with additional radial and azimuthal modes
  - Can use an interative solver to check only for a couple modes (most stable, most unstable)
- More accurate LD
- Transition to Python3