ICFA mini-Workshop on "Mitigation of Coherent Beam Instabilities in particle accelerators" MCBI 2019

MCBI in low emittance rings

S. White

Acknowledgments: J. Chavanne, S. Liuzzo and R. Nagaoka

ESRF | The European Synchrotron

OUTLINE

Low emittance rings design

Impact on collective effects

Collective instabilities in low emittance rings

Mitigation of collective instabilities

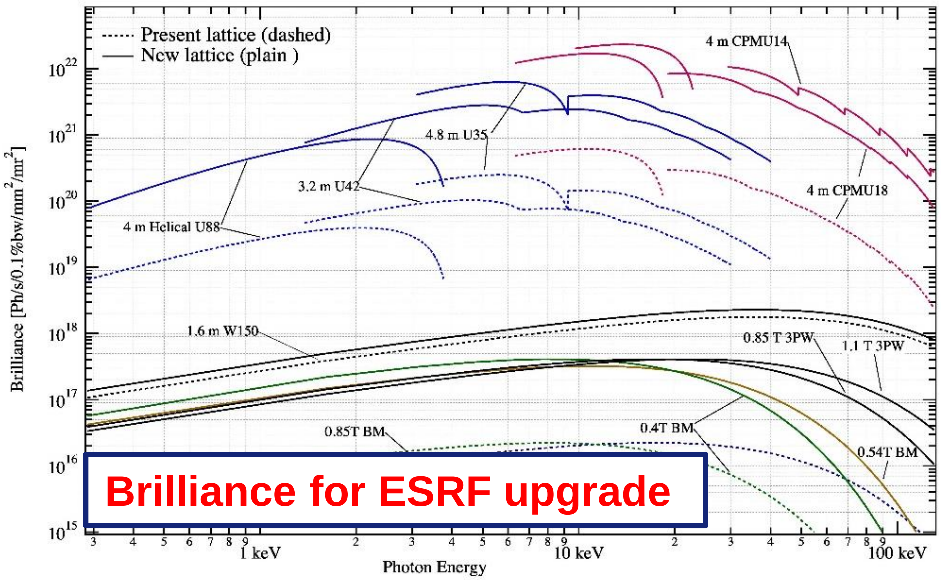
BRILLIANCE

$$B_n = \frac{F_n}{4\pi^2\left(\varepsilon_x + \frac{\lambda_n}{4\pi}\right)\left(\varepsilon_y + \frac{\lambda_n}{4\pi}\right)}, F_n \propto I$$

High current and low emittance

$$\varepsilon_{x,y} < \frac{\lambda}{4\pi}$$

Diffraction limit at λ_n=10nm (~10keV) is ~10 pmrad



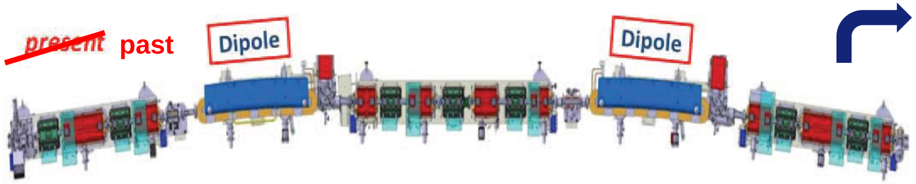
Brilliance for ESRF upgrade

- **ε_y: coupling correction**
- $\varepsilon_x = C_q \frac{\gamma^2 I_5}{J_x I_2} \propto \frac{\beta_x D_x}{\rho}, \varepsilon_x^{DBA} \approx 5.036e^{-13} E^2 \theta^3$
    - **Beam/photon energy**
    - **Optics tuning**
    - **Bending angle / number of dipoles / space / €**
    - **Partition number: combined function magnets**
- **Beam current: RF power and collective effects**

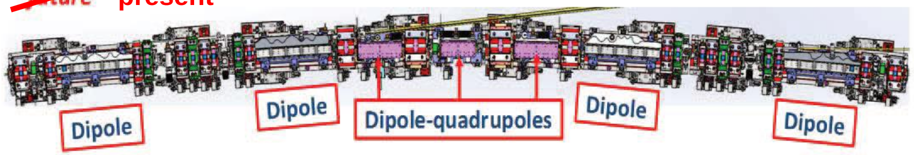
EXAMPLE OF ESRF LOW EMITTANCE LATTICE

DBA lattice (already “low emittance”)
2 dipoles per cell
16 superperiods (mirrored cell above, 32 cells in total).
Achromatic condition broken for lower emittance (ε_x from 7 nm.rad to **4 nm.rad**).

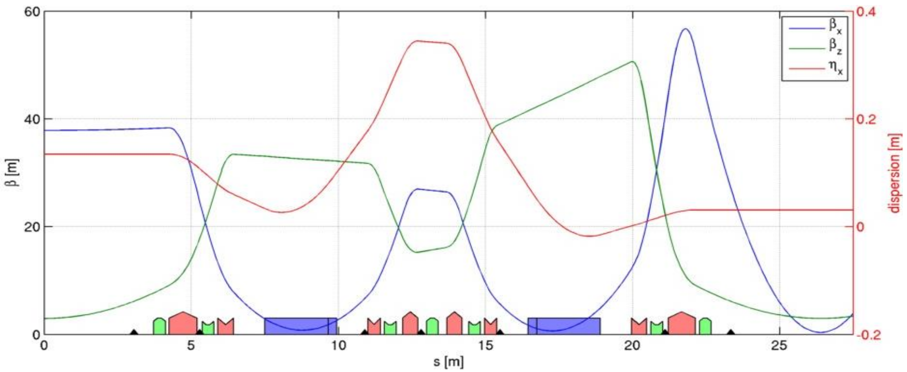
~~present~~ past



~~future~~ present



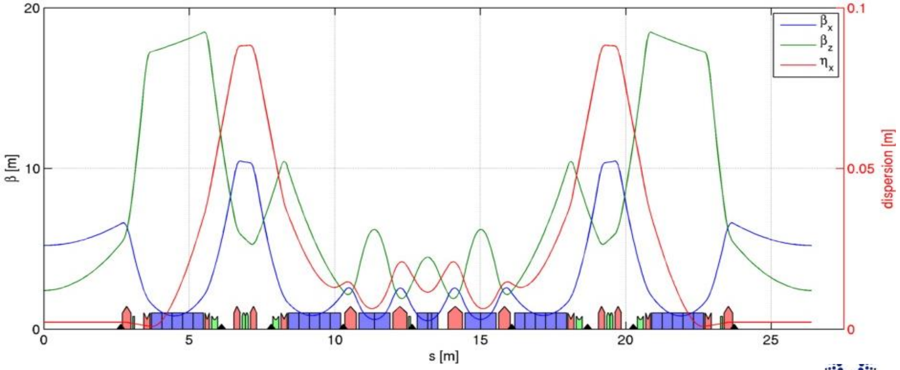
HMBA lattice (ultra “low emittance”)
7 dipoles per cell
strong focusing and consequently sextupoles
32 cells in total: 31 + 1 injection
ε_x = 0.135 nm.rad



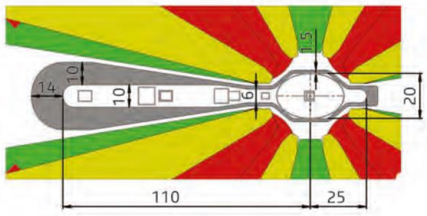
dipoles

quadrupoles

sextupoles

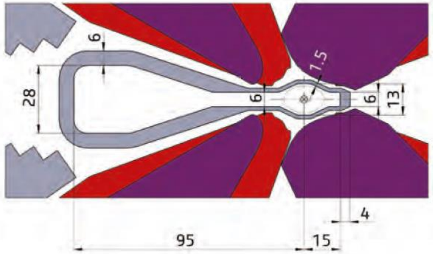


IMPACT ON COLLECTIVE EFFECTS

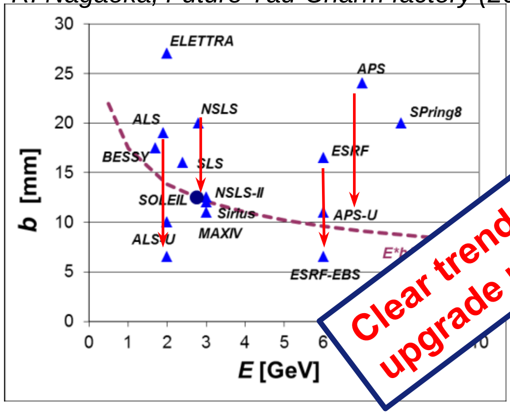


Upstream/down stream chamber
TM cut-off = 9.33 GHz

Central (strong focusing) chamber
TM cut-off = 13.76 GHz



R. Nagaoka, Future Tau-Charm factory (2018)



Clear trend in recent upgrade programs

- **Reduce emittance with increased number of dipoles:**
  → strong distributed focusing and sextupoles
  → reduction of dynamic aperture
  → reduced dispersion: lower α
  → reduction of the magnets and vacuum chambers aperture (32mm → 20/13mm)
  → reduced conductance, vacuum (?)

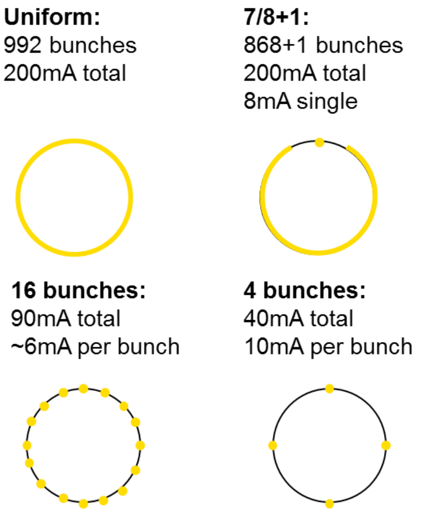
- **Improve photon characteristics:**
  → Reduce source size, mini-β optics
  → Low in-vacuum undulator gaps
  → Reduced straight section chamber aperture

- **Increased beam coupling impedance partially compensated by reduced β-functions**

- **Impedance minimization is essential and the most effective mitigation (see talk by R. Nagaoka)**

PARAMETERS AND OPERATIONAL MODES

- **Modern light sources cover a wide range of parameters on which collective instabilities strongly depend:**
  - **Energy, dimension:** radiation damping, instability growth rate
  - **Time structure:** multiple bunches low current, few bunches high current, hybrid
  - **Optics manipulation:** short bunch modes, anti-bends (low or negative α)



Uniform:
992 bunches
200mA total

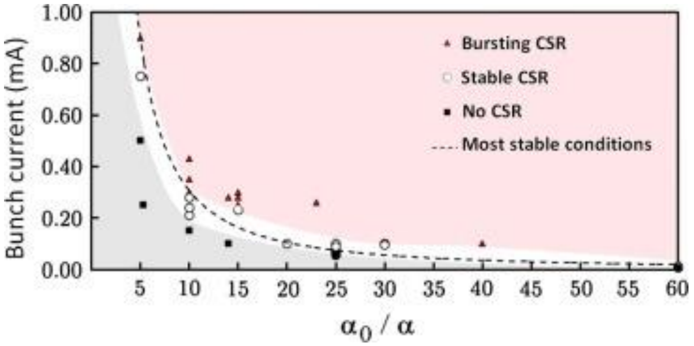
7/8+1:
868+1 bunches
200mA total
8mA single

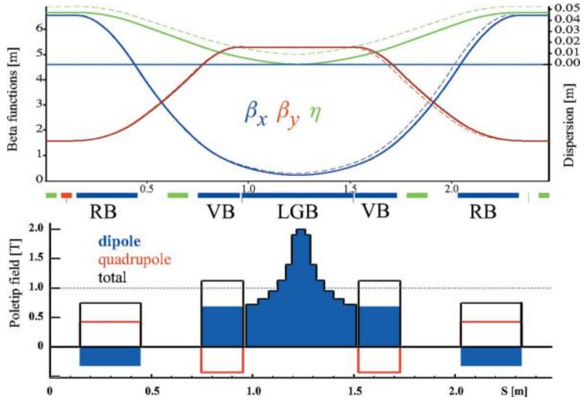
16 bunches:
90mA total
~6mA per bunch

4 bunches:
40mA total
10mA per bunch

Main ESRF filling modes

J. Barros et al. “Characteristics and development of the coherent synchrotron radiation sources for THz spectroscopy” (SOLEIL)





A. Streun et al. “SLS-2 – the upgrade of the Swiss Light Source”

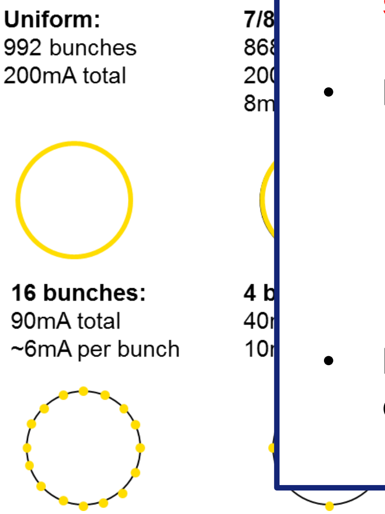
PARAMETERS AND OPERATIONAL MODES

- **Modern light sources cover a wide range of parameters on which collective instabilities strongly depend:**
  - **Energy, dimension:** radiation damping, instability growth rate
  - **Time s** hybrid
  - **Optics**)

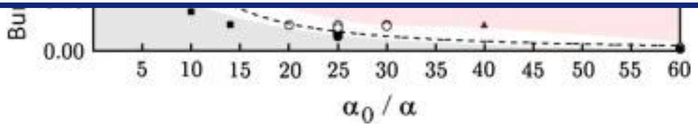
- **Low emittance rings face single/multi-bunch instabilities in all planes with different sources and sometimes simultaneously**

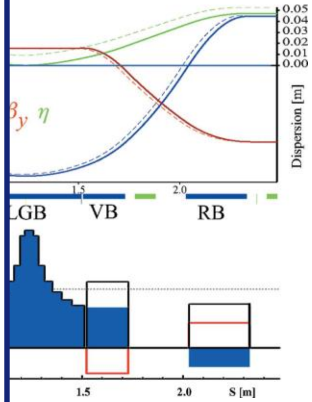
- **New lattice designs:**
  - **Enhanced impedance**
  - **Longer damping**
  - **Slower vacuum conditioning (?)**
  - **Shorter bunch length and smaller Q_s/α**

- **Low emittance rings are expected to be more difficult to operate: efficient mitigation measures to be anticipated**



Main ESRF filling modes





A. Streun et al. "SLS-2 – the upgrade of the Swiss Light Source"

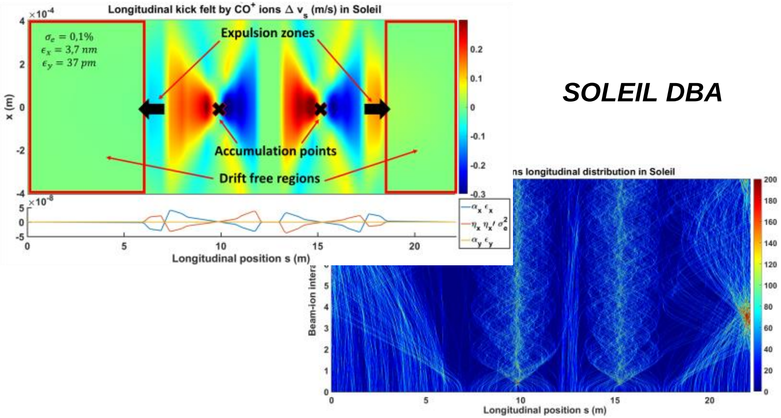
ION INSTABILITIES

- **Residual gas can be ionized by interaction with the beam or synchrotron radiation**

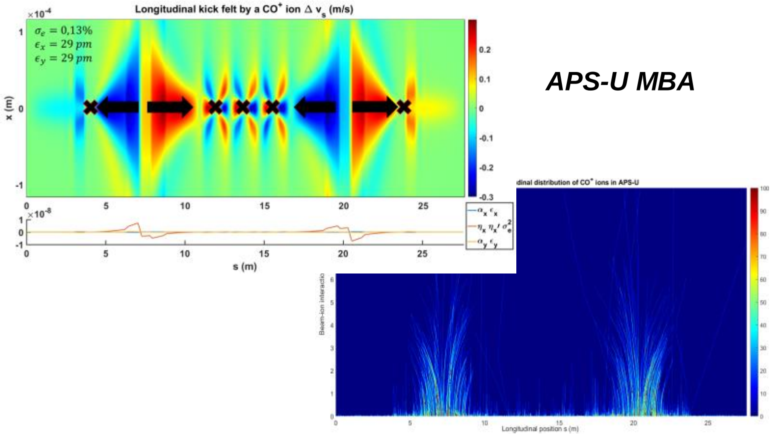
- **Ion trapping:**
  - Ions are attracted and trapped in the electron beam potential
  - Routinely observed in several machines
  - Tune shift/spread, emittance blow-up, lifetime reduction, beam oscillations
- **Mitigations**:
  - Gap in bunch train (most used)
  - Clearing electrodes
  - Beam shaking
  - Bunch-by-bunch feedback
- **Appears to be less critical in low emittance rings, to be confirmed experimentally**

- Fast beam-ion instability observed at SOLEIL following local outgassing. Saturates bunch-by-bunch feedback and results in full beam loss. Potential issue for LER

A. Gamelin (LER 2018)



SOLEIL DBA



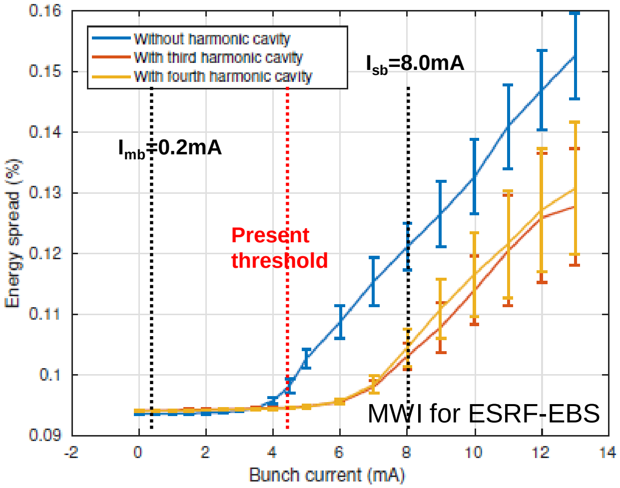
APS-U MBA

MICROWAVE INSTABILITIES

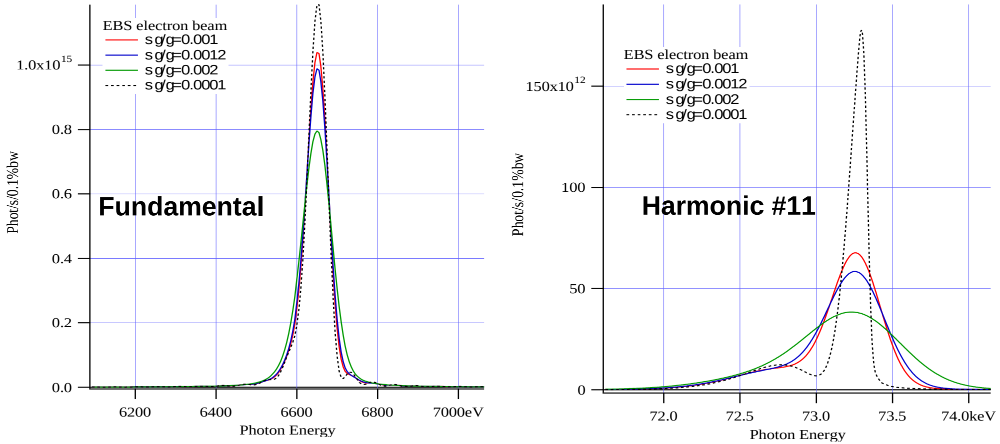
- **High frequency longitudinal impedance can drive microwave instability:**
  - Source can be CSR impedance or beam coupling impedance
  - Threshold effect above which the energy spread increases with the bunch length
  - Generally relevant for high current/bunch modes (threshold ~several mA) or special low α modes (threshold lower for short bunches)
  - **Affects the performance of beam lines using higher harmonics of undulators spectra**

- **Mitigation:** bunch lengthening with harmonic cavity

N. Carmignani et al. IPAC2017



Calculation by J. Chavanne for ESRF parameters



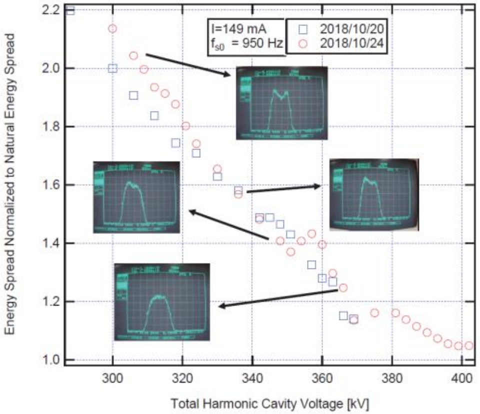
Undulator:
Period [mm]: 16
Length [m]: 2
K []: 2.1

Collecting aperture:
0.6 mm (H)
0.4 mm (V)
Distance from source: 30 m

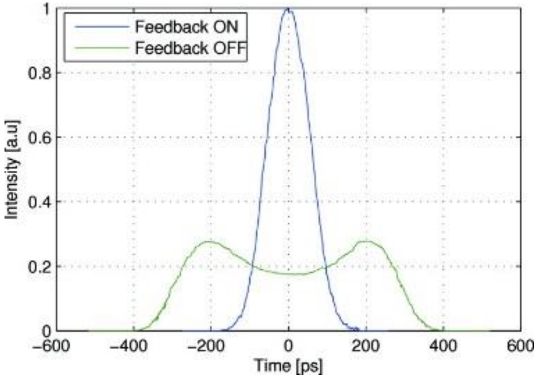
CAVITY HOM INDUCED INSTABILITIES

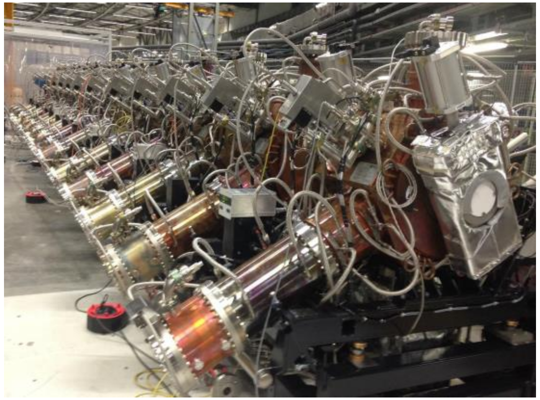
- **Coupled bunch instabilities driven by high-Q higher order harmonics of a cavity**
- **Exist both in transverse and longitudinal planes and may be a severe limitation to current ramp-up**

- **Mitigations:**
    - Temperature tuning of the cavities
    - Bunch-by-bunch feedback system
    - Bunch lengthening with harmonic cavities
    - HOM-damped cavity design
    - Bunch-by-bunch fluctuations

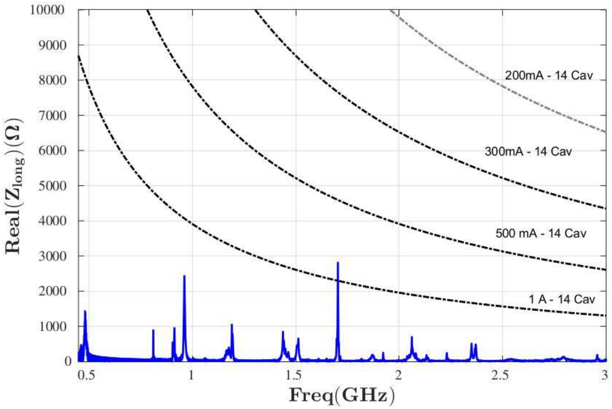


P. Tavares: IPAC19 & Commissioning and first-year operational results of the MAX IV 3 GeV ring"", J. Synch. Rad. (2018)





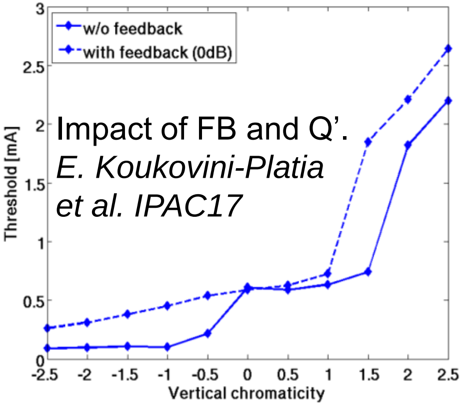
A. D'Elia: ESLS-RF (2018)



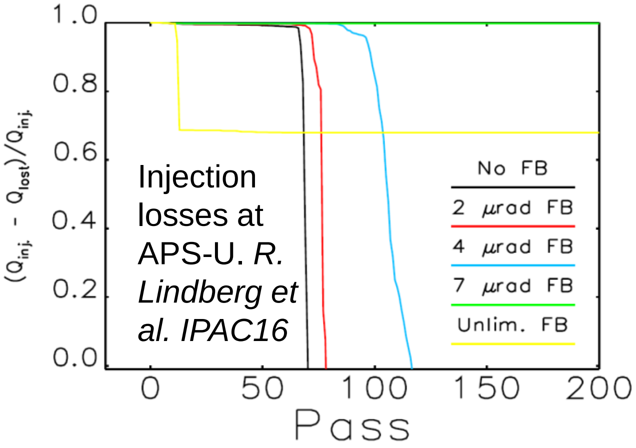
TMCI AND HEADTAIL INSTABILITIES

- **Multi-bunch modes are generally operated below the TMCI threshold while single bunch modes can be operated well above** (ESRF: 0.5mA threshold at Q'=0, multibunch current/bunch 0.2mA, max. single bunch current 10mA)
- **Results in beam loss or emittance blow-up at high chromaticity**
- **Injection can also be impacted:** injection saturation of high current bunches (ESRF), reduction of injection efficiency with small DA (APS-U)

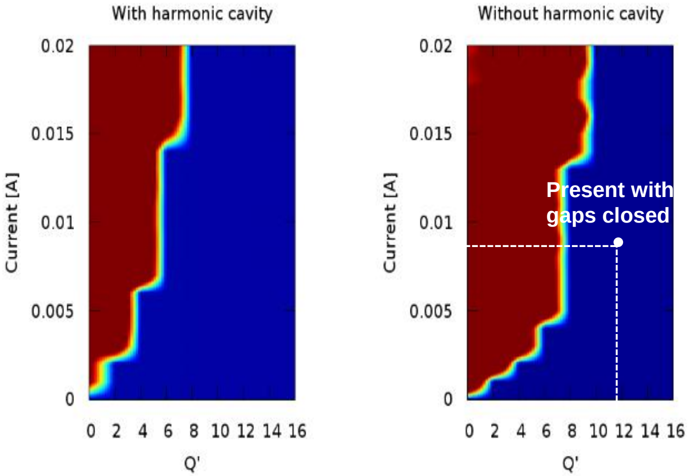
- **Mitigations:**
  - (Large) positive chromaticity (at the cost of lifetime)
  - Bunch-by-bunch feedback
  - Bunch lengthening with harmonic cavity



Impact of FB and Q'. *E. Koukovini-Platia et al. IPAC17*



Injection losses at APS-U. *R. Lindberg et al. IPAC16*



Present with gaps closed

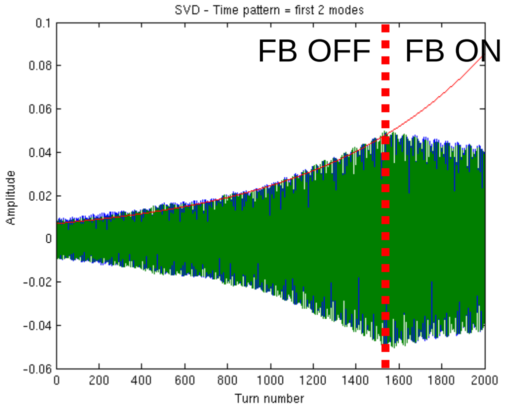
ESRF stability versus chromaticity with and w/o harmonic cavity

TRANSVERSE COUPLED BUNCH

- **In most cases driven by the long range resistive wall wakefield**
- Combination of feedback and chromaticity very effective: **generally not a limitation**

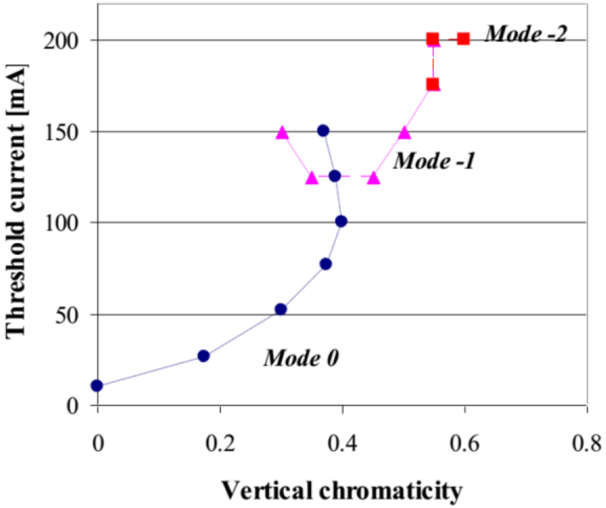
- **Low emittance rings: with reduced apertures a degradation can be expected**

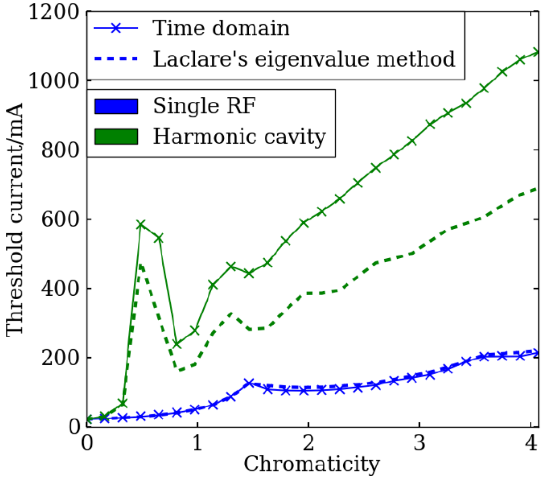
- **Mitigations: same as single bunch**



ESRF MB instability with feedback, E. Plouviez (2016)

ESRF MB instability thresholds versus Q' (R. Nagaoka, 2002)





Resistive wall MB instability thresholds with harmonic cavity (R. Cullinan et al., IPAC16)

SUMMARY

- **Recent low emittance rings MBA lattice designs aim at a significant reduction of horizontal emittance:**
    - increased number of dipole (sometimes anti-bends)
    - strong distributed focusing and sextupoles
- **Consequences:**
    - longer synchrotron damping
    - reduced α and Q_s
    - reduced dynamic aperture
    - smaller vacuum chamber apertures
- **These tend to increase impedance or enhance sensitivity to collective instabilities:**
    - partially compensated by lower β functions
    - and a number of mitigations measures: high chromaticity, bunch-by-bunch feedback, HOM-damped cavities, harmonic cavitiy

- **Impedance reduction is essential and the most effective mitigation: there is some room for improvement w.r.t ~20 years old machines**

- **At ESRF a significant effort was done** (zero impedance flanges, HOM-damped cavities, better conducting dipole vacuum chamber, smooth transitions, absorbers and pumping holes in ante-chamber…) **and the model predicts only a minor degradation w.r.t the previous machine** (to be confirmed next year) **but not much "knobs" left**

NEXT STEP?

- **Presently ESRF (and other light sources?) is serving a wide range of users with very different needs, for example:**
  - small 6D emittance, large number of bunches, small gaps, sometimes using higher undulator harmonics
  - high current per bunch, few bunches, emittance less critical, generally using the fundamental
  - **large number of running modes sometimes combined (hybrid modes): complex operation, simultaneous optimization of all modes difficult, design constraints**

- **Achieving 10pm round beams while maintaining this diversity seems very difficult** (not only because of collective effects)

- **Some users start to realize that they will not be able to handle the heat load of the full low emittance ESRF-EBS photon beam** and are considering stepping back to a single in-vacuum undulator with low gap at the center of a mini-β straight

- **Should we start thinking about machines dedicated to “low emittance” users community?**
  - low bunch current with large number of bunches
  - aggressive lattice with ultra-low emittance
  - short mini-β straight sections
  - low gap in-vacuum undulator with short period