Transverse Coherent Instabilities in Storage Rings with Harmonic Cavities

Francis Cullinan, Ryutaro Nagaoka
(Synchrotron SOLEIL, St. Aubin, France)
Galina Skripka, Pedro Fernandes Tavares
(MAX IV, Lund, Sweden)

7th International Particle Accelerator Conference, Busan, Korea, May 2016

Motivation

Trend in the design of modern light source storage rings to have a small vacuum chamber aperture

- Small-bore magnets for stronger focusing
- High resistive-wall impedance leads to transverse coupled-bunch instabilities
- Geometric impedance also increased

Another trend is the use of bunch lengthening harmonic cavities, in some cases, tuned to flat potential condition:

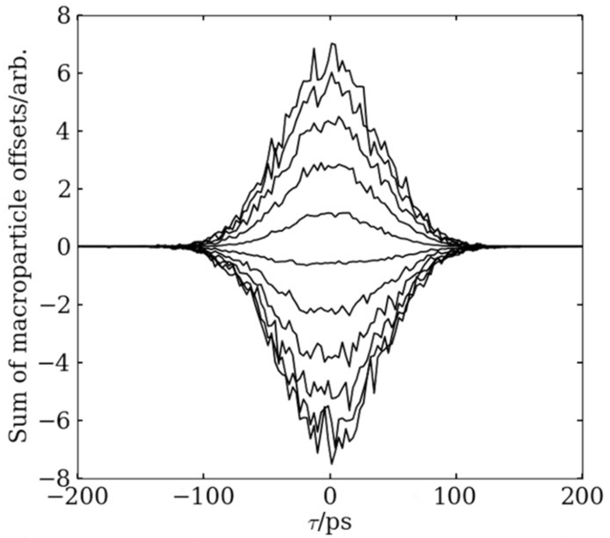
- Increases the Touschek lifetime
- Reduces emittance dilution due to intrabeam scattering
- Increases the threshold currents of transverse coupled-bunch instabilities

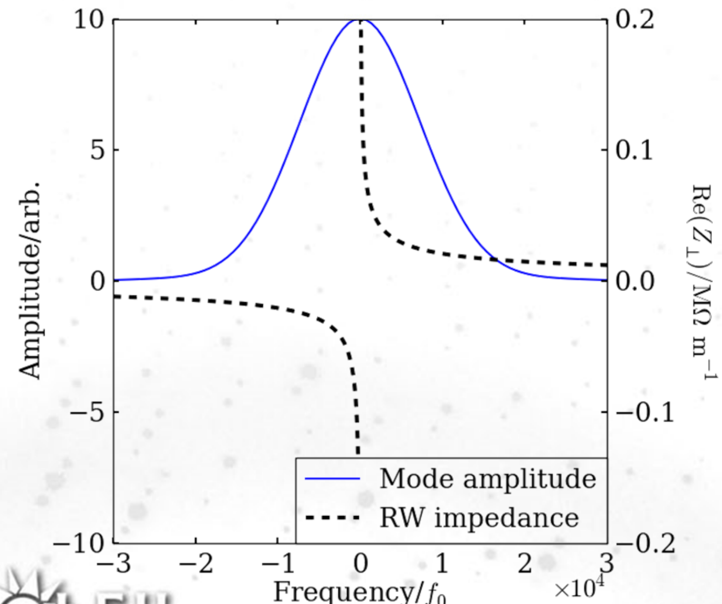
Outline

- Transverse coupled bunch instabilities
- Transverse dipolar bunch motion for different chromaticities
- Explanation for stabilisation in a harmonic cavity flattened potential
  - Examples from MAX IV vertical plane
- Harmonic cavities with different machine parameters

F. Cullinan et al., 2016, Transverse Coupled-Bunch Instability Thresholds in the Presence of a Harmonic-Cavity-Flattened RF Potential, submitted to PRAB.

Coupled Bunch Motion





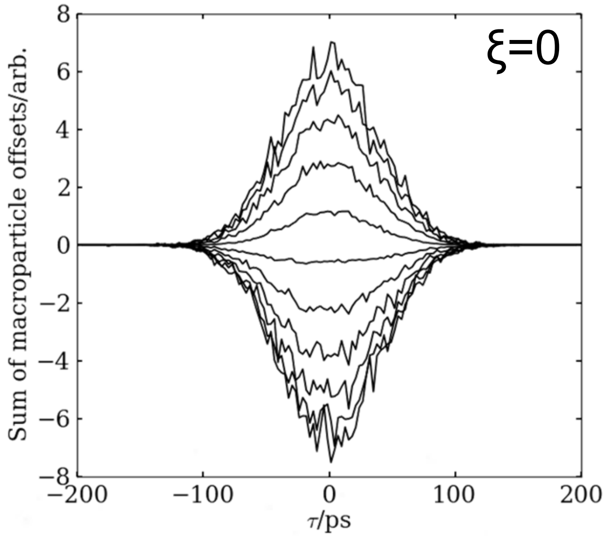
- Betatron oscillations of different bunches couple through longrange wakefields
- Coupled bunch modes interact at certain frequencies:

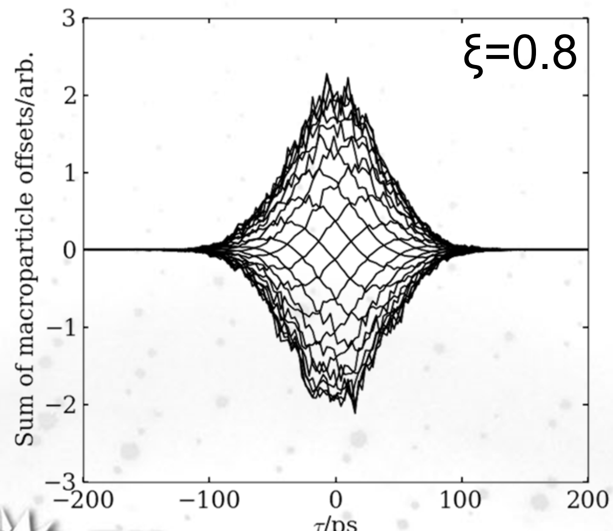
$$\omega_p = (Mp + \mu)\omega_0 + \omega_\beta$$

M – number of bunches
μ – coupled bunch mode number
p – Integer between $\pm\infty$
ω_0 – Angular revolution frequency
ω_β – Angular betatron frequency

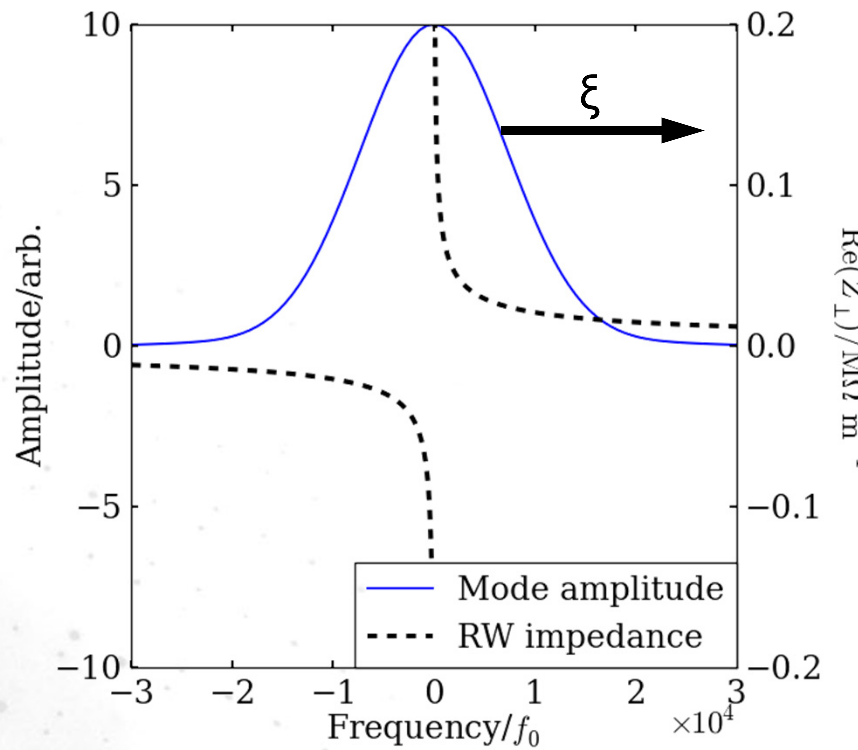
- Bunch spectrum and impedance determines strength of interaction
- Lowest negative frequency coupled-bunch mode μ=-1 dominant for resistive-wall instability

Effect of Chromaticity



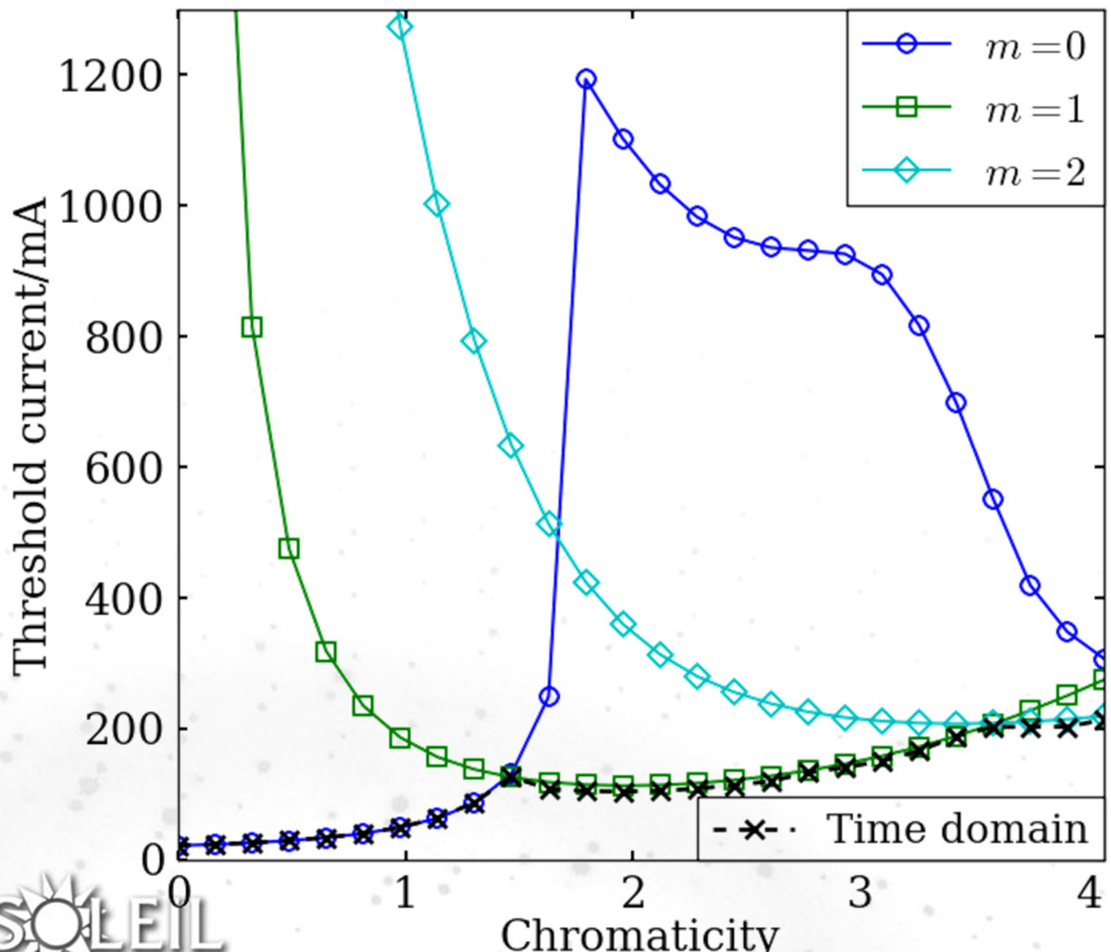


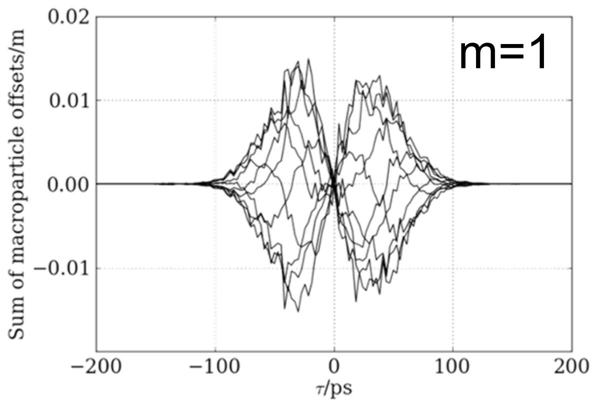
- At zero chromaticity, whole bunch performs betatron oscillations in phase
- Effect of chromaticity is betatron phase advance along the bunch
- In the frequency domain, shift in frequency

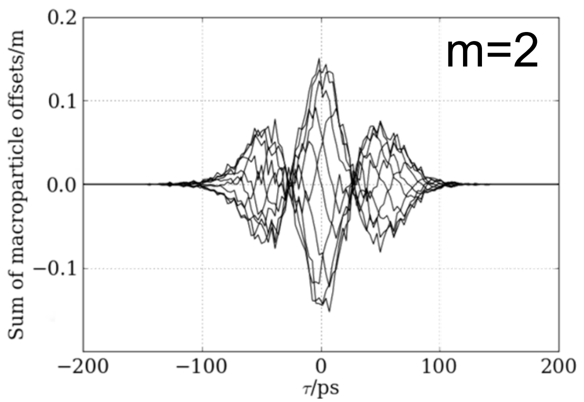


Single RF System

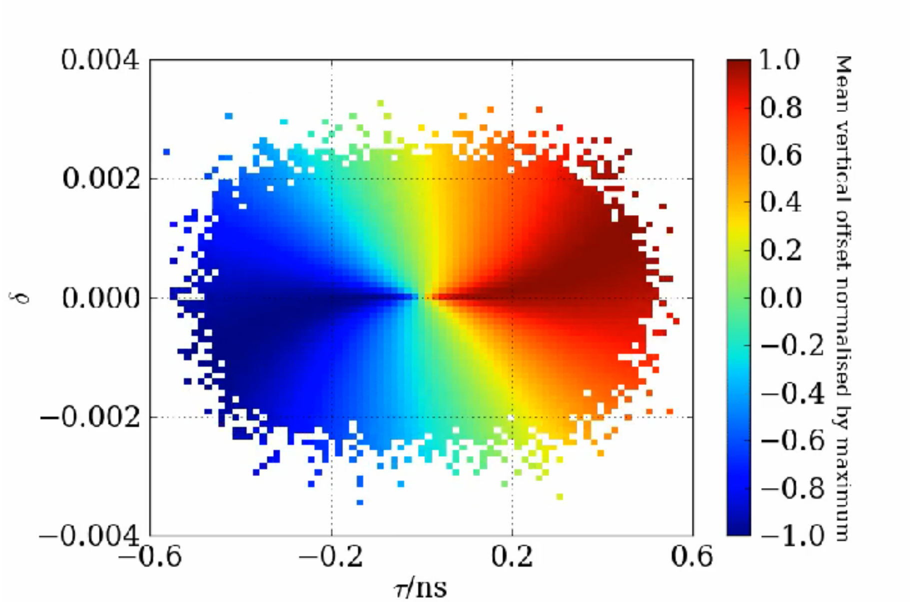
- Laclare's eigenvalue method (frequency domain calculation based on the linearised Vlasov equation)
- Excellent agreement with macroparticle simulations

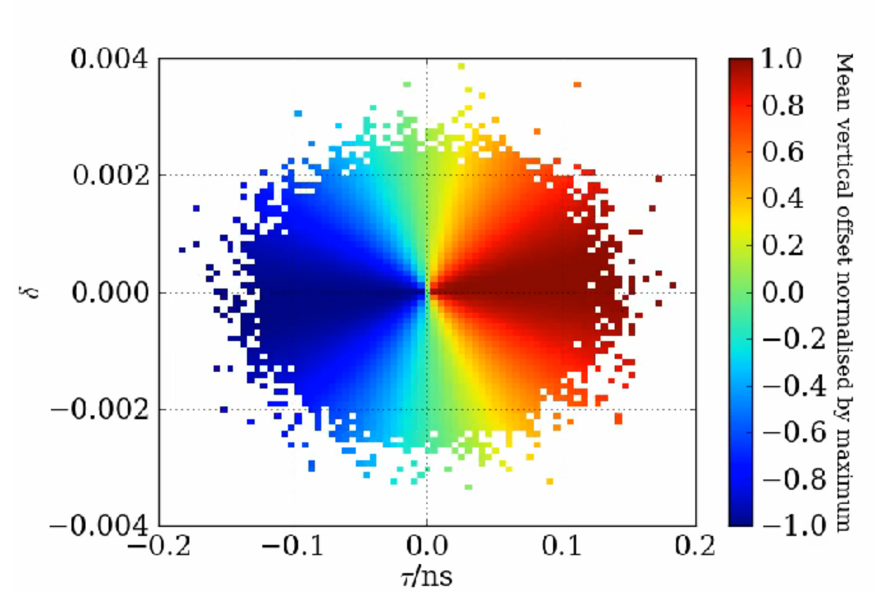


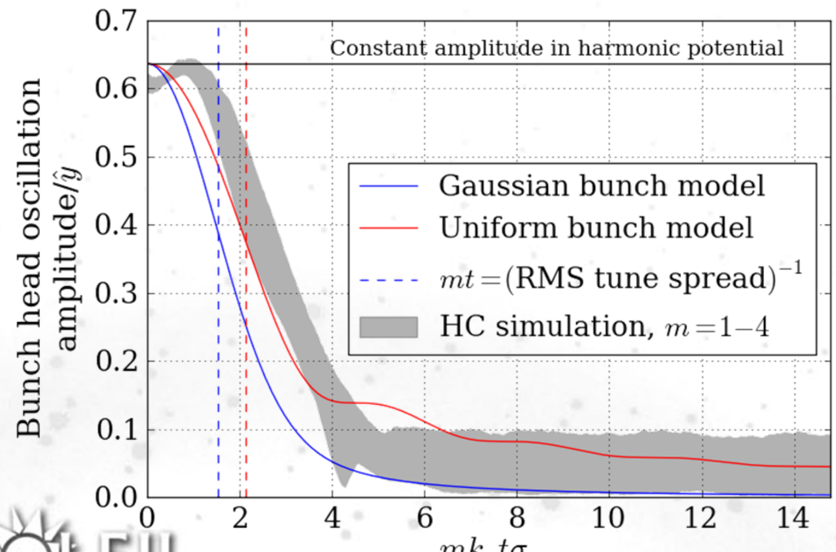




Azimuthal Head-Tail Modes





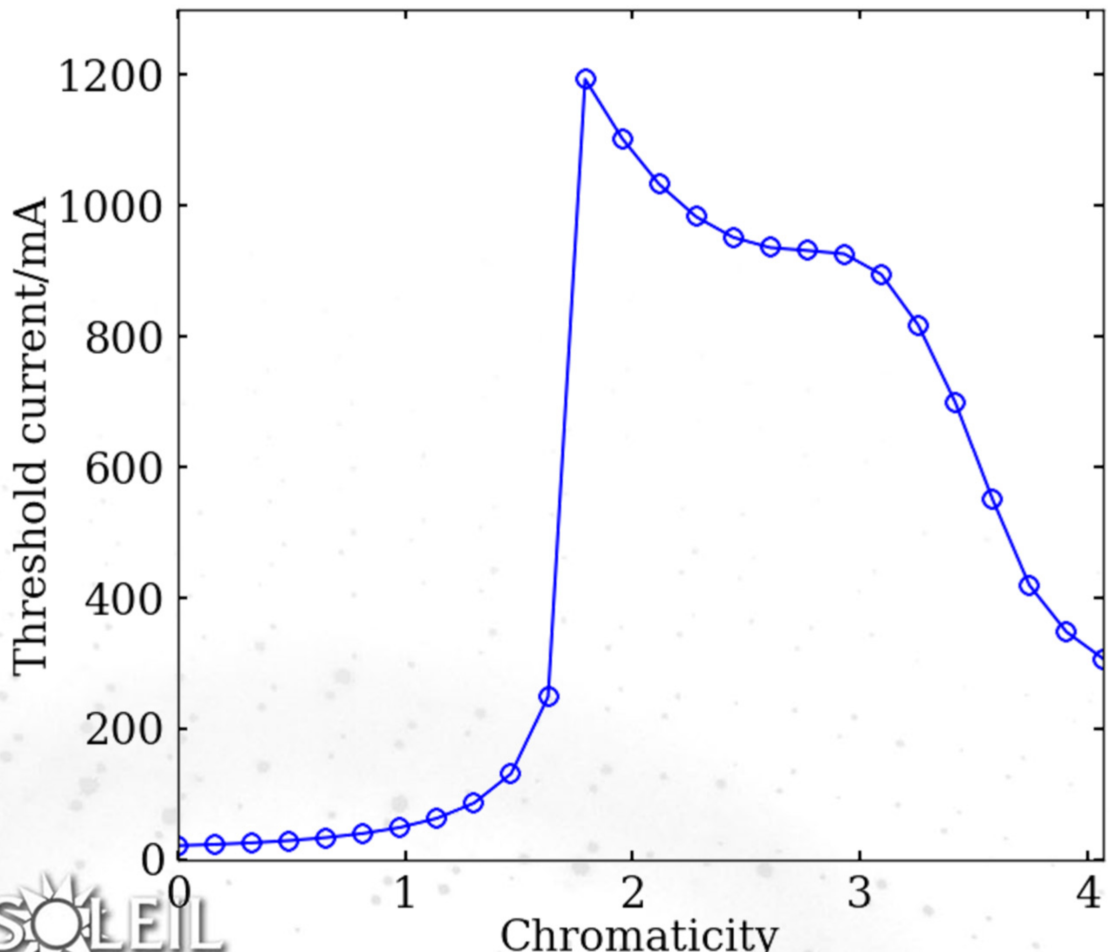


- Synchrotron tune spread leads to break up of m>0 head-tail modes
- Lifetime is around the inverse RMS synchrotron tune spread
  - For MAX IV, <1/9th of the radiation damping time

F. Cullinan et al., IPAC 2015, Richmond, Virginia, MOPWA011.

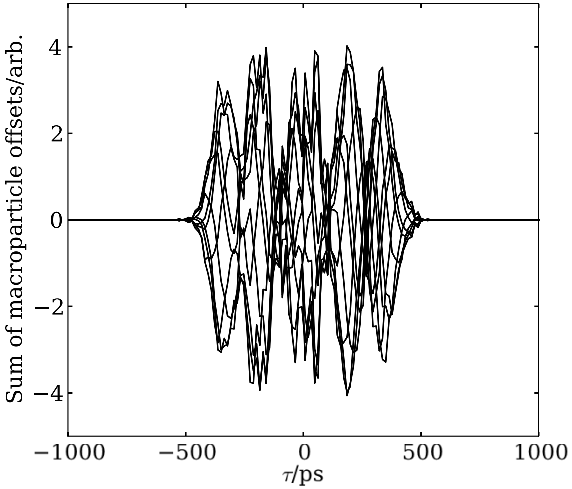
Single RF System

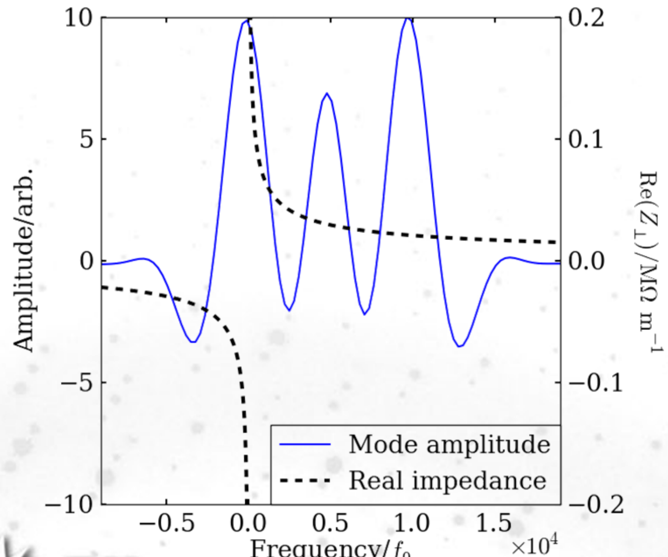
- Laclare's eigenvalue method (frequency domain calculation based on the linearised Vlasov equation)
- Excellent agreement with macroparticle simulations

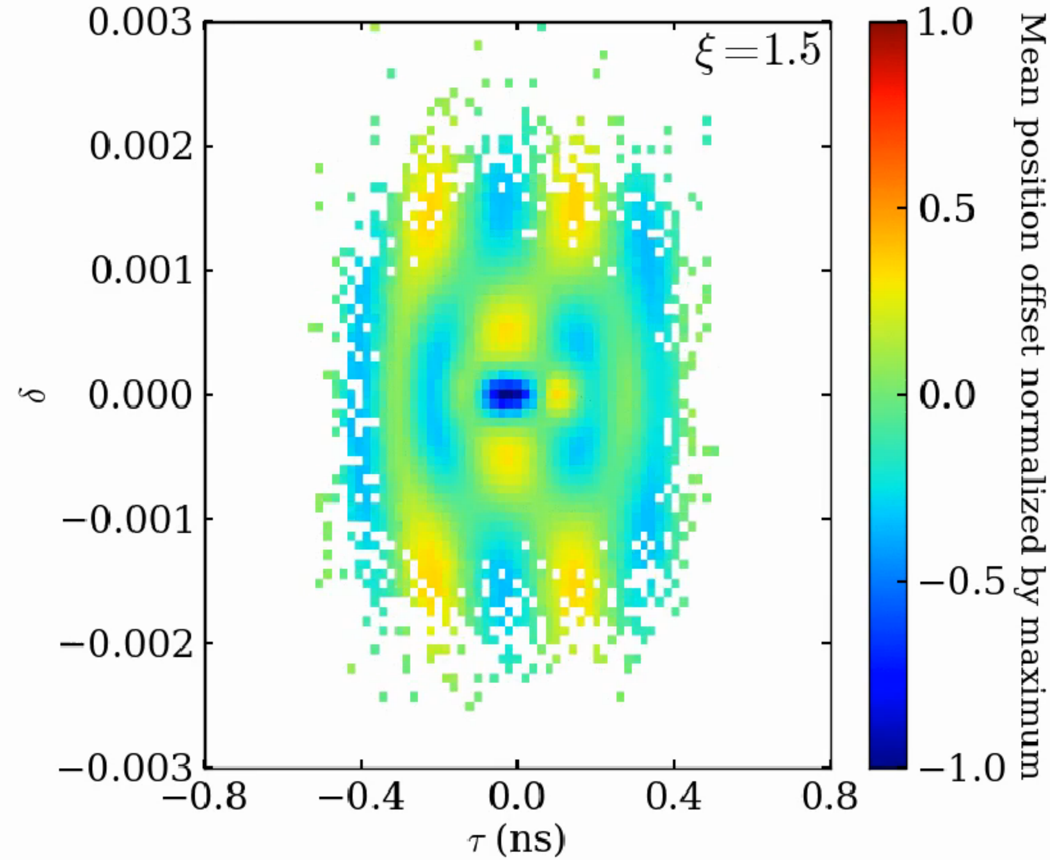


Radial Mode Structure – ξ=1.5

- Indefinite stabilisation with chromaticity halted by the emergence of radial structure in the head-tail mode of zeroth azimuthal order



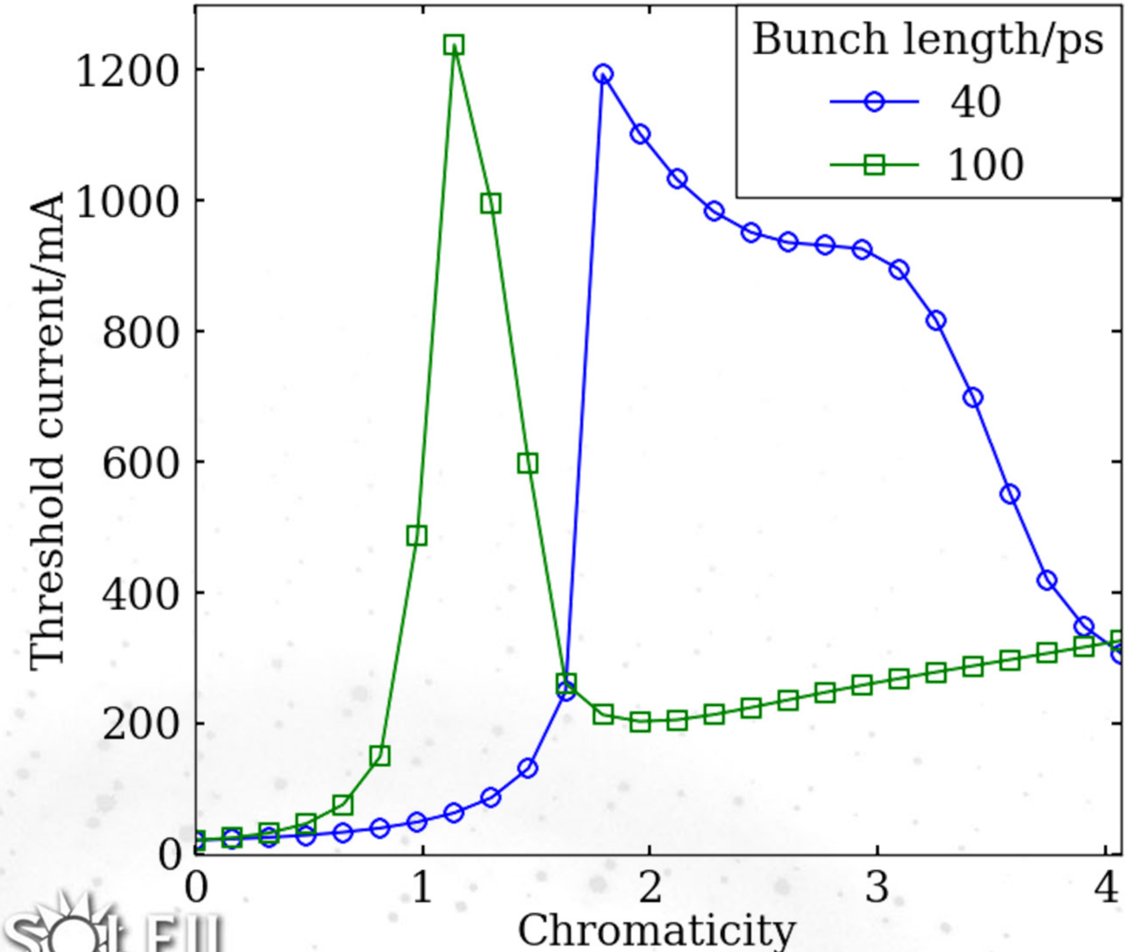




Bunch Lengthening

Bunch lengthening leads to an approximate inverse scaling along the chromaticity axis

No azimuthal head-tail mode but threshold current peaks then starts to decrease

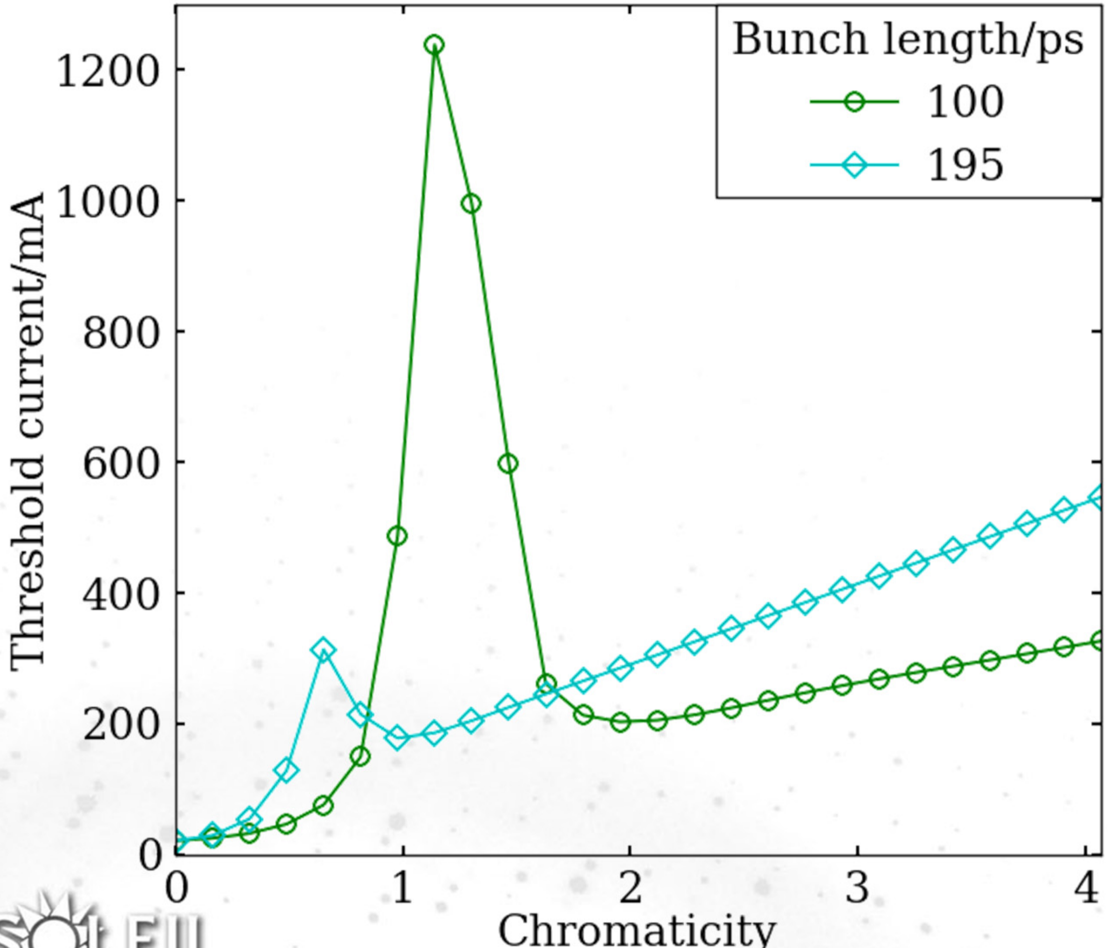


At high chromaticity, threshold current appears to increase linearly

Bunch Lengthening

Bunch lengthening leads to an approximate inverse scaling along the chromaticity axis

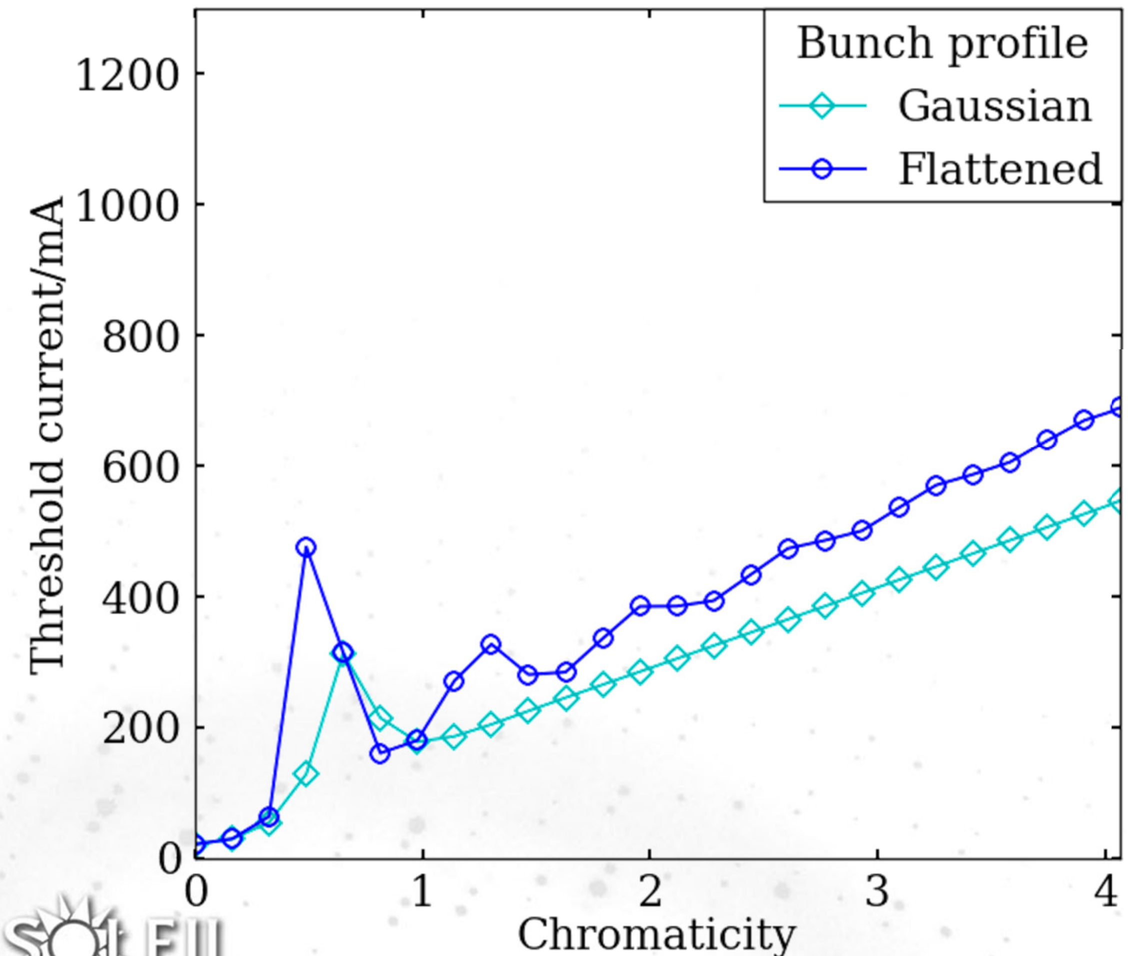
No azimuthal head-tail mode but threshold current peaks then starts to decrease

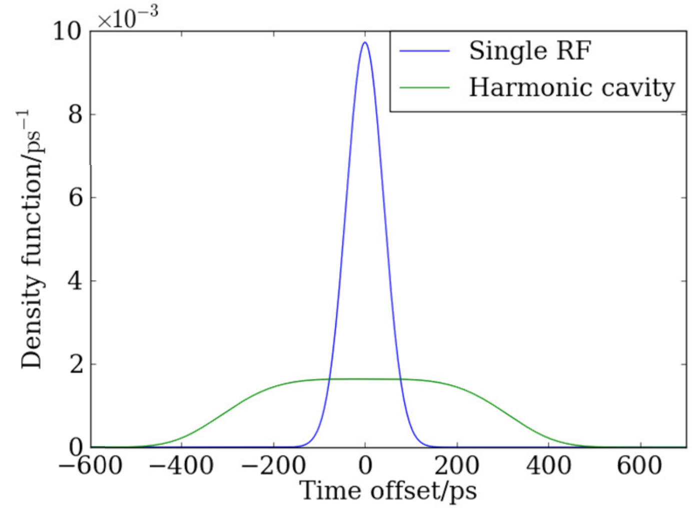


At high chromaticity, threshold current appears to increase linearly

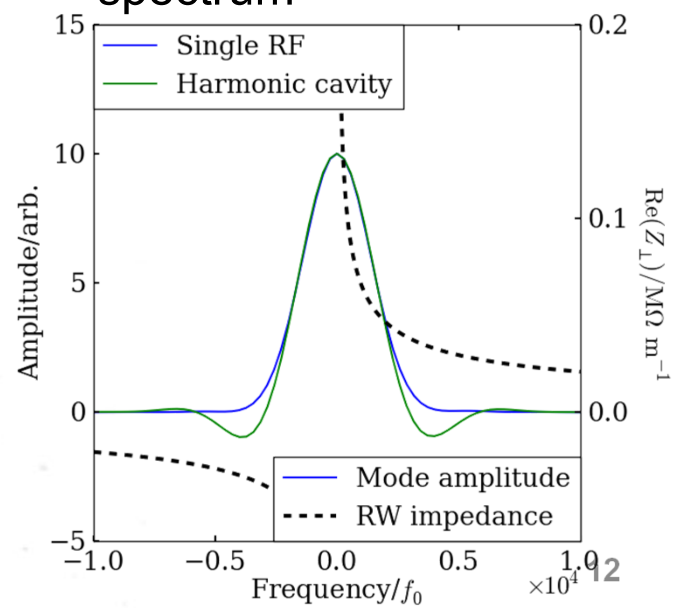
Non-Gaussian Bunch Profile

Non-Gaussian bunch profile leads to
- Slightly higher threshold current
- extra peaks at higher chromaticity



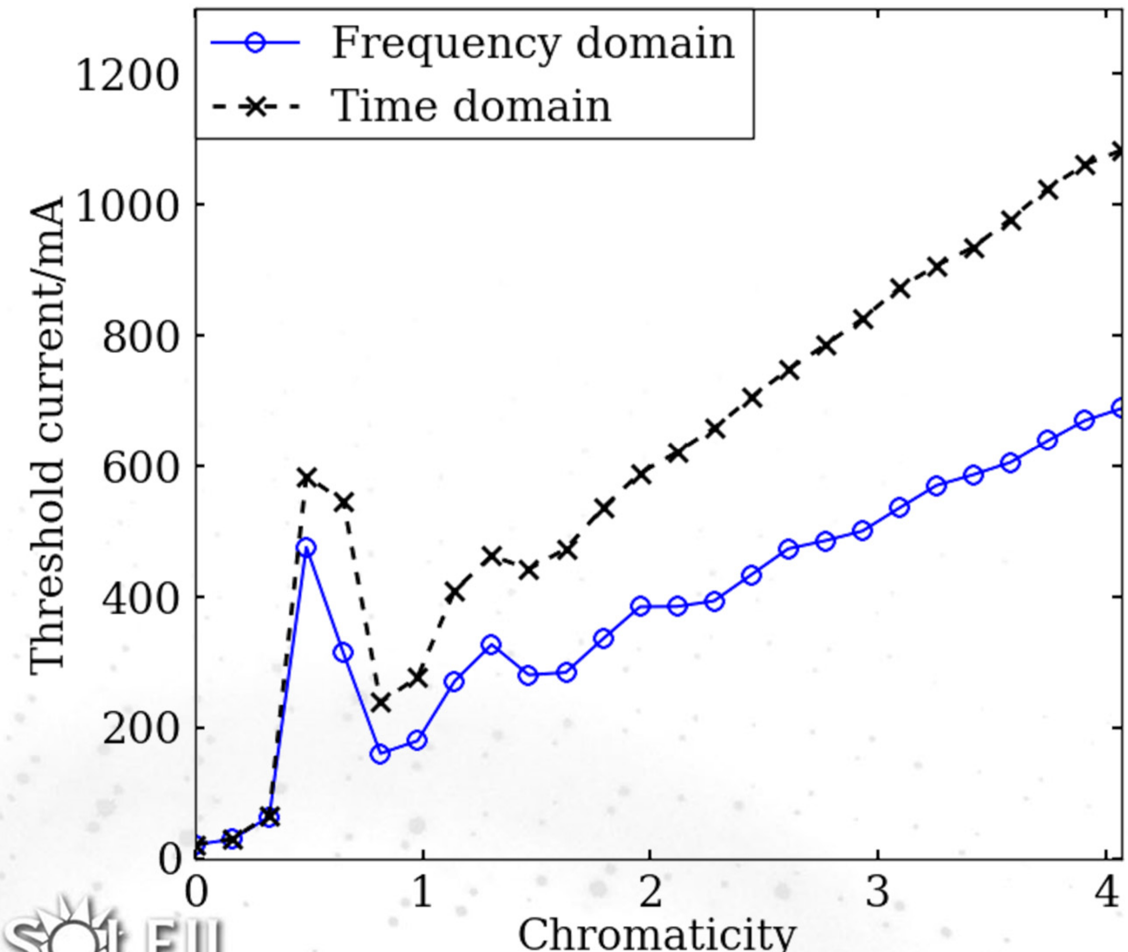


Due to ripples around cenral peak in bunch spectrum

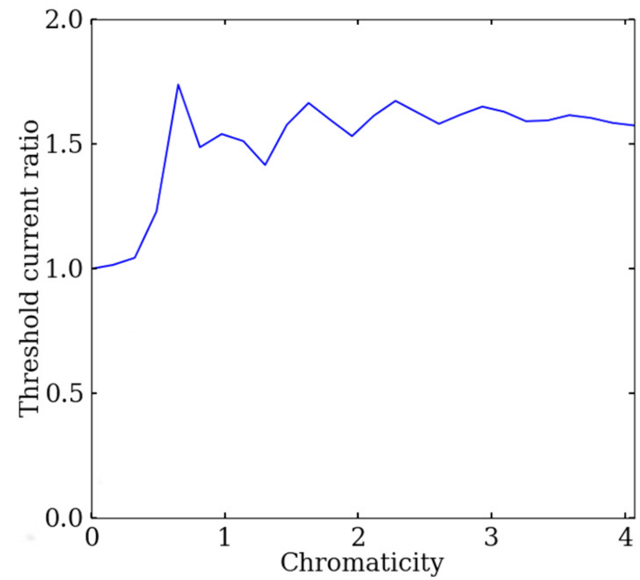


Nonradial Bunch Distribution

Compare frequency domain calculation that assumes radial distribution in longitudinal phase space with time domain macroparticle simulation that accurately models nonradial distribution.

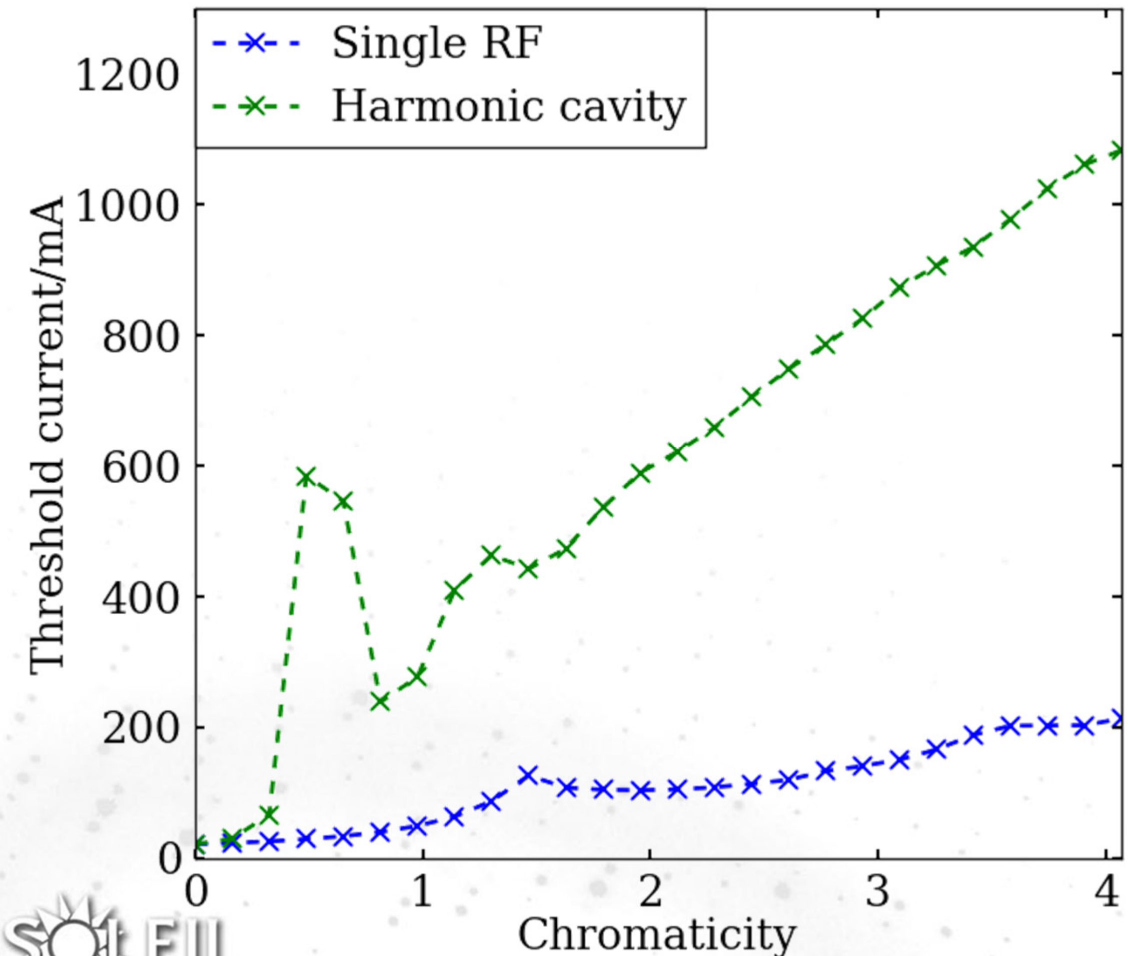


After peak at low chromaticity, effect is a factor of ≈1.6

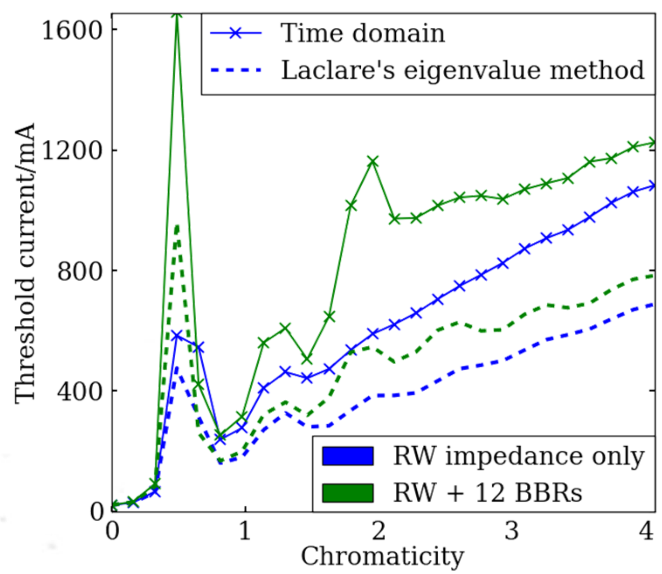


Total

Time domain macroparticle simulations of single RF system and with harmonic cavity



BBRs have nonnegligible effects at certain chromaticities but resistive-wall dictates overall trend



Effect for Different Machine Parameters

Use Laclare's eigenvalue method to evaluate effect of harmonic cavity for different machine parameters:

- Bunch length
- Radio frequency
- Machine circumference

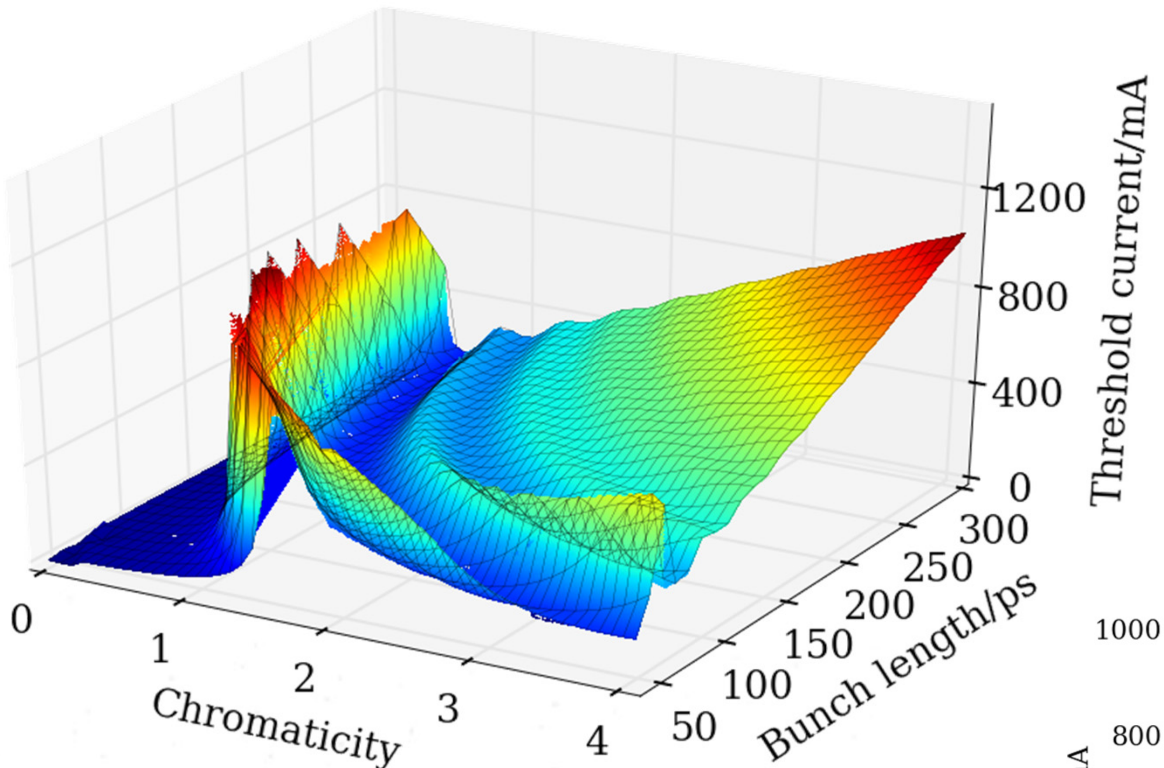
Unless stated:

- 100 ps bunch length
- Otherwise, MAX IV parameters:

Energy/GeV	3.0
Radio frequency/MHz	99.931
Momentum compaction	3.07×10^{-4}
Circumference/m	528

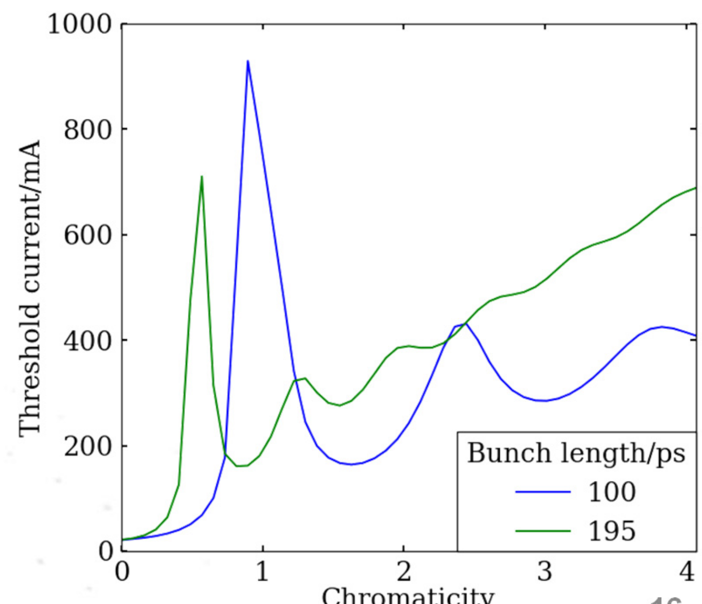
- Other parameters are just scalings in threshold currents

Bunch Length



Approximate inverse scaling with bunch length of threshold current against chromaticity

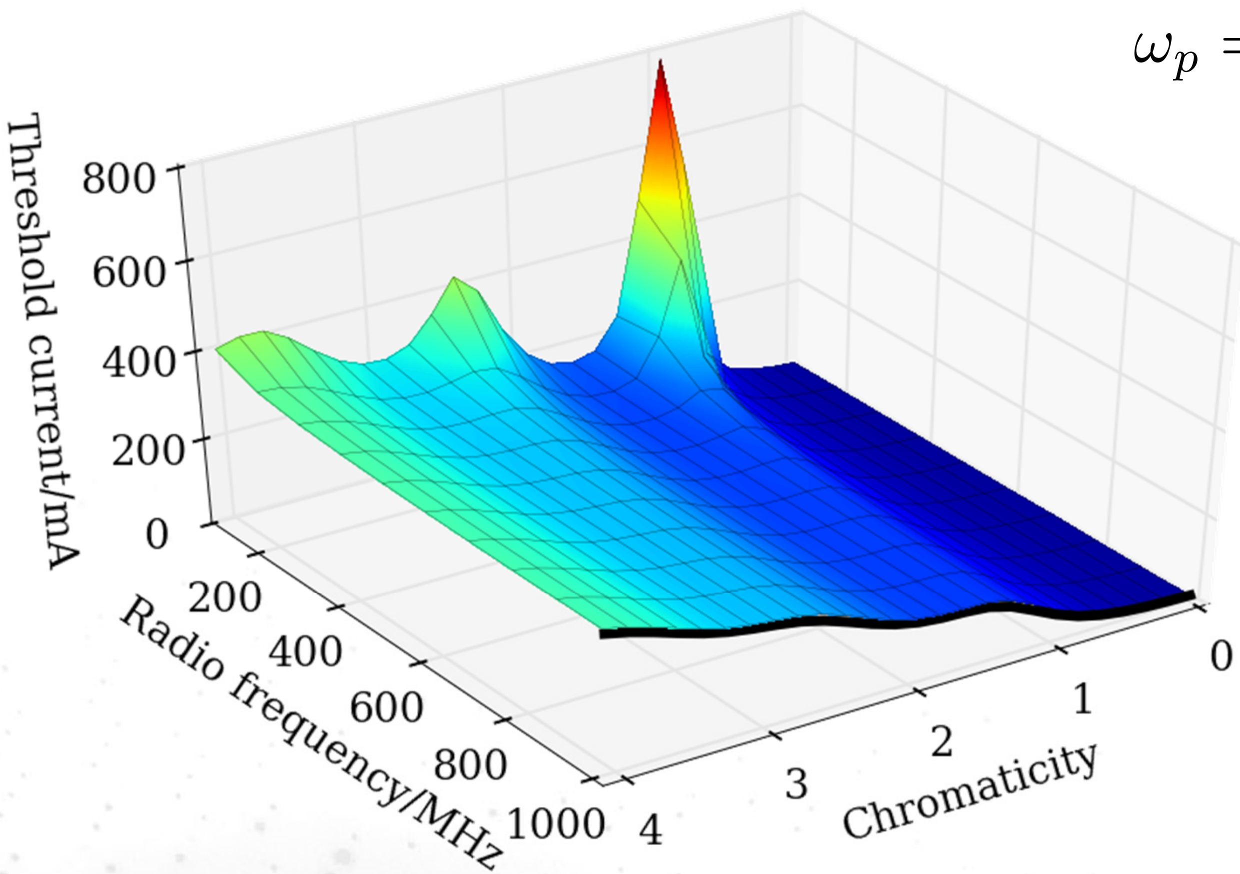
Lowest chromaticity peak gets narrower but not smaller



Different bunch lengths can be generated using different harmonic cavities. For MAX IV:

- 11th harmonic for 100 ps
- 3rd harmonic for 195 ps

Radio Frequency



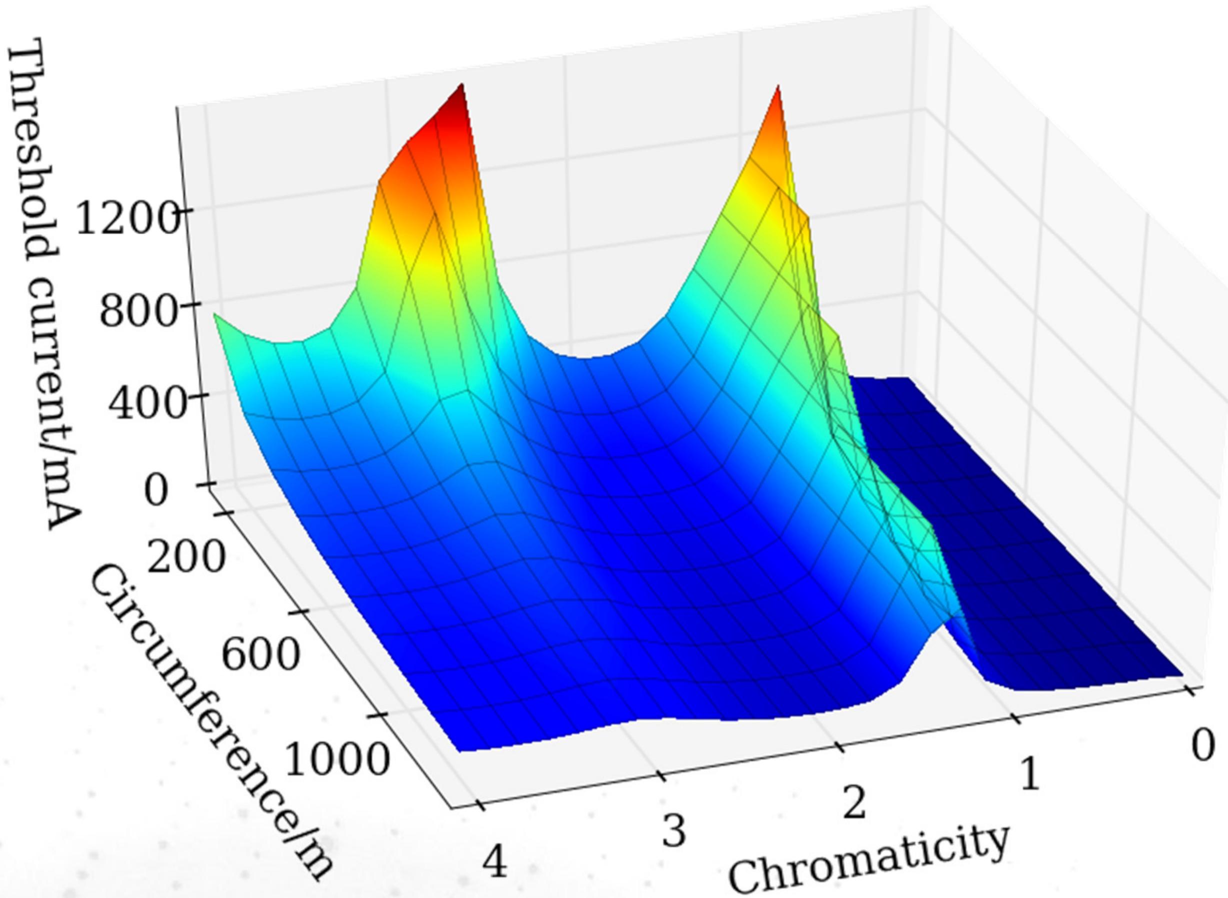
$$\omega_p = (Mp + \mu)\omega_0 + \omega_\beta$$

Increase in frequency leads to separation of coupled-bunch mode lines

Increase in number of bunches, coupled-bunch modes

Dark line shows approximation for one coupled bunch frequency line – coupled-bunch mode μ=-1 (generally least stable against resistive wall impedance) at harmonic p=0.

Machine Size



Increase in machine size and at the same time:

- Reduce momentum compaction so chromatic frequency is the same
- Reduce wall resistivity so that impedance is the same

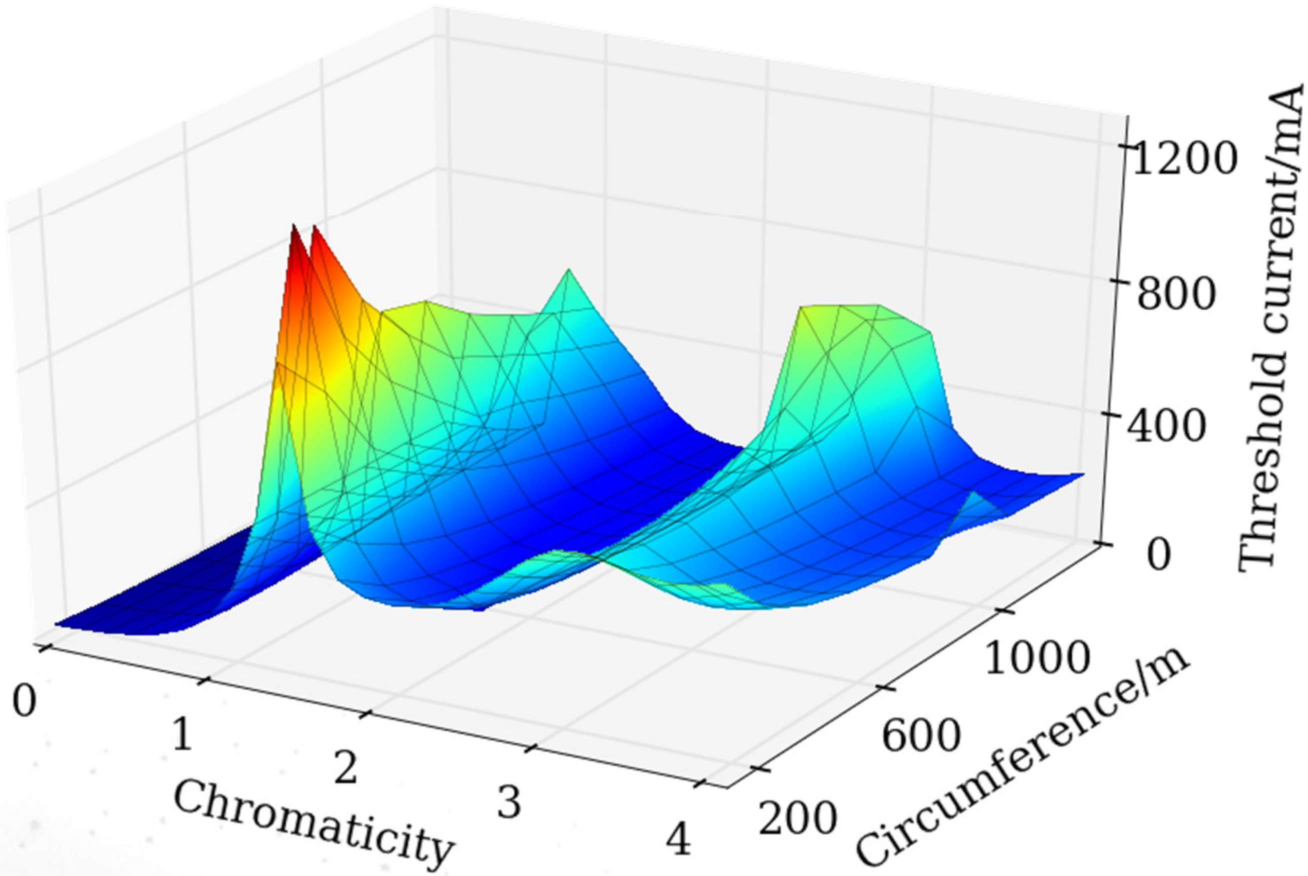
Effect:

- Reduces the revolution frequency
- Moves coupled-bunch line at smallest negative frequency towards high impedance
- Increases the number of bunches

Machine size:RF

Increase the machine size while reducing the RF to keep number of bunches constant (MAX IV RF and circumference coincide)

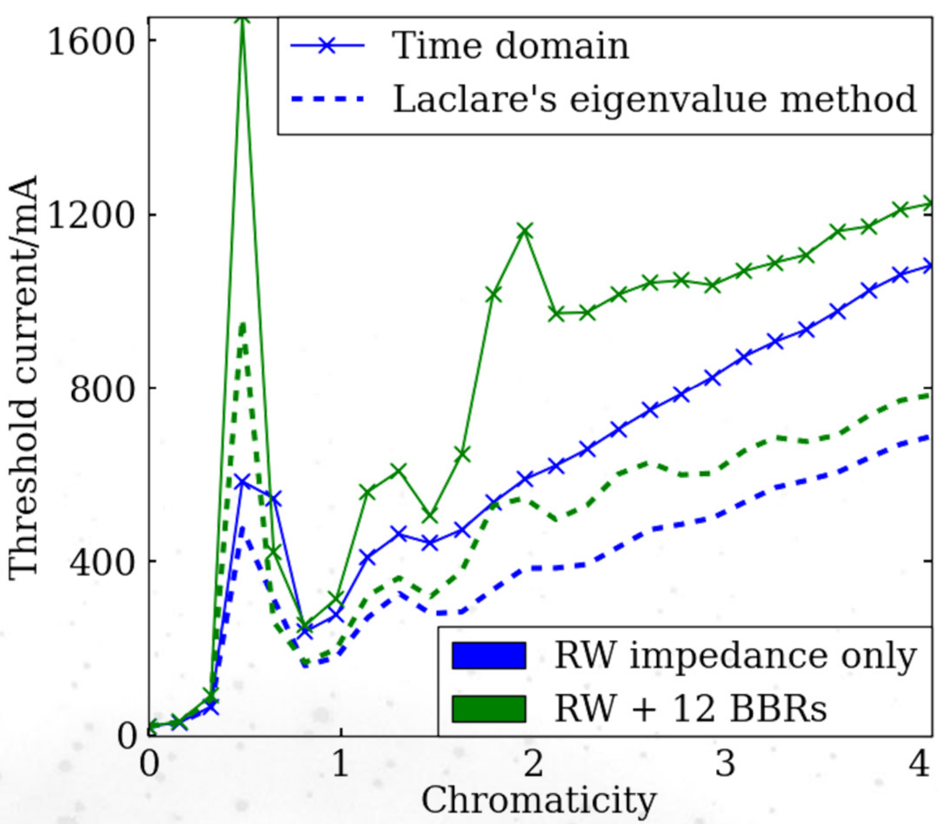
Beneficial features of a smaller machine can be retained to some extent



Conclusion and Outlook

- A harmonic-cavity-flattened RF potential can increase the threshold currents of transverse coupled-bunch instabilities
- Four features that contribute to this have been identified and studied
- Large peaks appear in curves of threshold current against chromaticity
- Longer bunches are not always better if these peaks are to be exploited
- Beneficial effects have been seen for machines with:
  - Lower RF
  - Smaller machine circumference
- Harmonic cavities at MAX IV are currently under commissioning (Skripka et al., WEPOWO35)

Resistive Wall Impedance

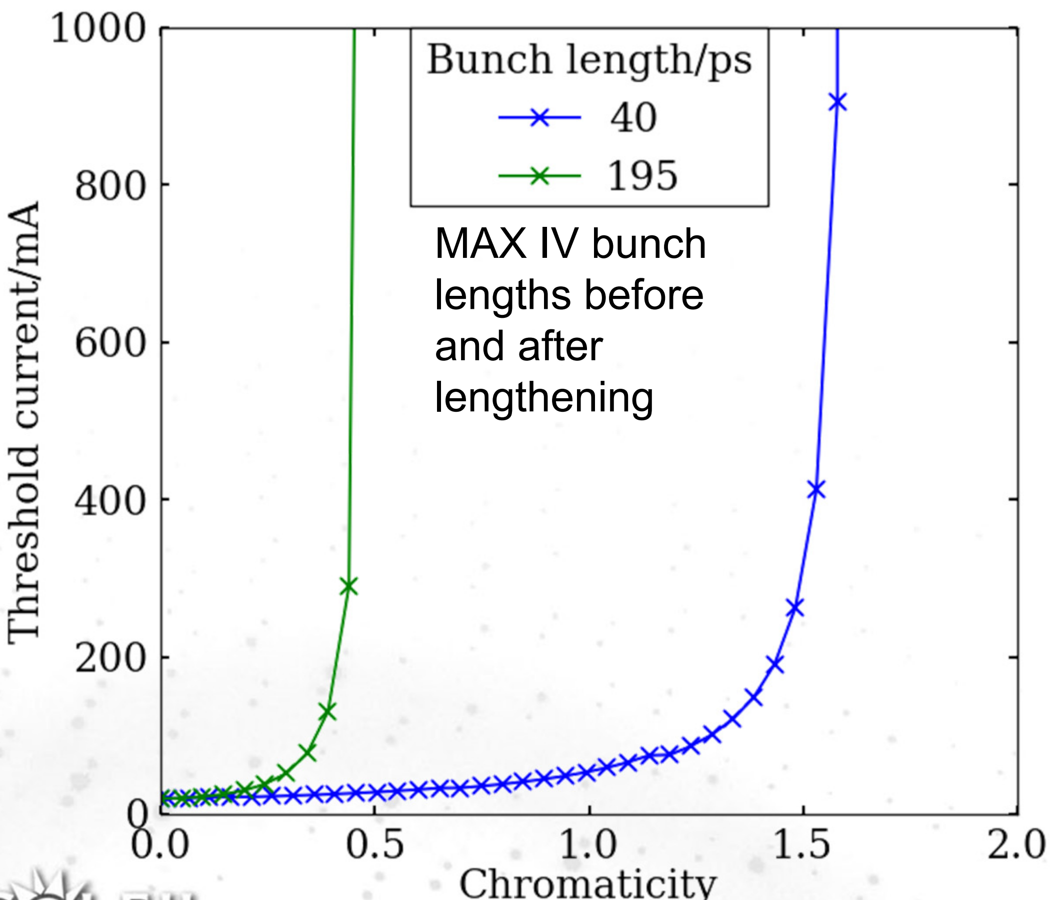


Appearance of radial structure is responsible for peak at chromaticity of ≈0.8

In both the macroparticle simulations and frequency domain calculations, resistive wall is responsible for overall trend in threshold current, particularly at low chromaticity.

Bunch Lengthening

See the effect of bunch lengthening applying the Sacherer approximation to dipolar bunch motion – frequency domain calculation multiplying the bunch spectrum by the impedance



MAX IV bunch lengths before and after lengthening

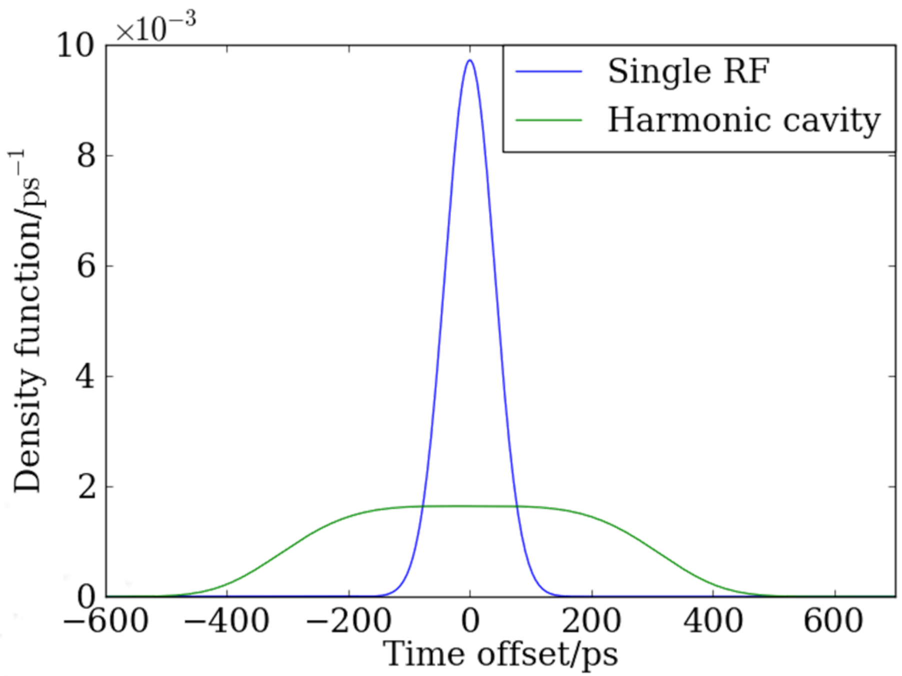
With positive momentum compaction, a positive chromaticity stabilises beam against resistive wall impedance

Bunch lengthening means a narrower bunch spectrum and so quicker stabilisation

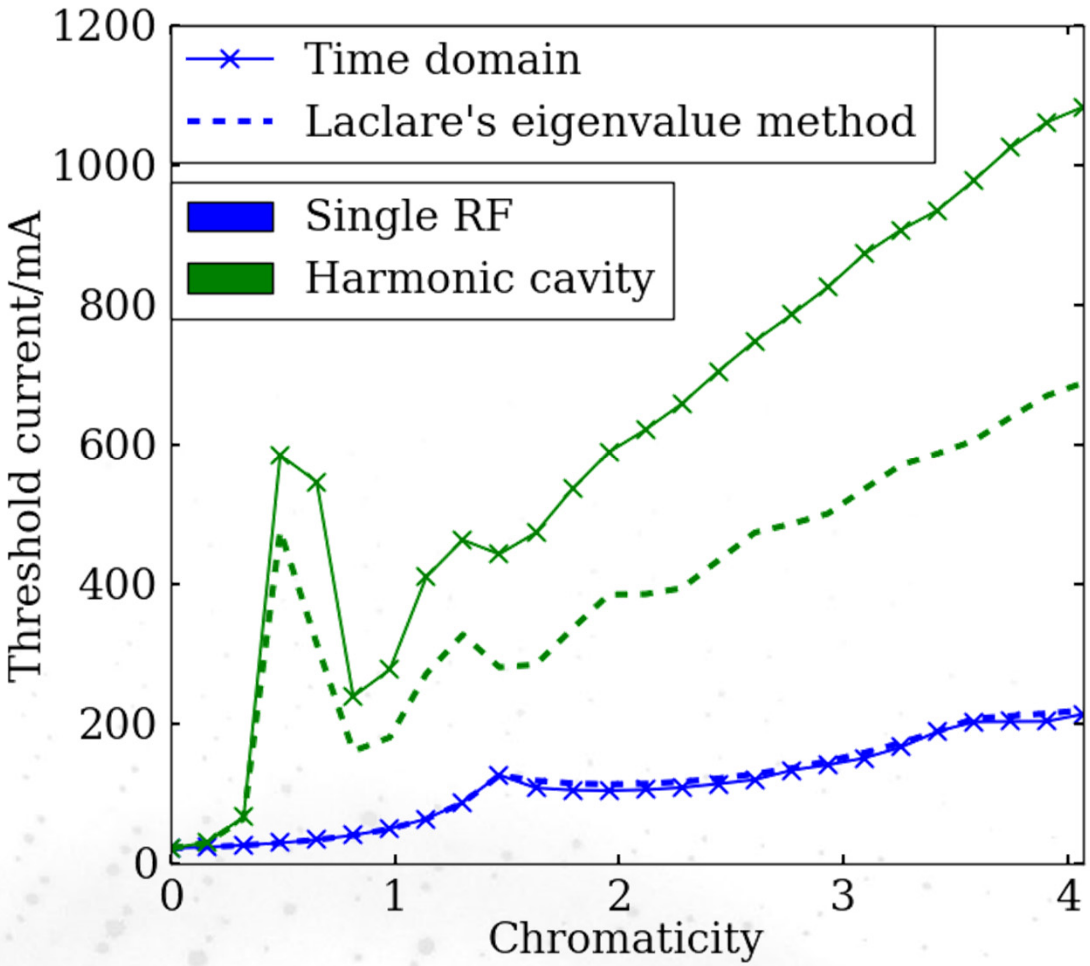
Harmonic Cavity

Aspects of a harmonic cavity flat potential that have a significant impact on threshold currents:

- Longer bunch (for MAX IV ≈factor 5)
- Synchrotron tune spread
- Distribution in time offset not Gaussian
- Distribution in synchrotron phase space not radial



Simulation Results

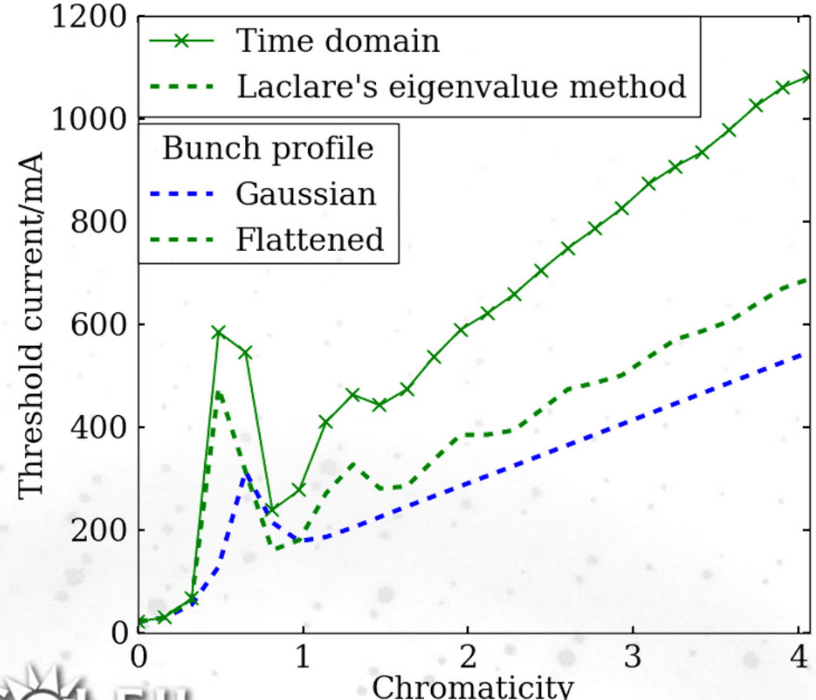


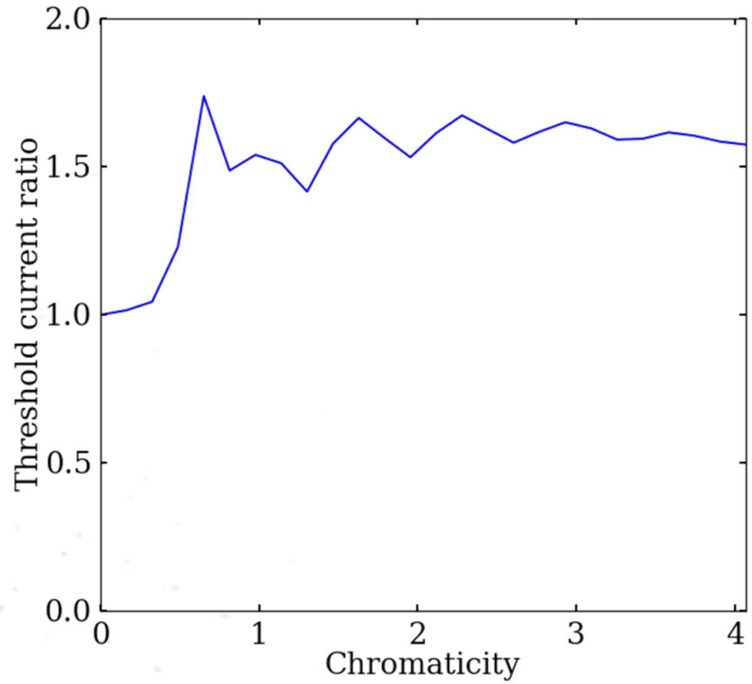
- Macroparticle simulations
- Compare to Laclare's eigenvalue method
  - Frequency domain calculation solving the linearised Vlasov equation
- Initial stabilisation of dipolar motion is at lower chromaticity with harmonic cavity
- Flattened bunch profile used in Laclare's eigenvalue method to compare to results with harmonic cavity
  - Solved for dipolar motion only

Non-Gaussian and Nonradial

At high chromaticity, non-Gaussian bunch profile leads to a slight increase in threshold current and small, secondary peaks

Nonradial distribution in longitudinal phase space ($\exp(-a\tau^4)$ in time, Gaussian in energy) leads to an increase by a factor ≈1.6

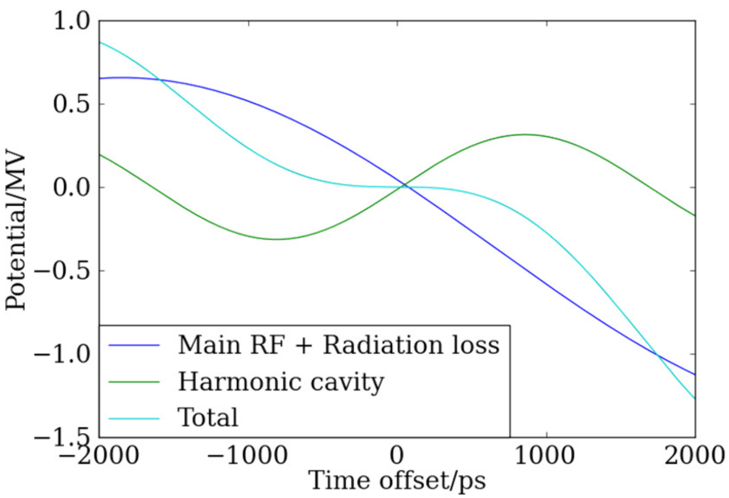


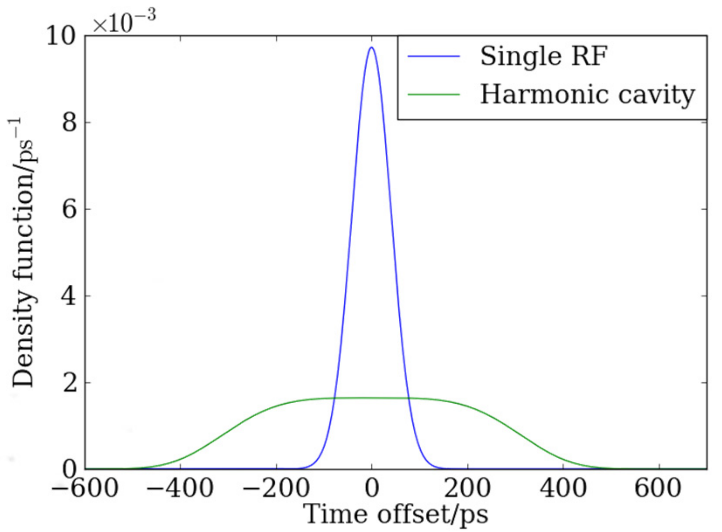


Harmonic Cavity

Flat potential condition:

- 1st and 2nd derivatives of RF potential zero at synchronous phase
- Distribution in time offset exp(-aτ⁴)
- Distribution in energy unchanged, still Gaussian
- For small synchrotron amplitude, synchrotron tune proportional to amplitude

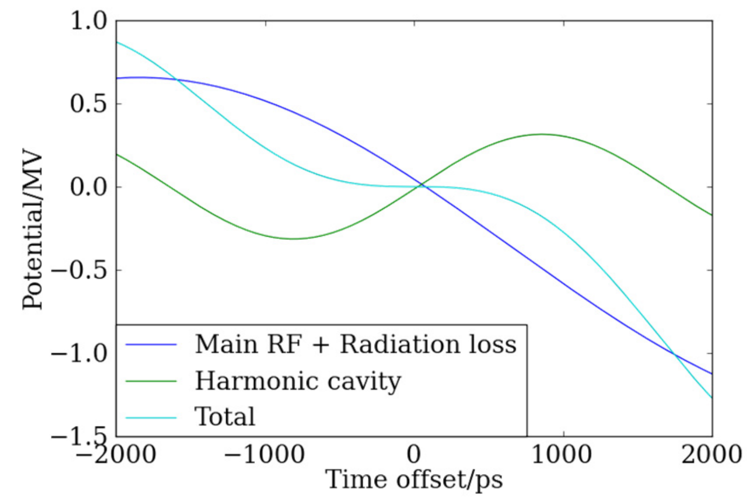


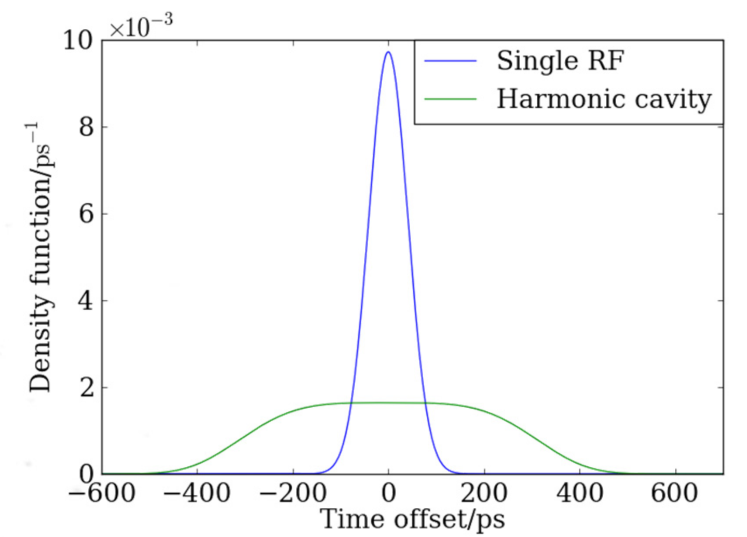


Harmonic Cavity

Aspects that significantly impact threshold currents:

- Longer bunch (for MAX IV ≈factor 5)
- Synchrotron tune spread
- Distribution in time offset not Gaussian
- Distribution in synchrotron phase space not radial

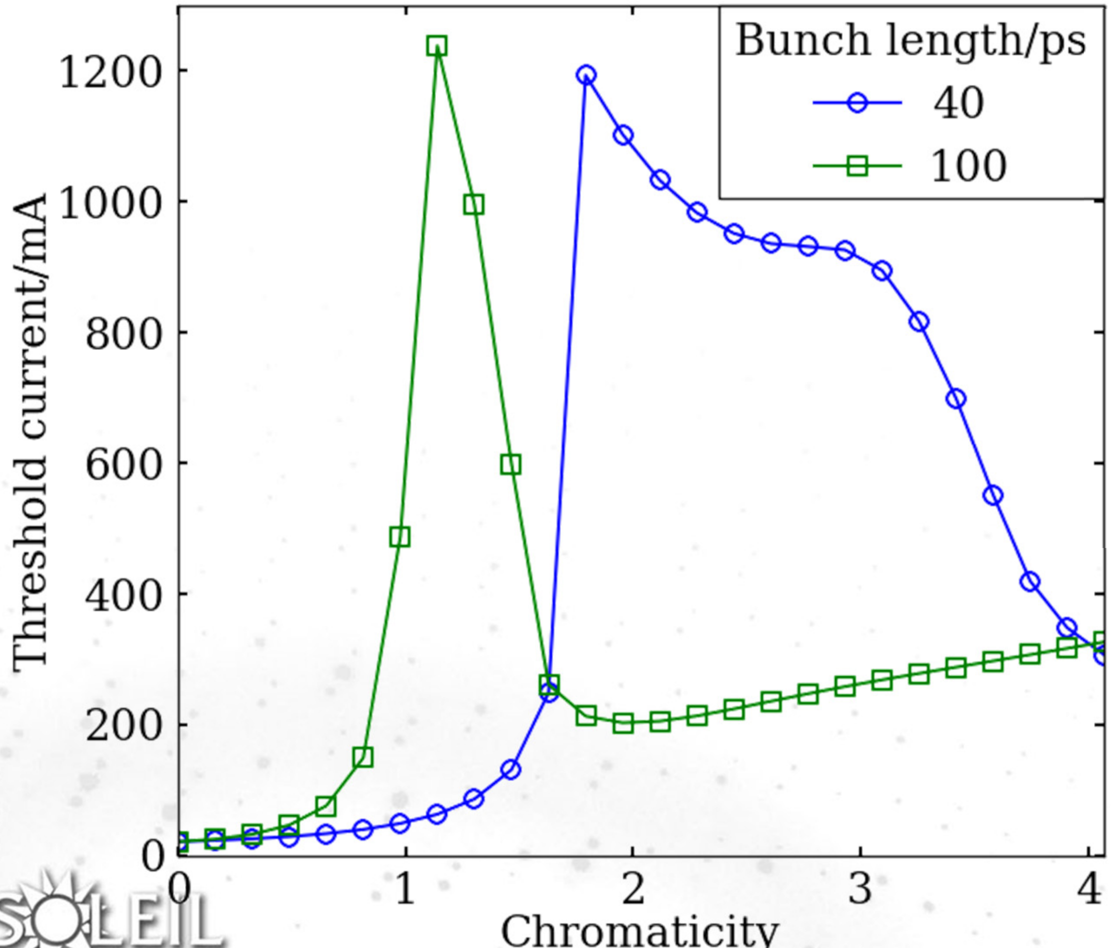


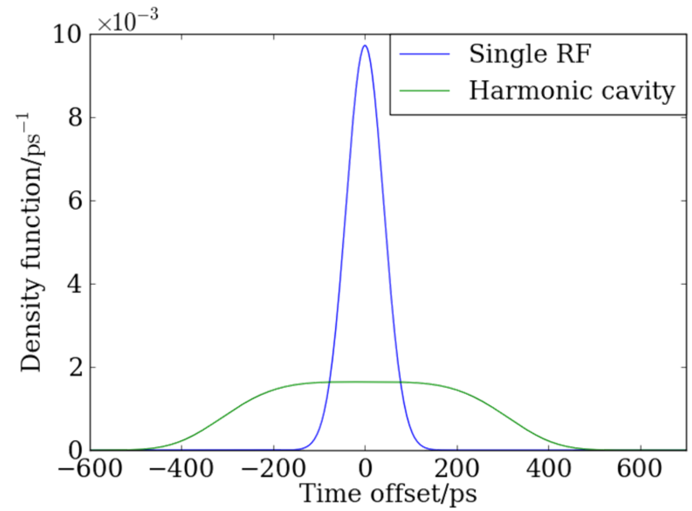


Bunch Lengthening

Bunch lengthening leads to an inverse scaling along the chromaticity axis

No azimuthal head-tail mode but threshold current peaks then starts to decrease





At high chromaticity, threshold current appears to increase linearly