LHC Beam-Beam and Crab Simulations

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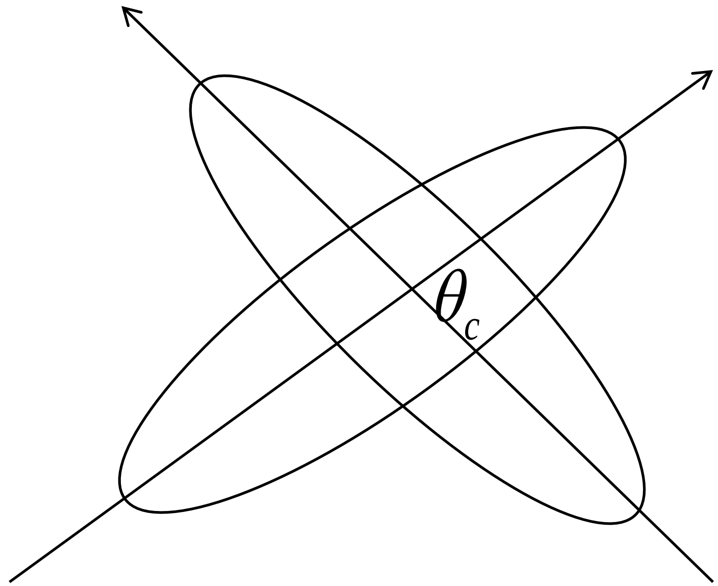
Outline

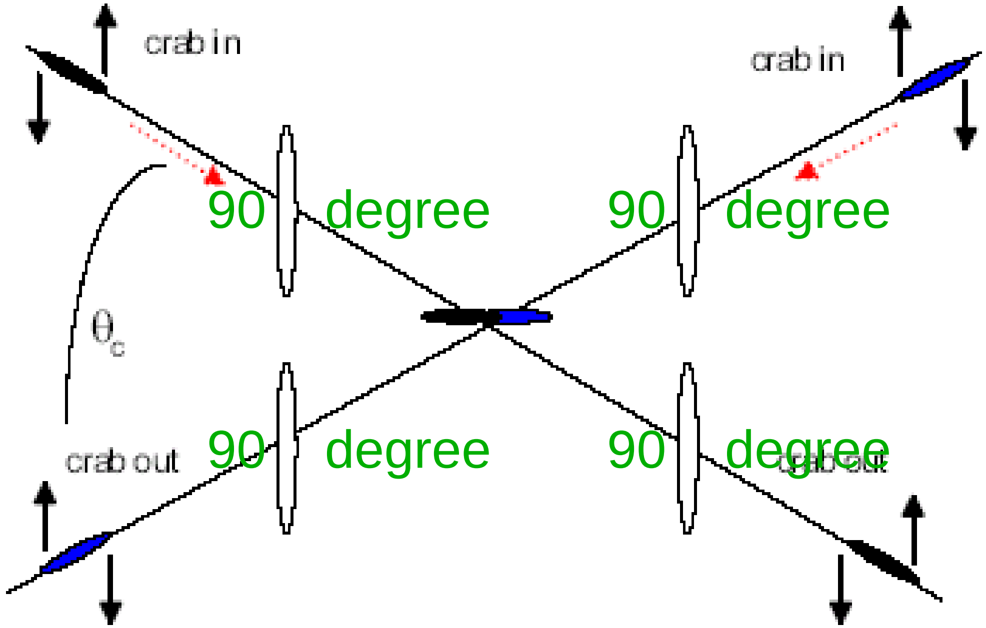
- Introduction
- Computational and Physics Models
- Strong-strong beam-beam tune scan with crab cavity compensation at LHC
- Effects of crab cavity jitters
- Summary and future work
- Appendix:
  - Offset beam-beam collision

Luminosity Loss from Crossing Angle Collision



$$L = L_0 \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\tan(\theta_c/2)\sigma_z}{\sigma_x}$$

Crab Cavity Compensation Scheme



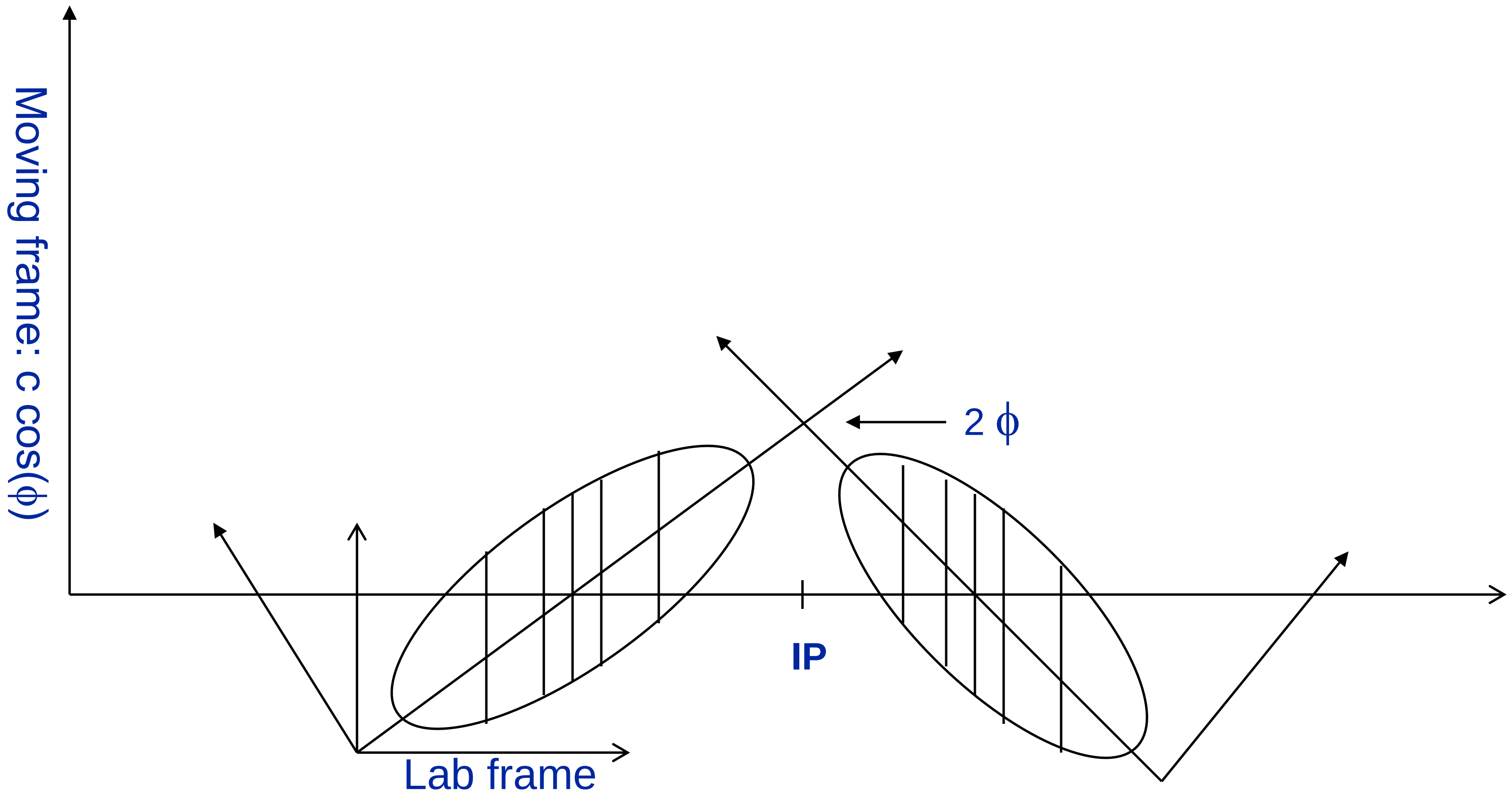
$$RF\ voltage:$$

$$V = \frac{cE_s \tan(\frac{\theta_c}{2})}{\omega\sqrt{\beta_{x,crab}\beta_x^*}}$$

BeamBeam3D: Parallel Strong-Strong / Strong-Weak Simulation

- Beam-Beam forces – integrated, shifted Green function method with FFT – O(N log(N)) computational cost
- Multiple-slice model for finite bunch length effects
- Parallel particle-based decomposition to achieve perfect load balance
- Lorentz boost to handle crossing angle collisions
- Arbitrary closed-orbit separation (static or time-dep)
- Multiple bunches, multiple collision points
- Linear transfer matrix + one turn chromaticity+thin lens sextupole kicks
- Conducting wire, crab cavity, and electron lens compensation

Head-on Beam-Beam Collision with Crossing Angle



Transform from the Lab Frame to the Boosted Moving Frame

$$x^* = x(1 + h_x^* \cos(\psi)\sin(\alpha)) + y h_x^* \sin(\psi)\sin(\alpha) + z\cos(\psi)\tan(\alpha), \tag{70}$$

$$y^* = x h_y^* \cos(\psi)\sin(\alpha) + y(1 + h_y^* \sin(\psi)\sin(\alpha)) + z\sin(\psi)\tan(\alpha), \tag{71}$$

$$z^* = x h_z^* \cos(\psi)\sin(\alpha) + y h_z^* \sin(\psi)\sin(\alpha) + z/\cos(\alpha), \tag{72}$$

$$p_x^* = p_x/\cos(\alpha) - h\cos(\psi)\tan(\alpha)/\cos(\alpha), \tag{73}$$

$$p_y^* = p_y/\cos(\alpha) - h\sin(\psi)\tan(\alpha)/\cos(\alpha), \tag{74}$$

$$p_z^* = p_z - p_x\cos(\psi)\tan(\alpha) - p_y\sin(\psi)\tan(\alpha) + h\tan^2(\alpha), \tag{75}$$

where ψ is the crossing plane angle in the $x-y$ plane, α is the half crossing angle in the $\tilde{x}-z$ plane, $h = p_z + 1 - \sqrt{(p_z+1)^2 - p_x^2 - p_y^2}$, $h_i^* = \frac{\partial}{\partial p_i^*} h^*(p_x^*, p_y^*, p_z^*)$, and $h^*(p_x^*, p_y^*, p_z^*) = h(p_x^*, p_y^*, p_z^*)$.

Refs: Hirata, Leunissen, et. al.

Thin Lens Approximation for Crab Cavity Deflection

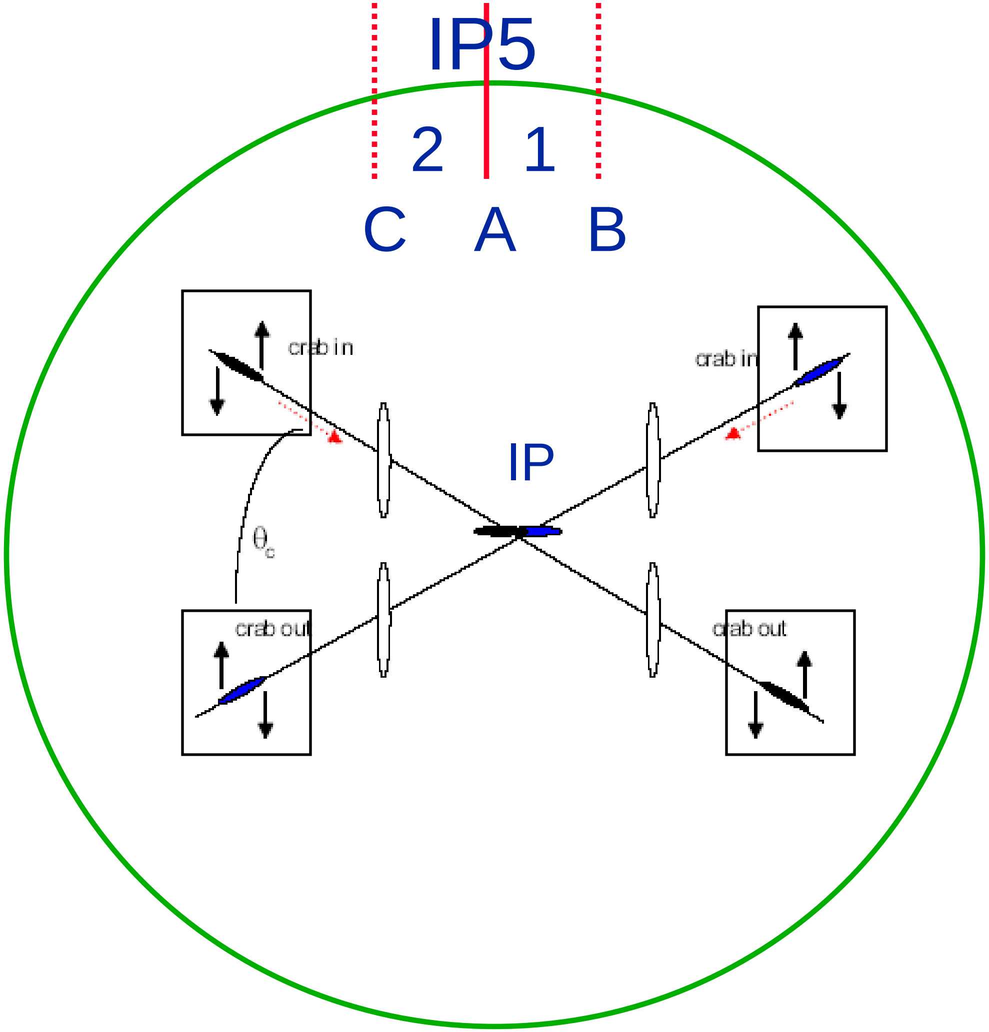
$$x^{n+1} = x^n$$

$$Px^{n+1} = Px^n + \frac{qV}{E_s}\sin(\omega z^n / c)$$

$$z^{n+1} = z^n$$

$$\delta E^{n+1} = \delta E^n + \frac{qV}{E_s}\frac{\omega}{c}\cos(\omega z^n / c)x^n$$

A Schematic Plot of LHC Collision at 1 IP and Crab Cavities



One Turn Transfer Map with Beam-Beam and Crab Cavity

$$M = Ma\ M1\ Mb\ M1^{-1}\ M\ M2^{-1}\ Mc\ M2$$

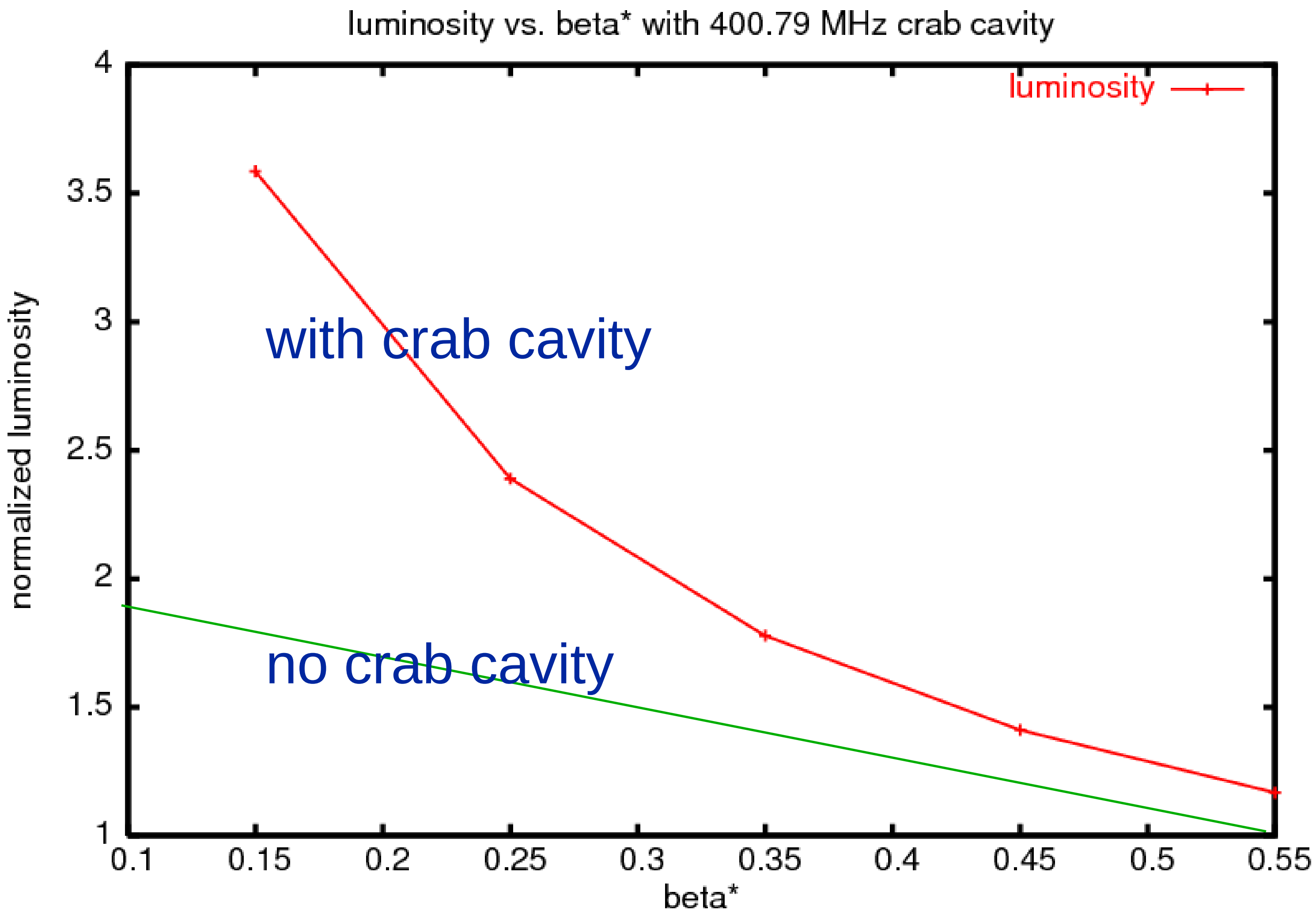
Ma: transfer map from head-on crossing angle beam-beam collision

Mb,c: transfer maps from crab cavity deflection

M1-2: transfer maps between crab cavity and collision point

M: one turn transfer map of machine

Luminosity vs. Beta* for LHC Crab Cavity Compensation



LHC Physical Parameters for Testing Crab Cavity

Beam energy (TeV)	7
Protons per bunch	11.5e10
β* (m)	0.25
Rms spot size (mm)	0.0112
Betatron tunes	(0.31,0.32)
Rms bunch length (m)	0.075
Synchrotron tune	0.0019
Momentum spread	0.111e-3
Crab cavity RF frequency (MHz)	400.0/800.0
$\beta^1_{crab}/\beta^2_{crab}$ (m)	2616/1023

Ref: Y. Sun, et al, PRSTAB 13, 031001 (2001)

Effects of Jitter

Amplitude and phase jitters of crab cavity will cause offset errors at the collision point.

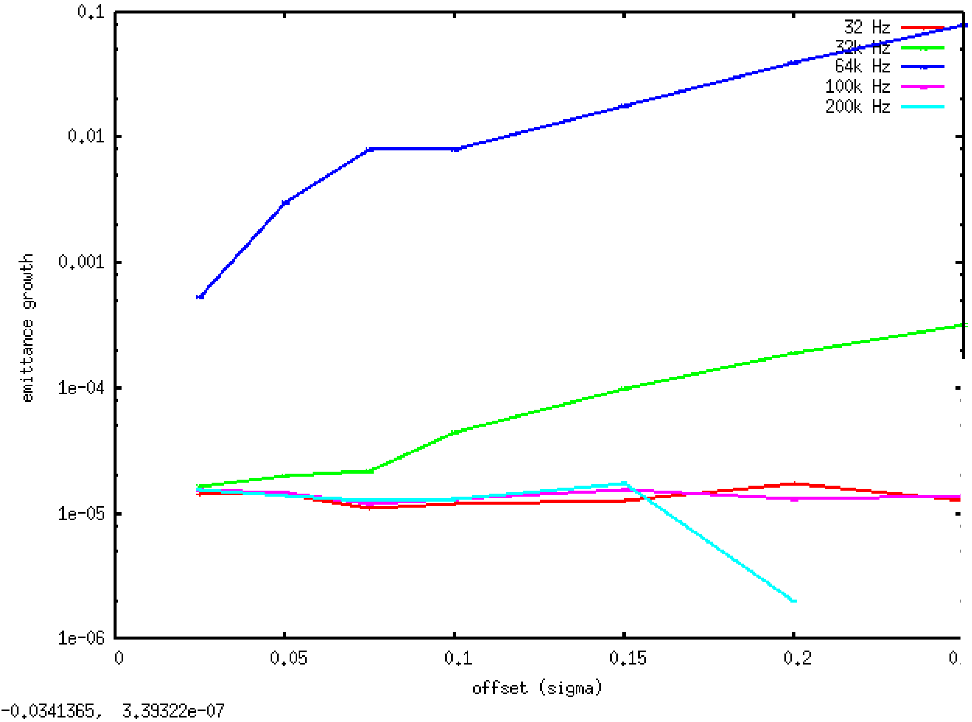
$$x = A\sin(2\pi f t)$$

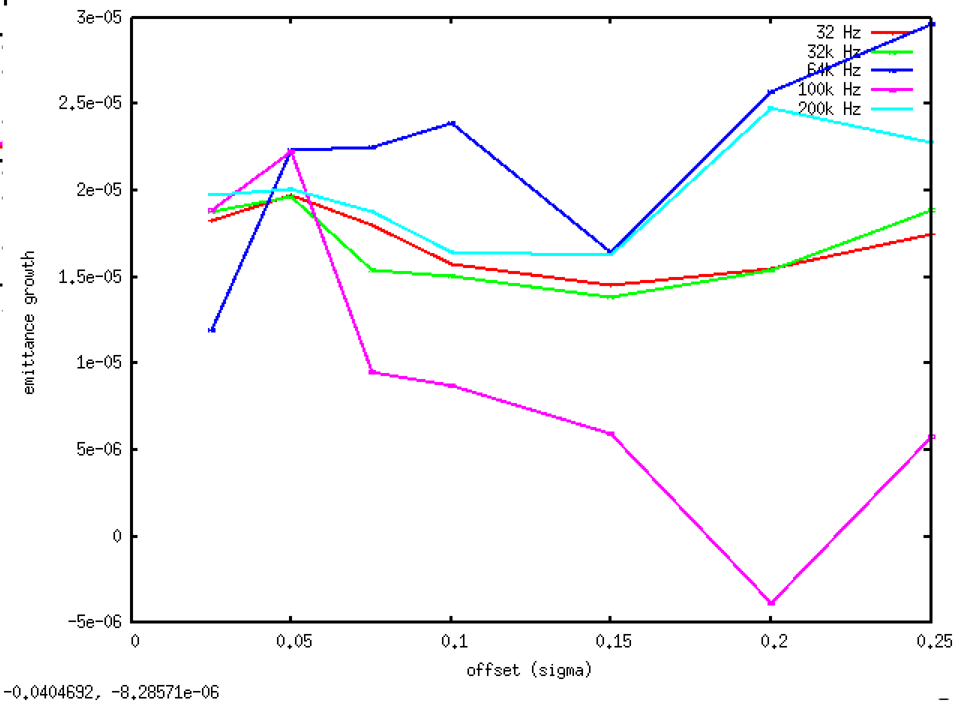
T0= 26.659e3/2.99792458e8=8.892485e-5 secs

A sin(2π 0.0028455952 i) -> 32 Hz
A sin(2π 2.84560 i) -> 32 kHz
A sin(2π 5.6911904 i) -> 64 kHz
A sin(2π 8.892485 i) -> 100 kHz
A sin(2π 17.78497 i) -> 200 kHz

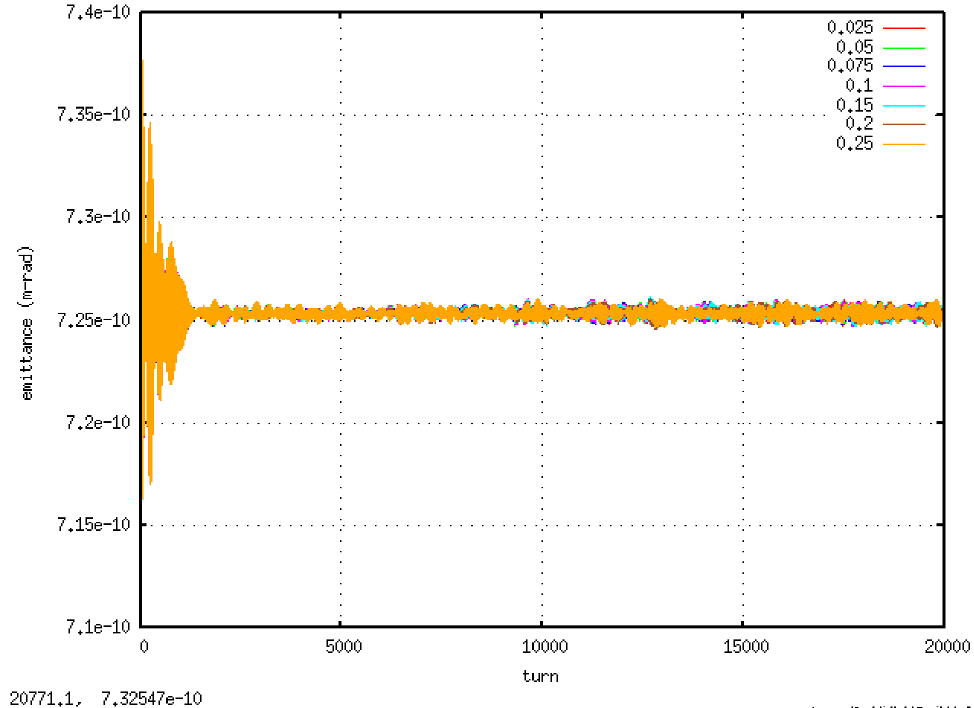
Ref:R. Calaga, et al. in Proceedings of PAC07

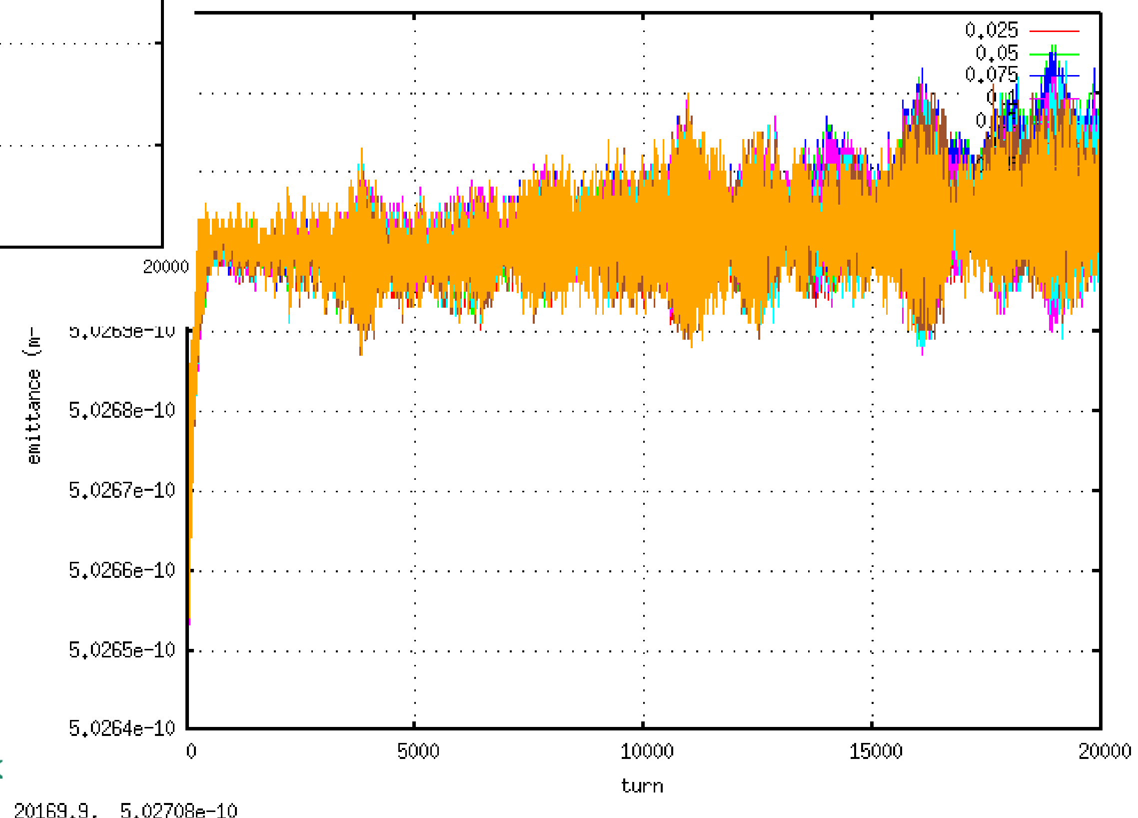
Emittance Growth after 20k Turns vs. Offset 400 MHz Crab Cavity



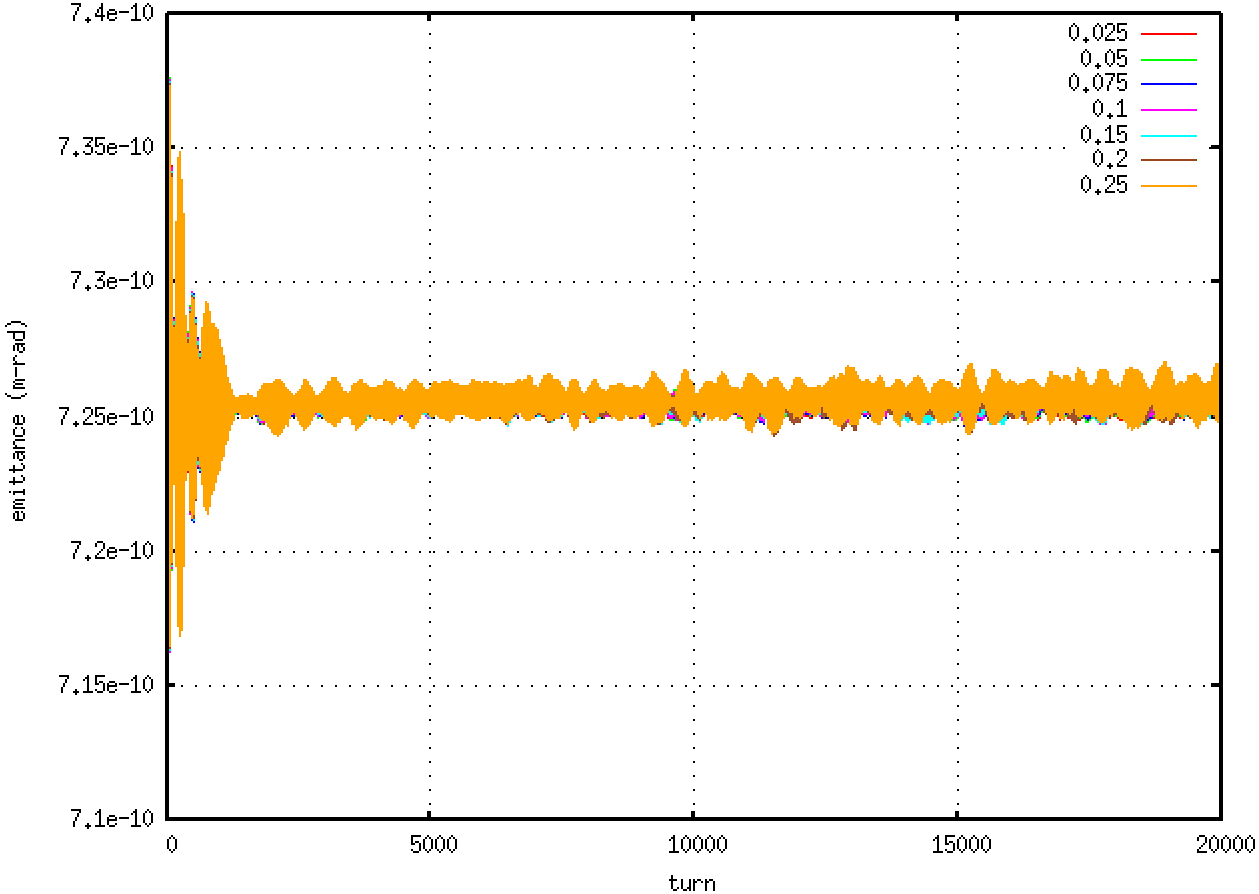


Emittance Evolution 400MHz Cavity, 32 Hz Modulation

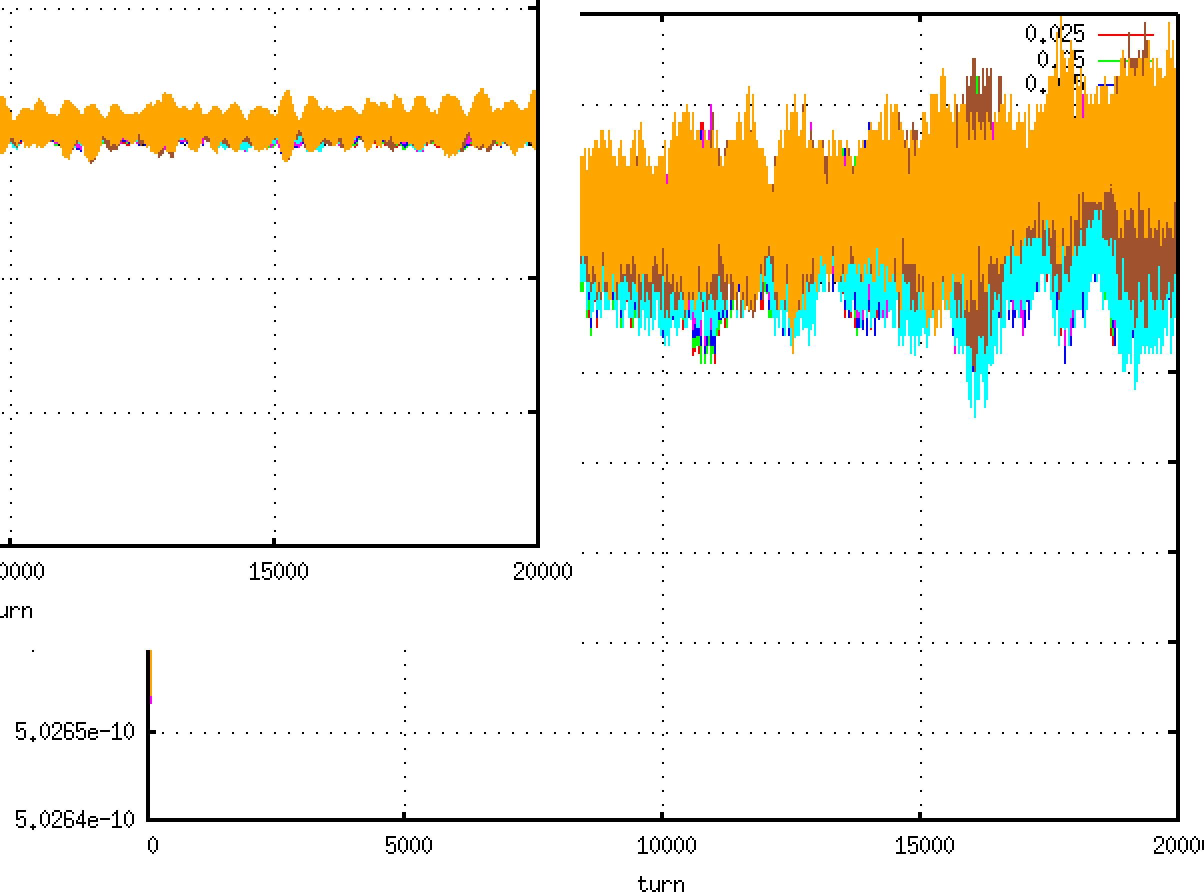




Emittance Evolution 400MHz Cavity, 32k Hz Modulation

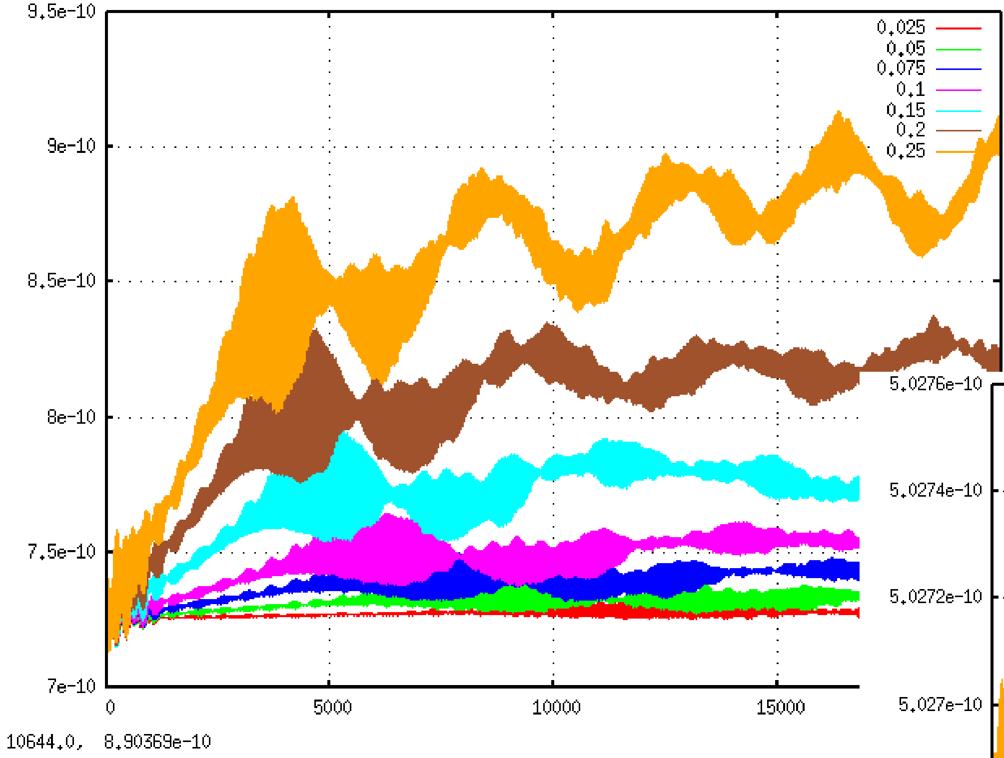


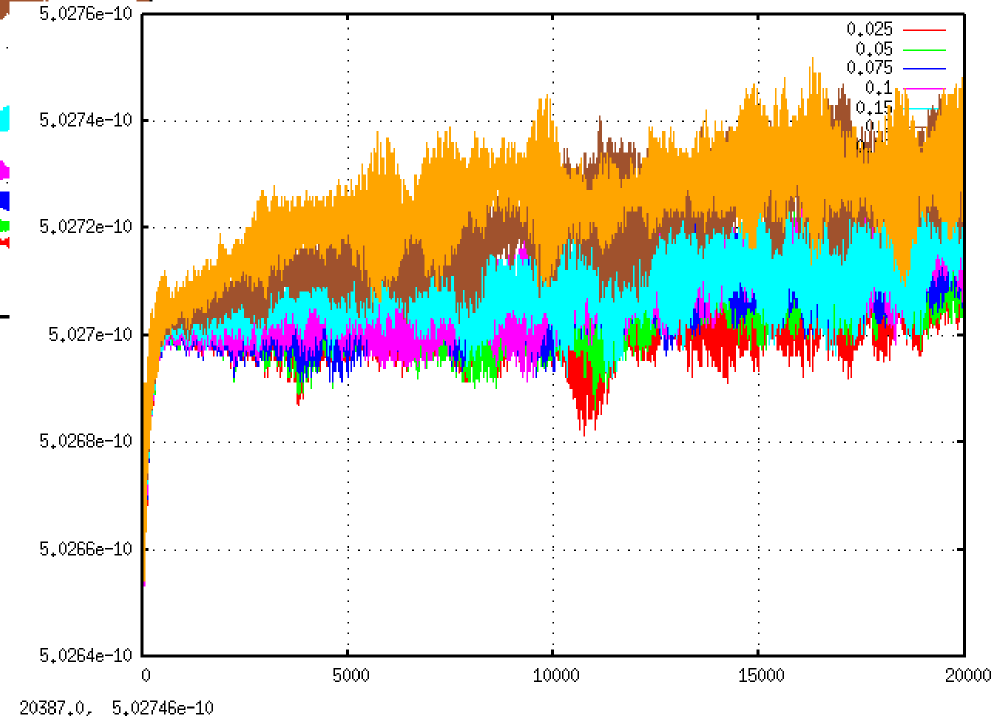
20622.8, 7.20065e-10



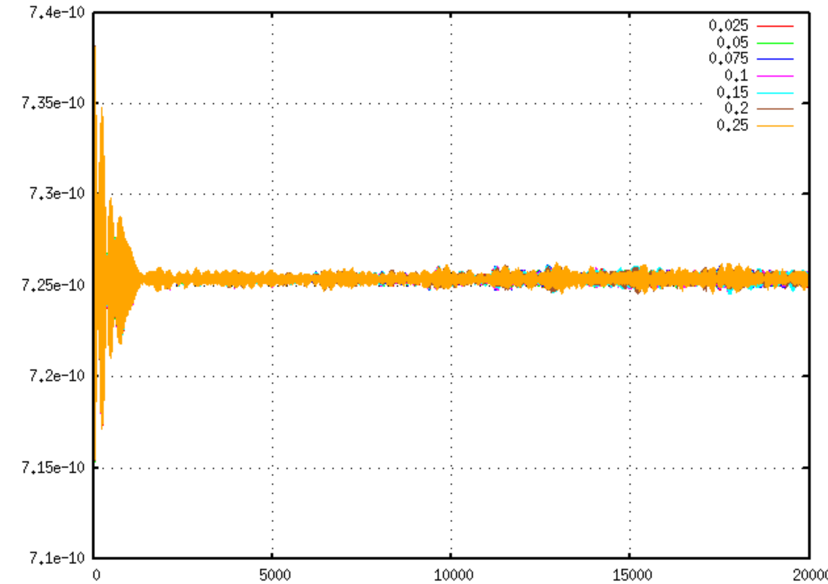
19120.1, 5.02694e-10

Emittance Evolution 400MHz Cavity, 64k Hz Modulation





Emittance Evolution 400MHz Cavity, 100k Hz Modulation



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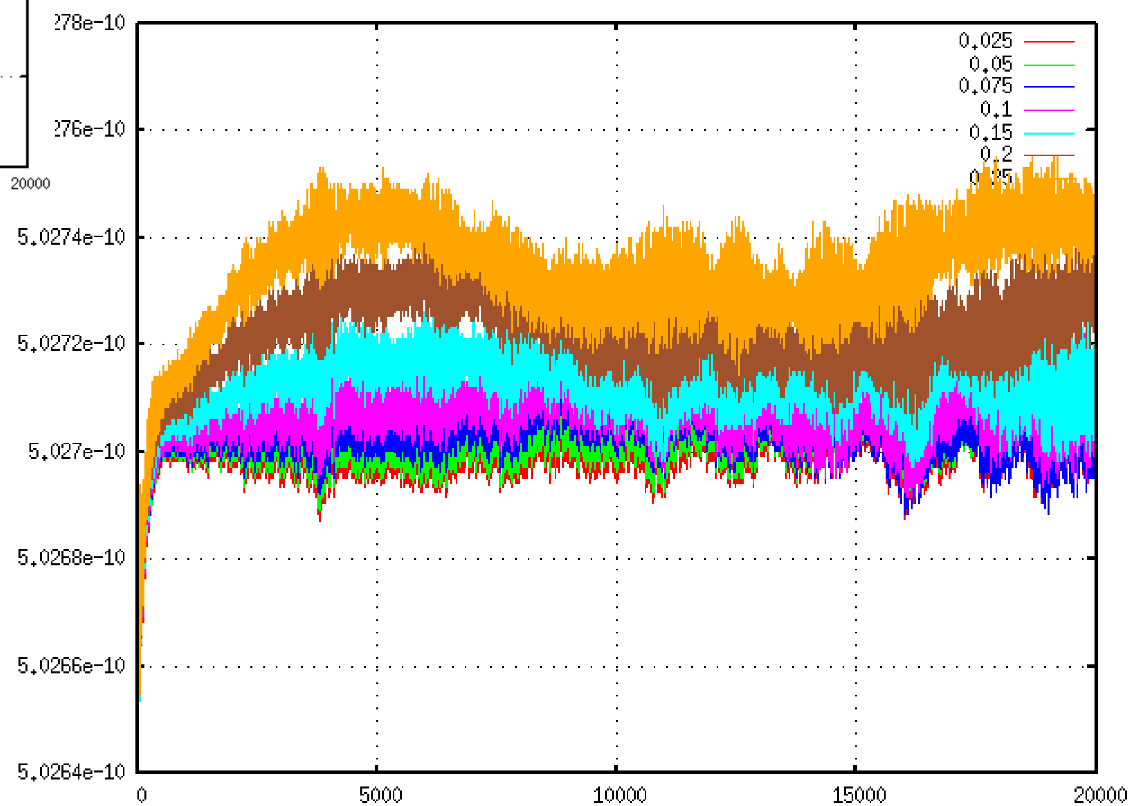
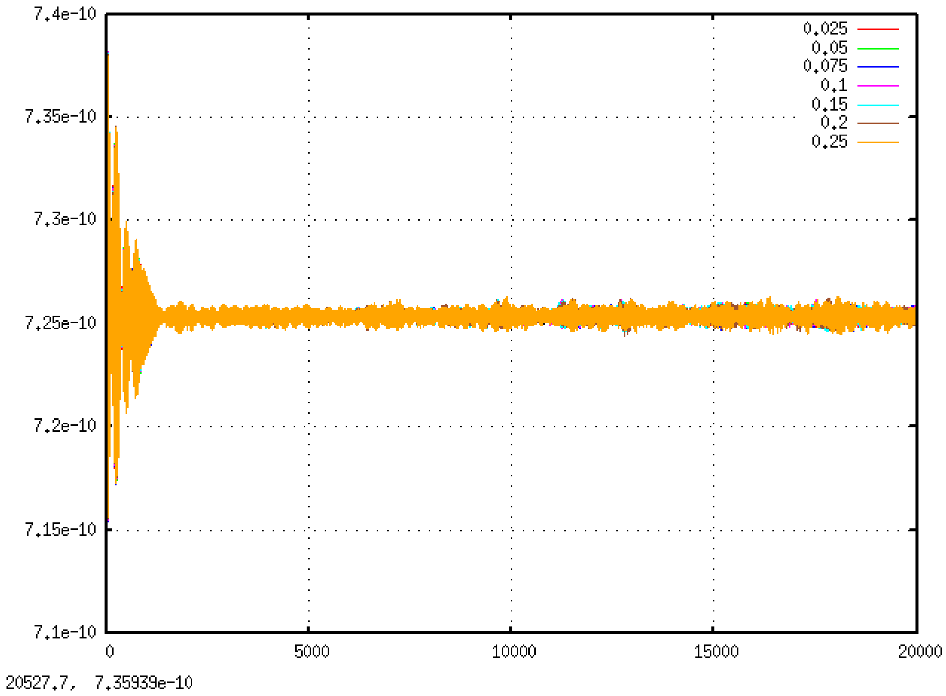
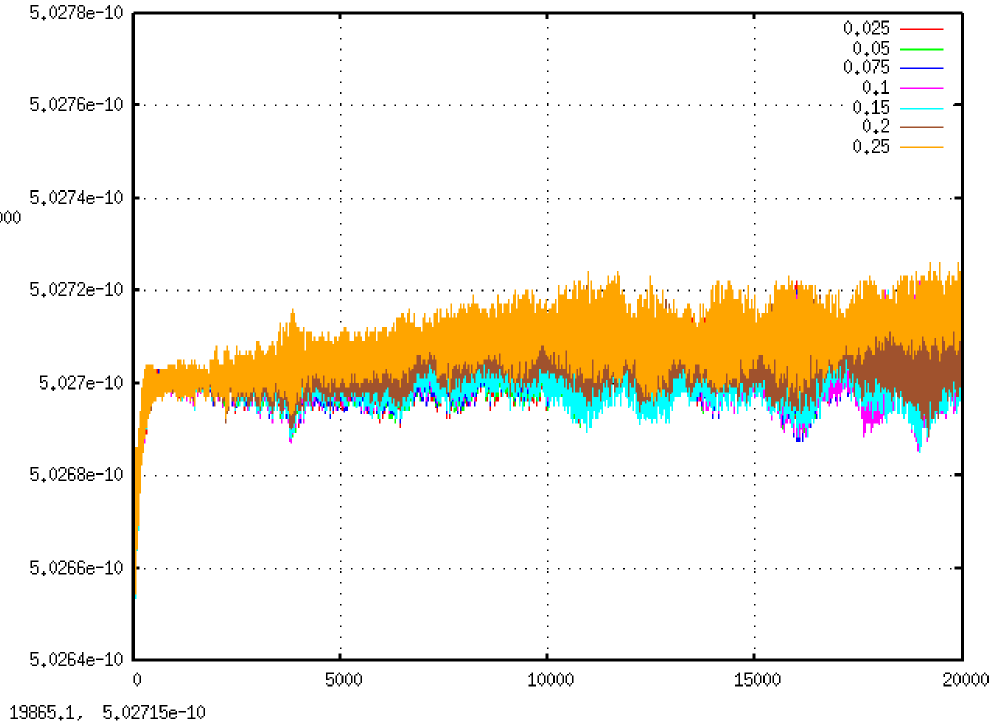


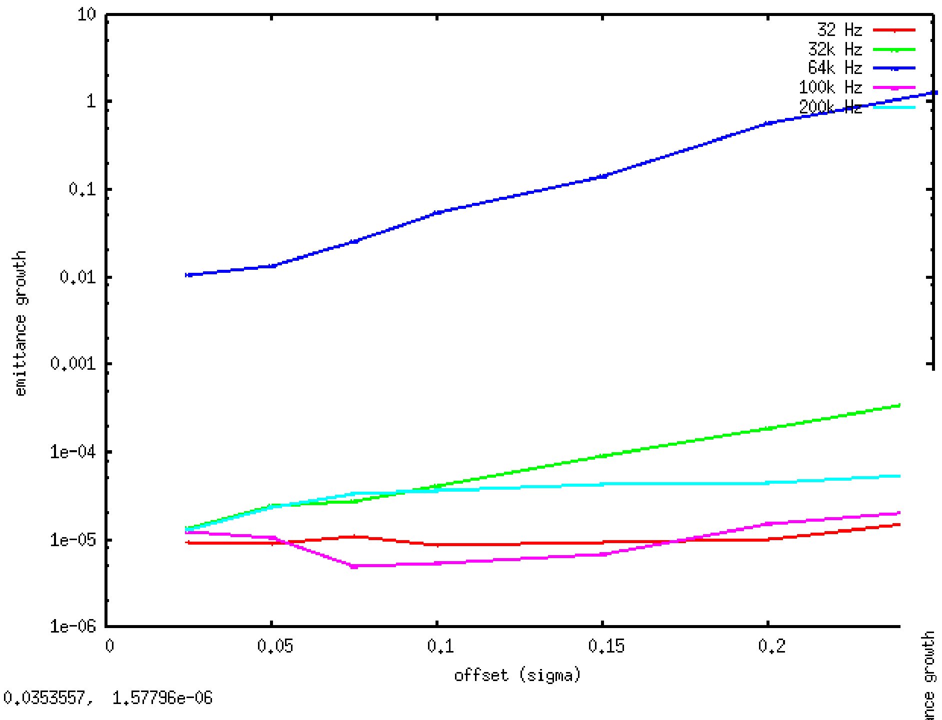
19302.3, 5.02738e-10

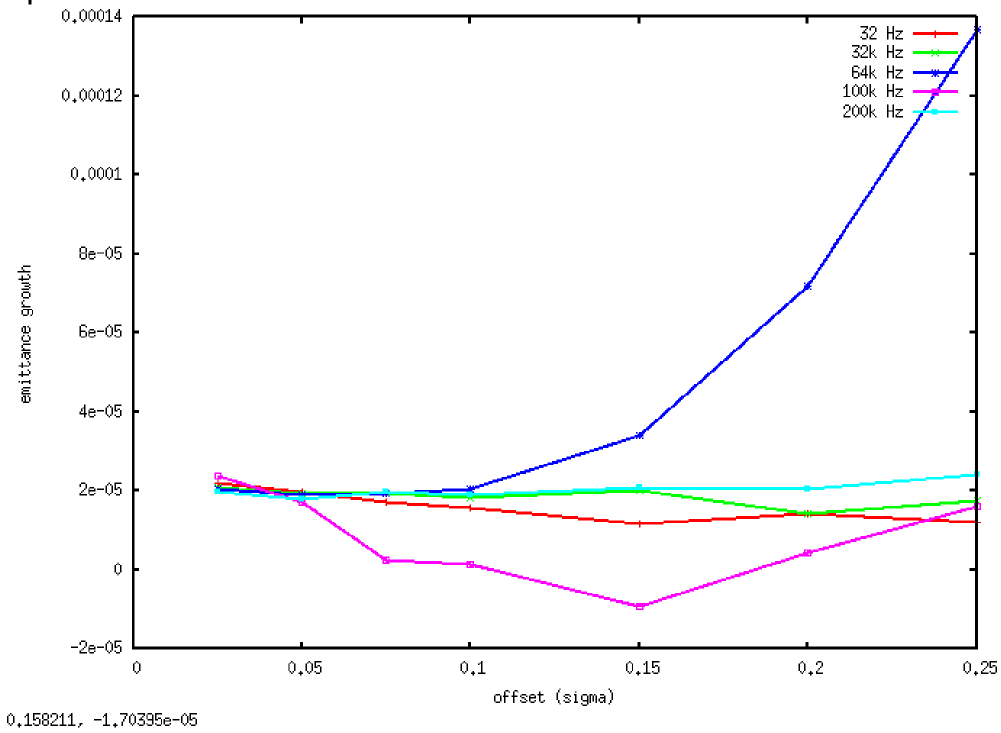
Emittance Evolution 400MHz Cavity, 200k Hz Modulation



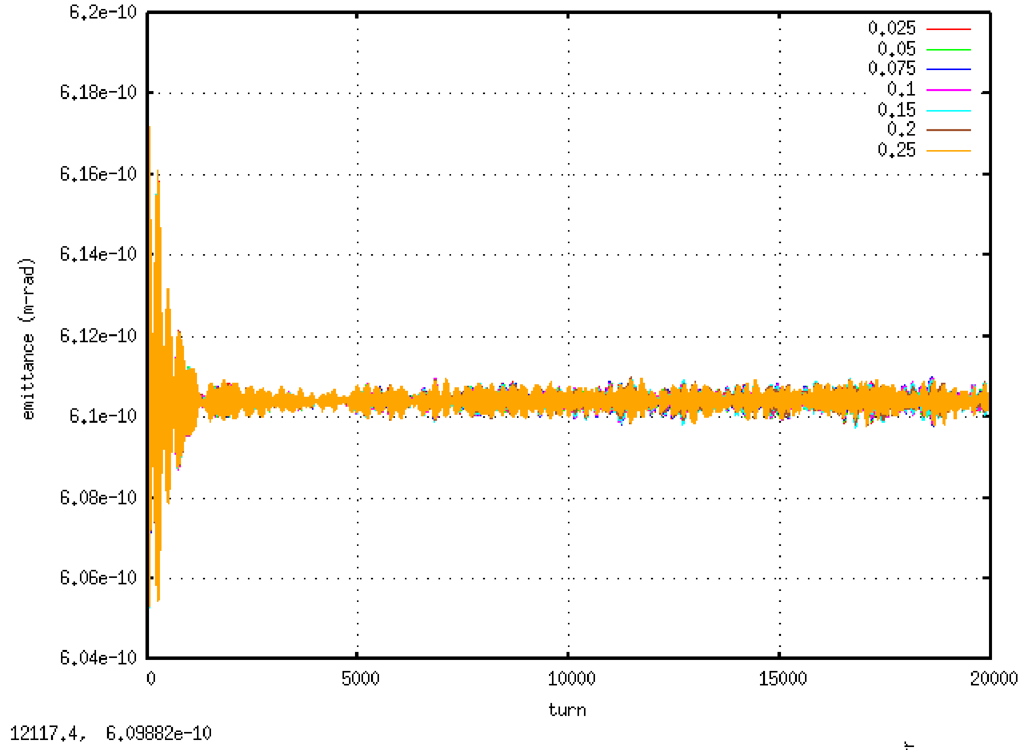


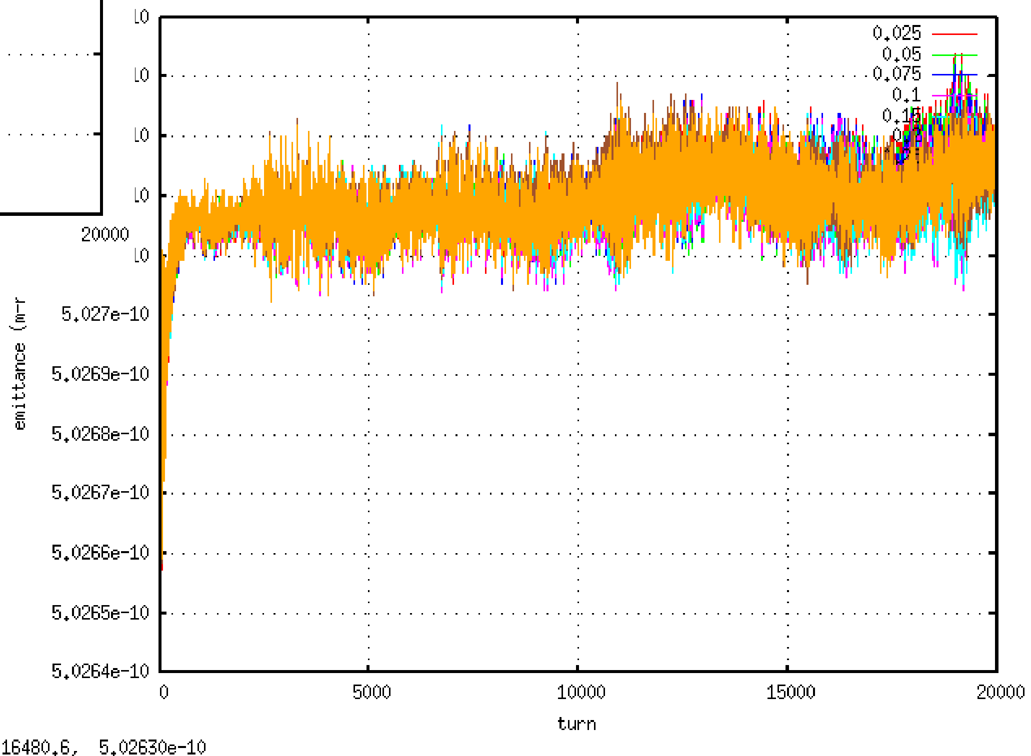
Emittance Growth after 20k Turns vs. Offset
800 MHz Crab Cavity



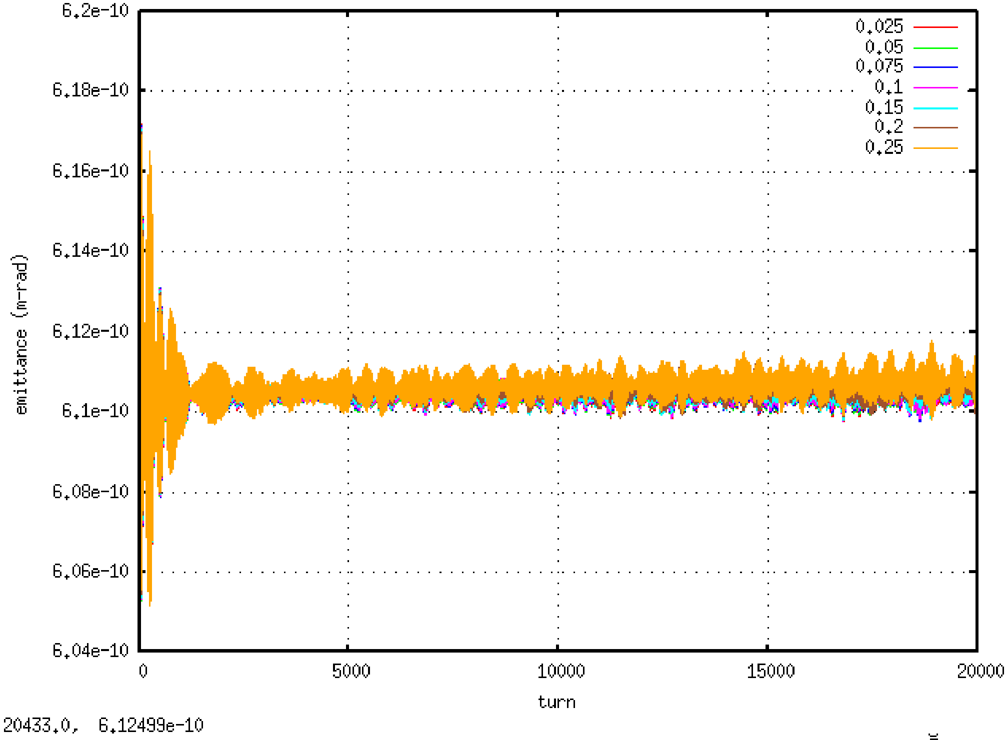


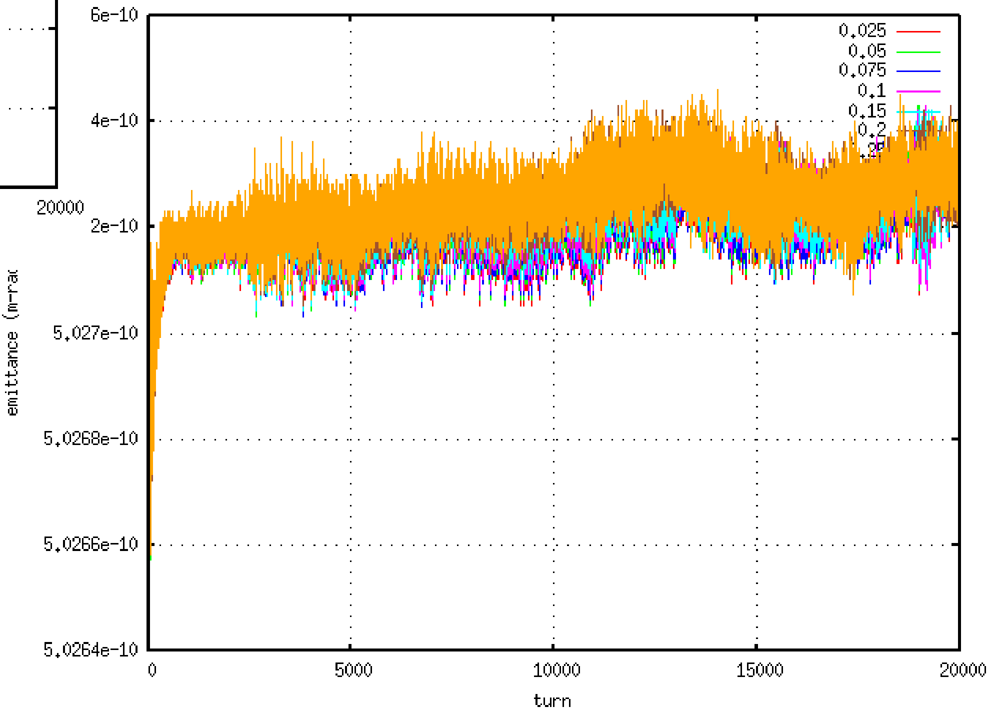
Emittance Evolution 800MHz Cavity, 32 Hz Modulation



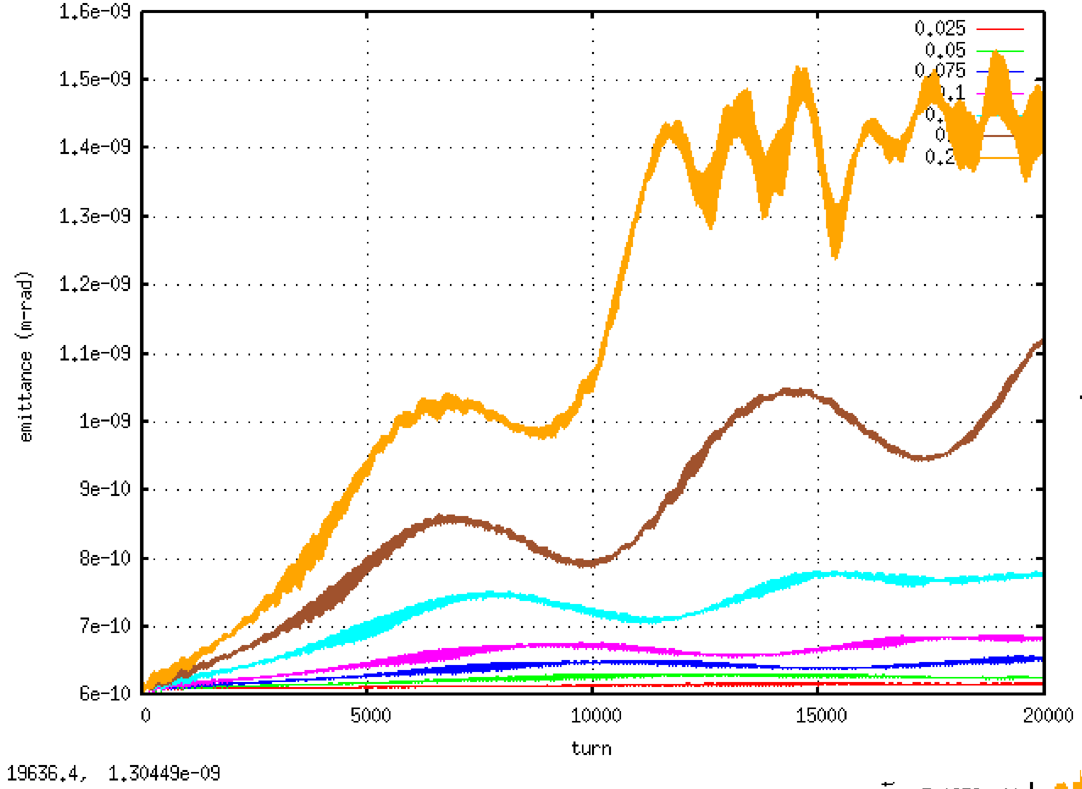


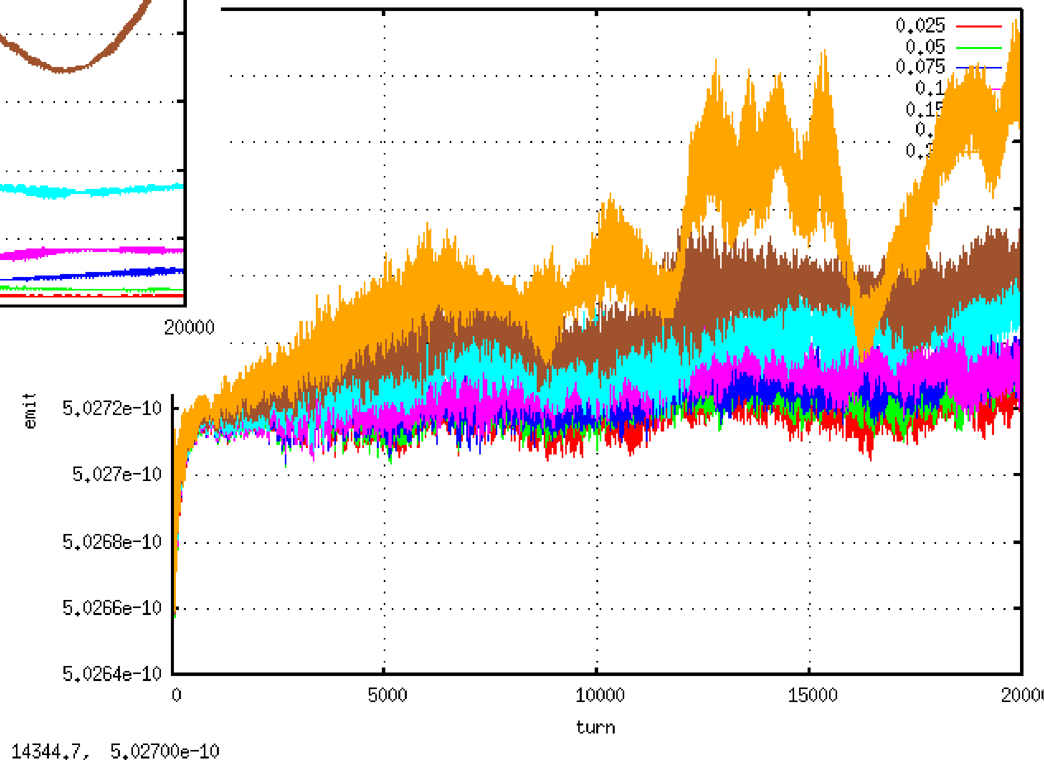
Emittance Evolution 800MHz Cavity, 32k Hz Modulation



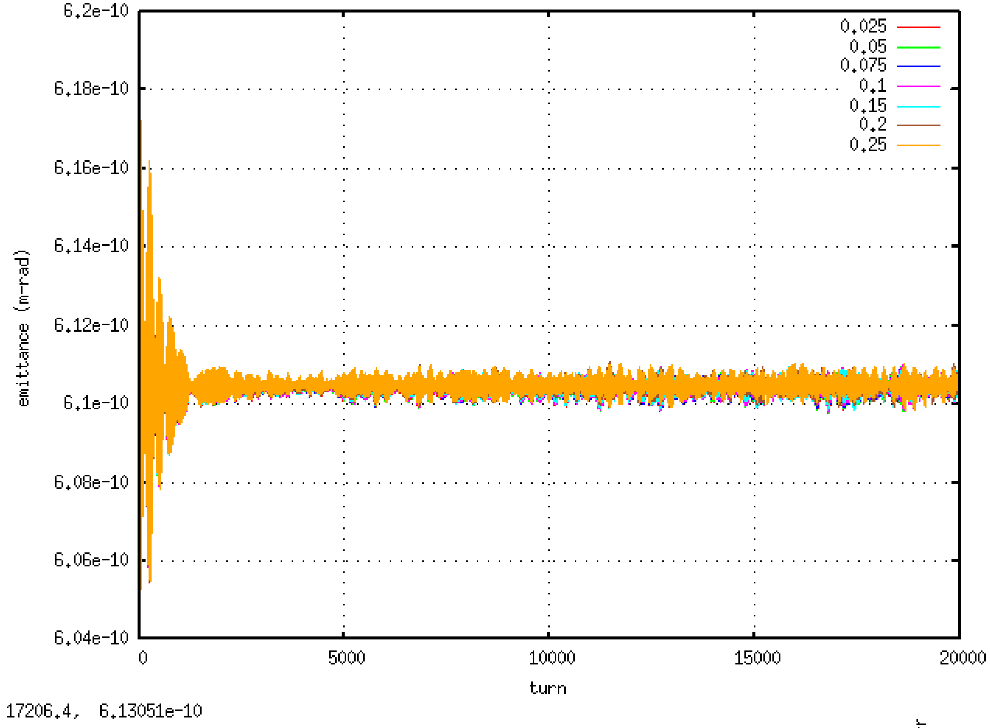


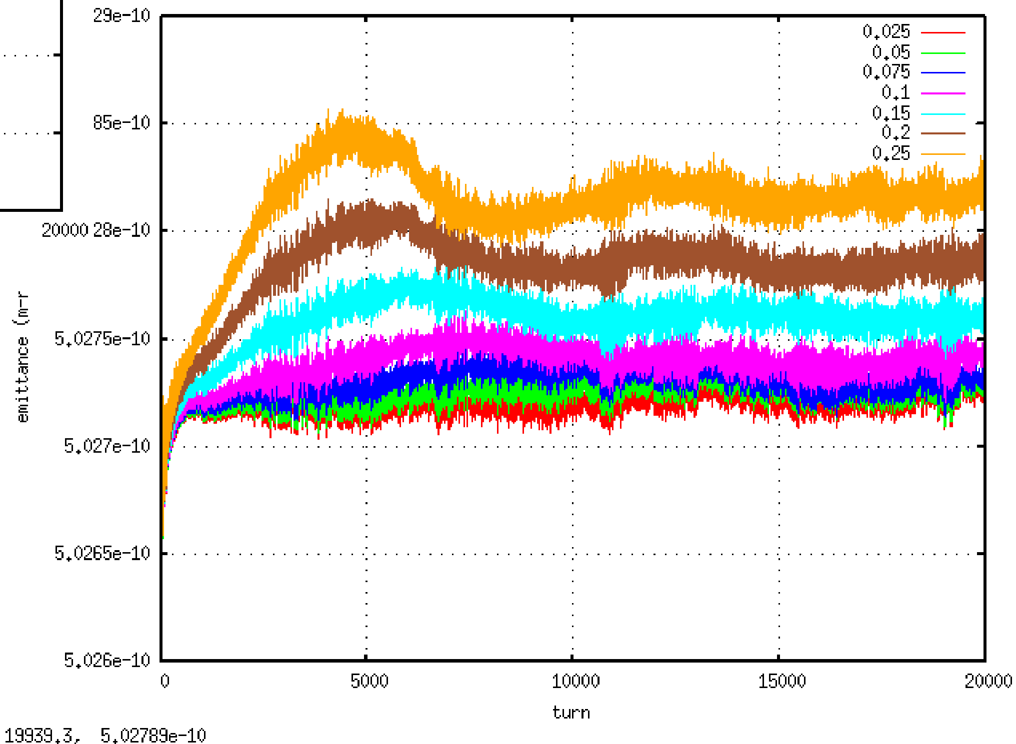
Emittance Evolution 800MHz Cavity, 64k Hz Modulation



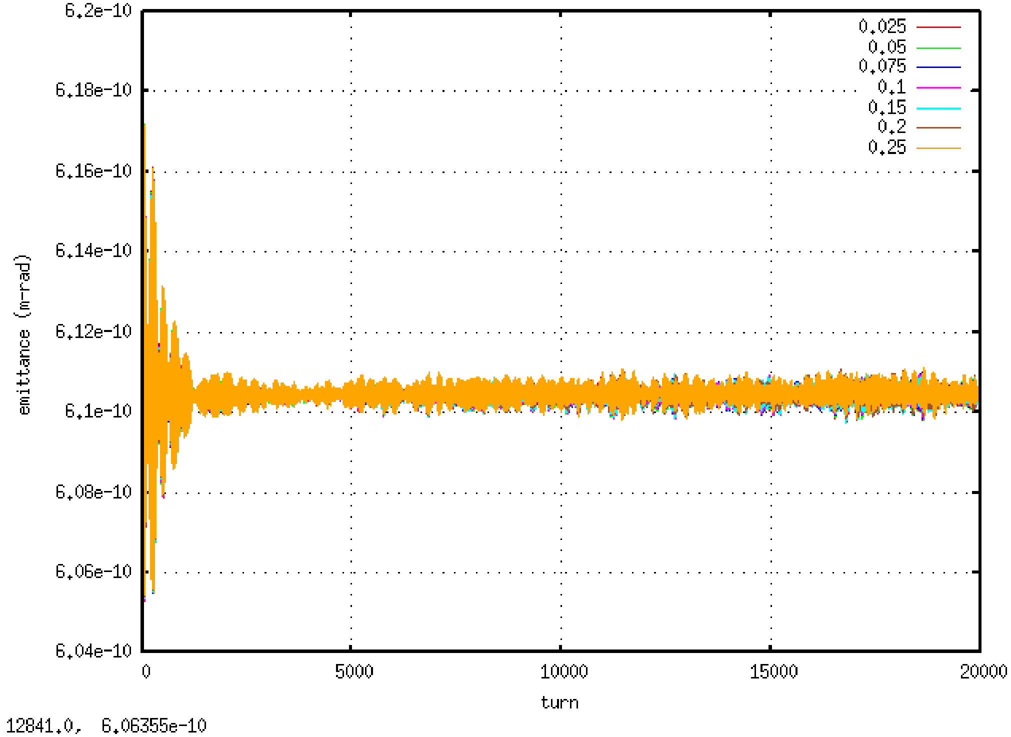


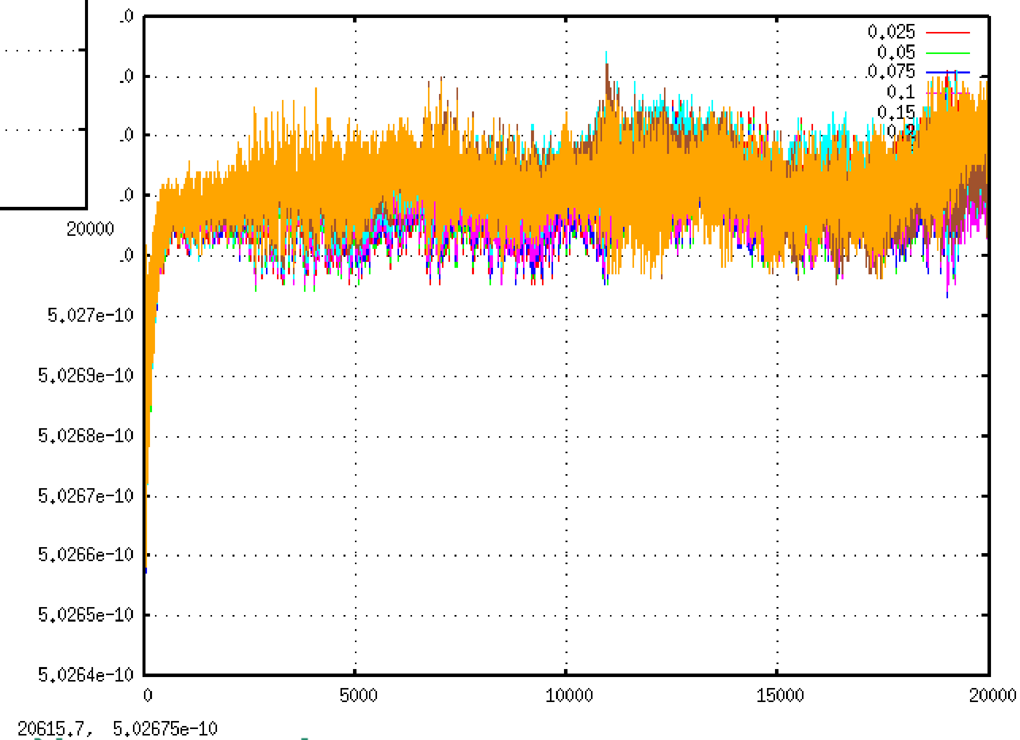
Emittance Evolution 800MHz Cavity, 100k Hz Modulation





Emittance Evolution 800MHz Cavity, 200k Hz Modulation





Horizontal rms size and Emittance Evolution
(800MHz Cavity, 64k Hz Modulation, 0.025 sigma)

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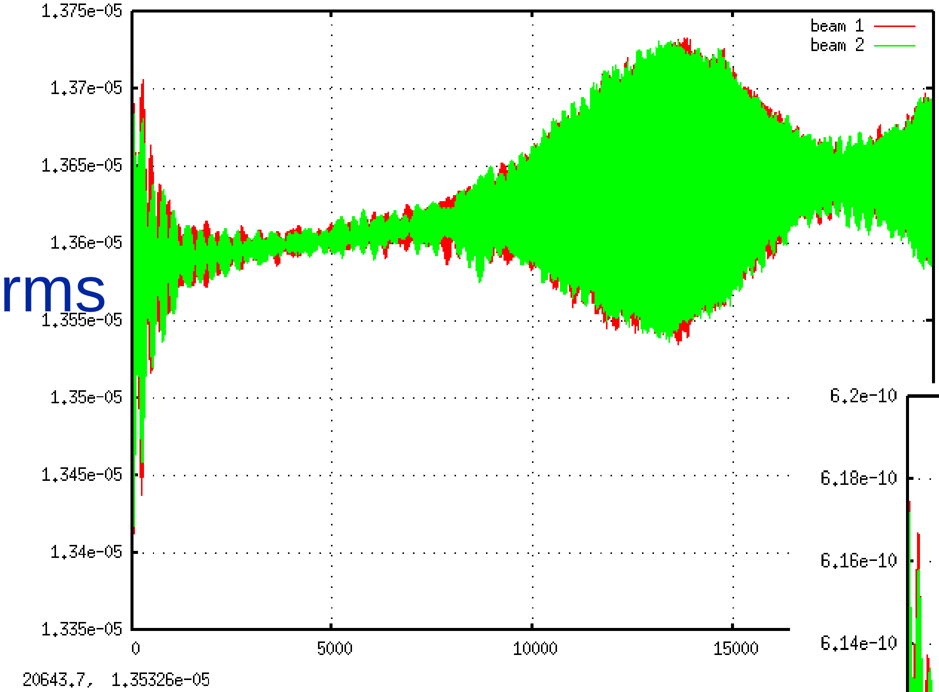
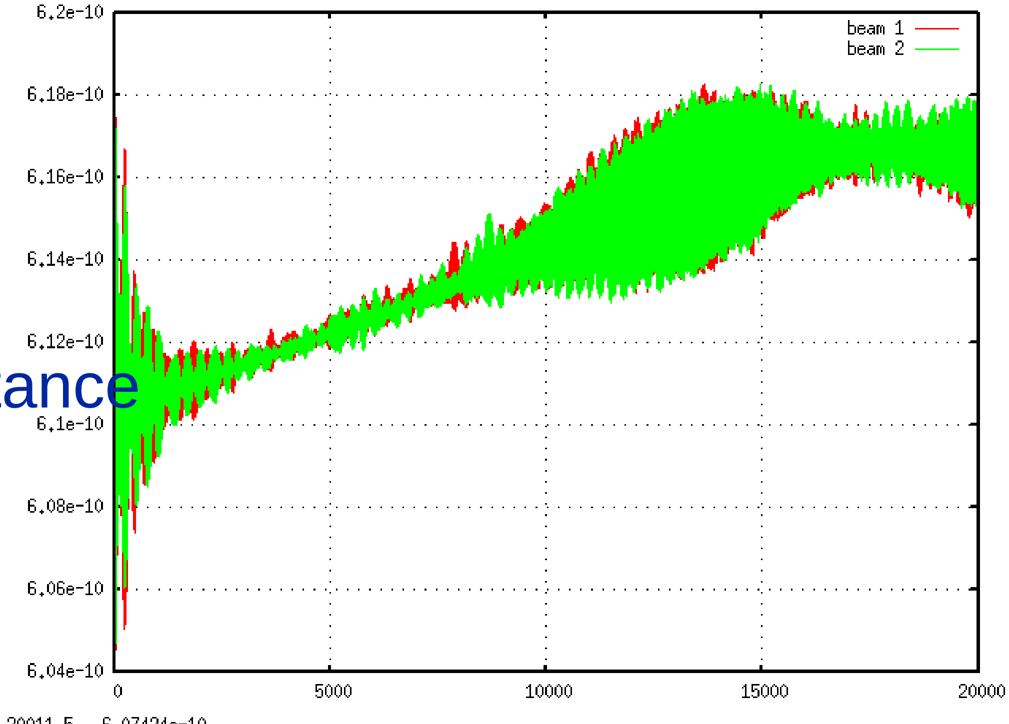
xrms

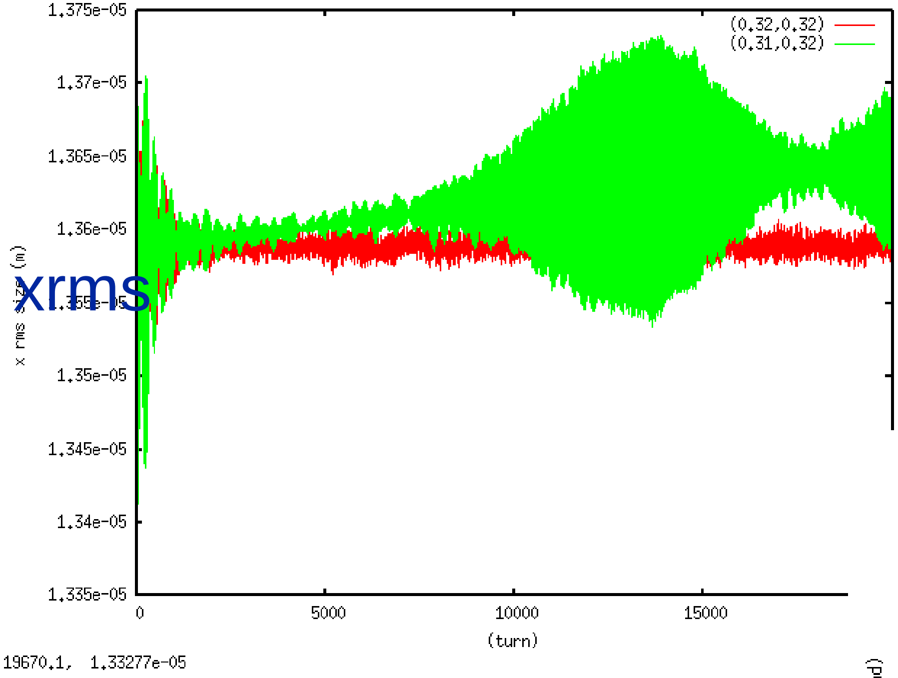


emittance

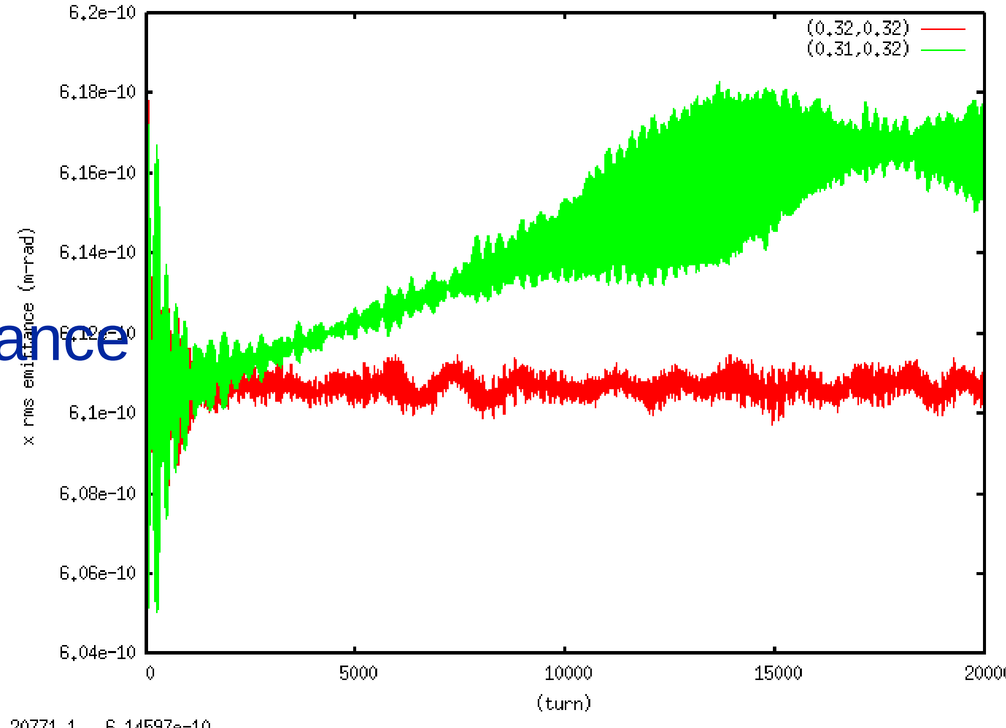


Horizontal rms size and Emittance Evolution with Different Working Points (800MHz Cavity, 64k Hz Modulation, 0.025 sigma)

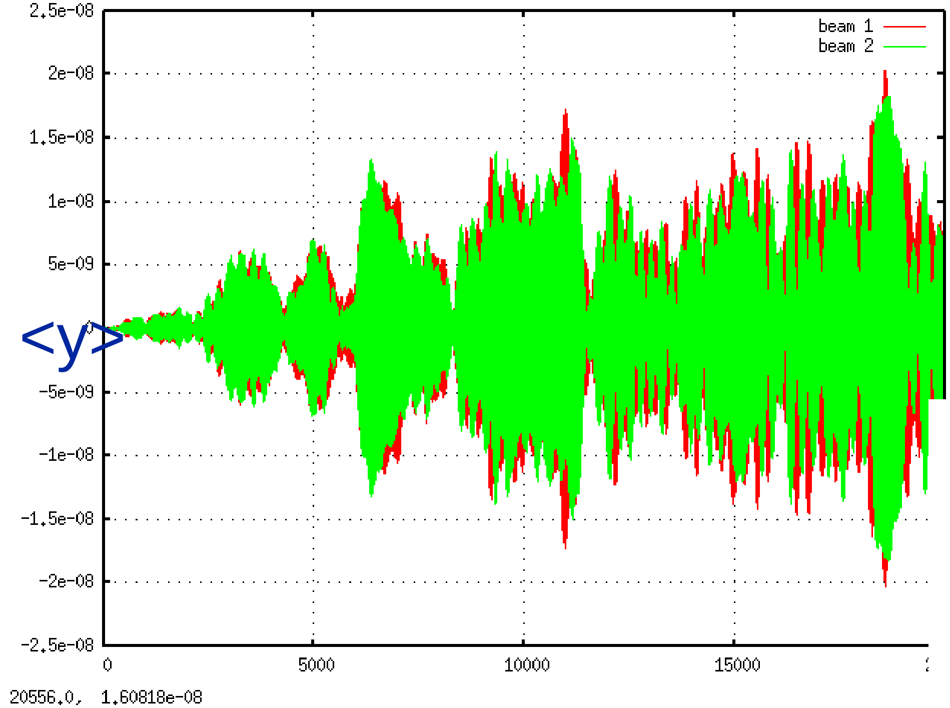
xrms



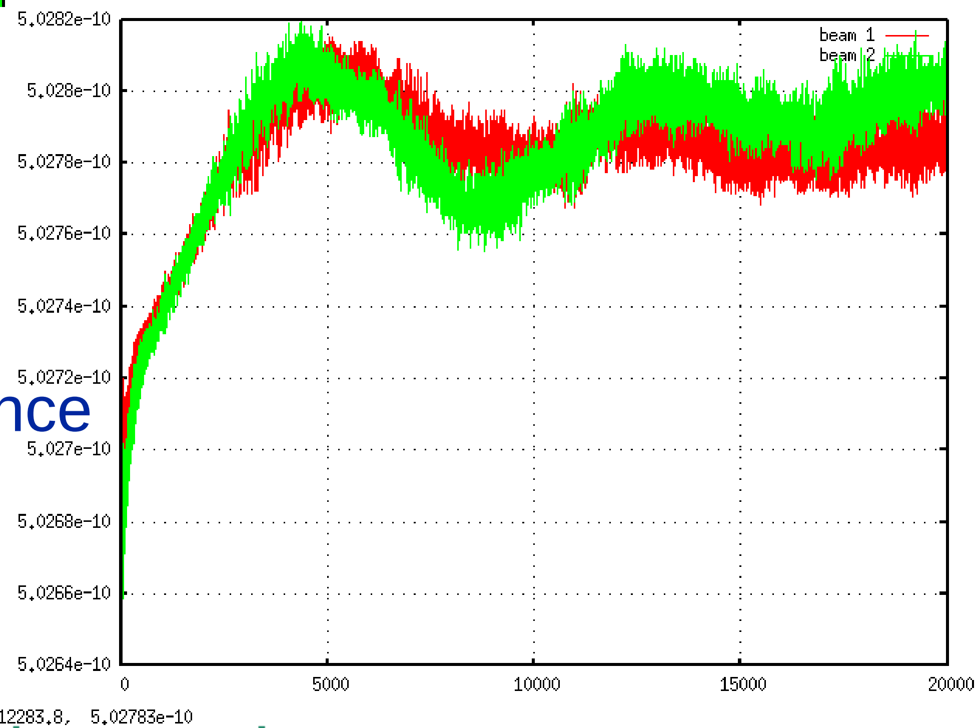
emittance



Vertical Central and Rms Emittance Evolution (800MHz Cavity, 100k Hz Modulation, 0.2 sigma)

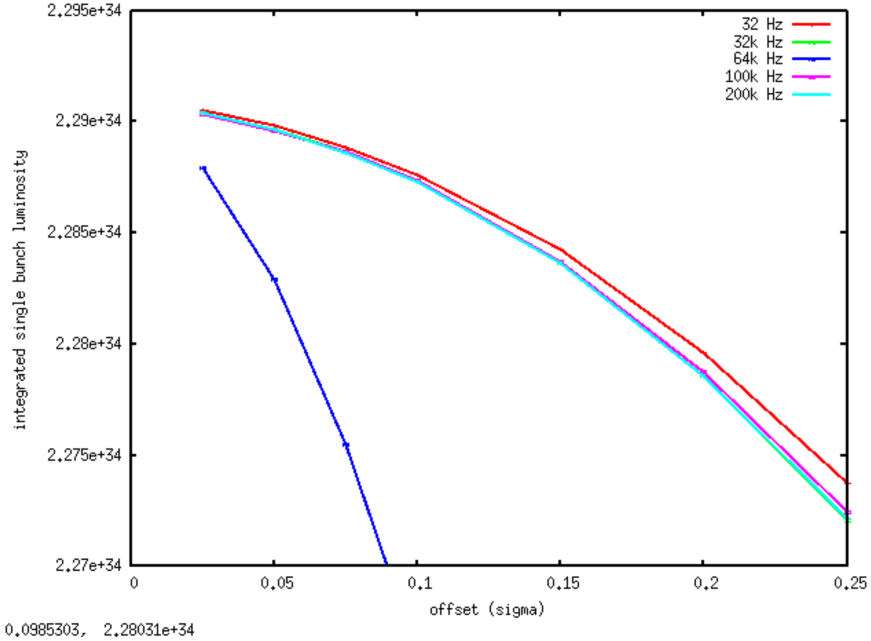


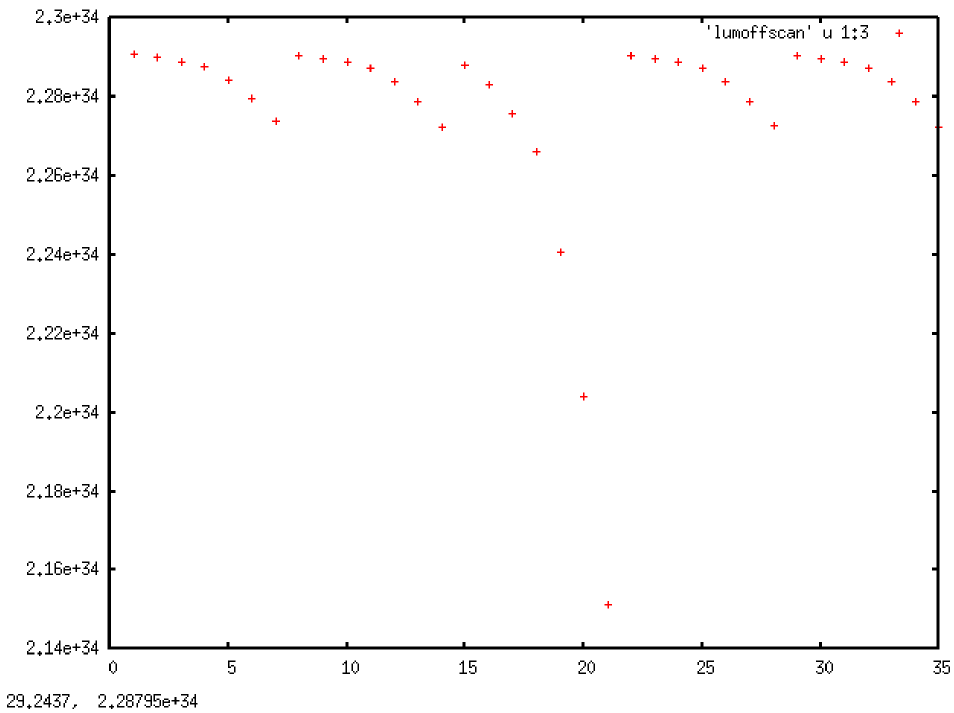
<y>



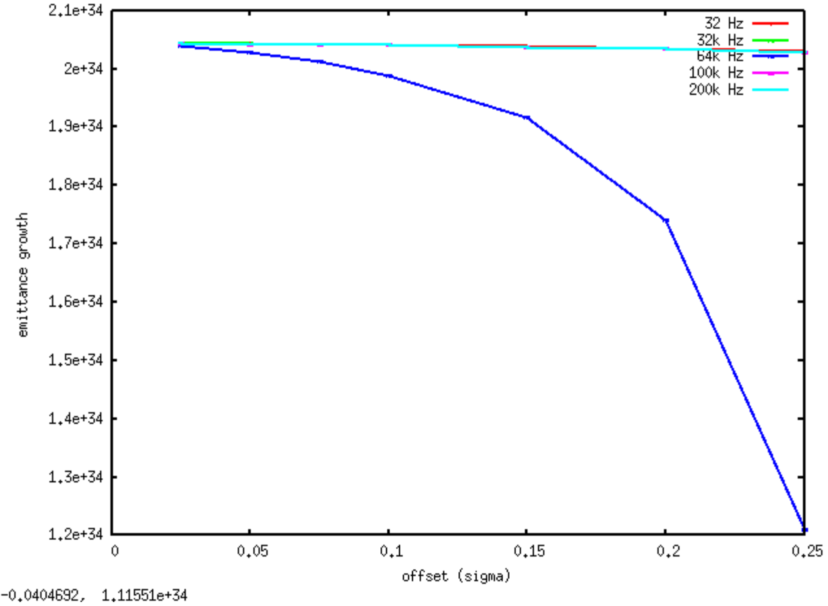
emittance

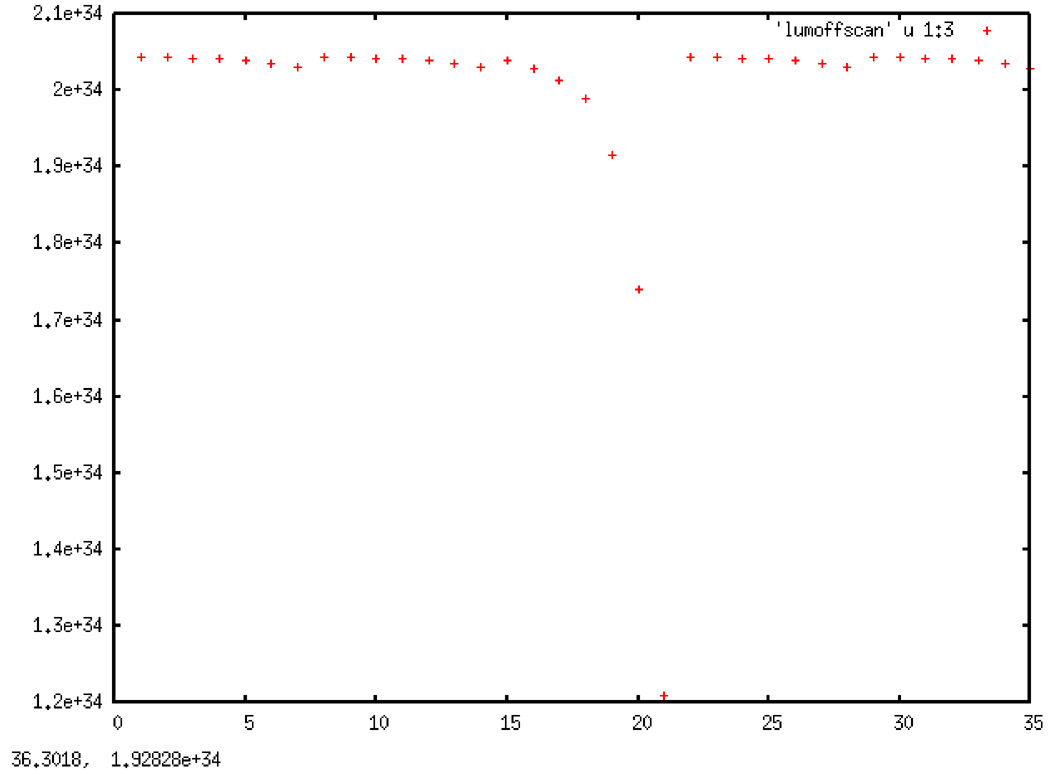
Integrated Lum. Vs. Offset with 400 MHz Crab Cavity





Integrated Lum. Vs. Offset with 800 MHz Crab Cavity

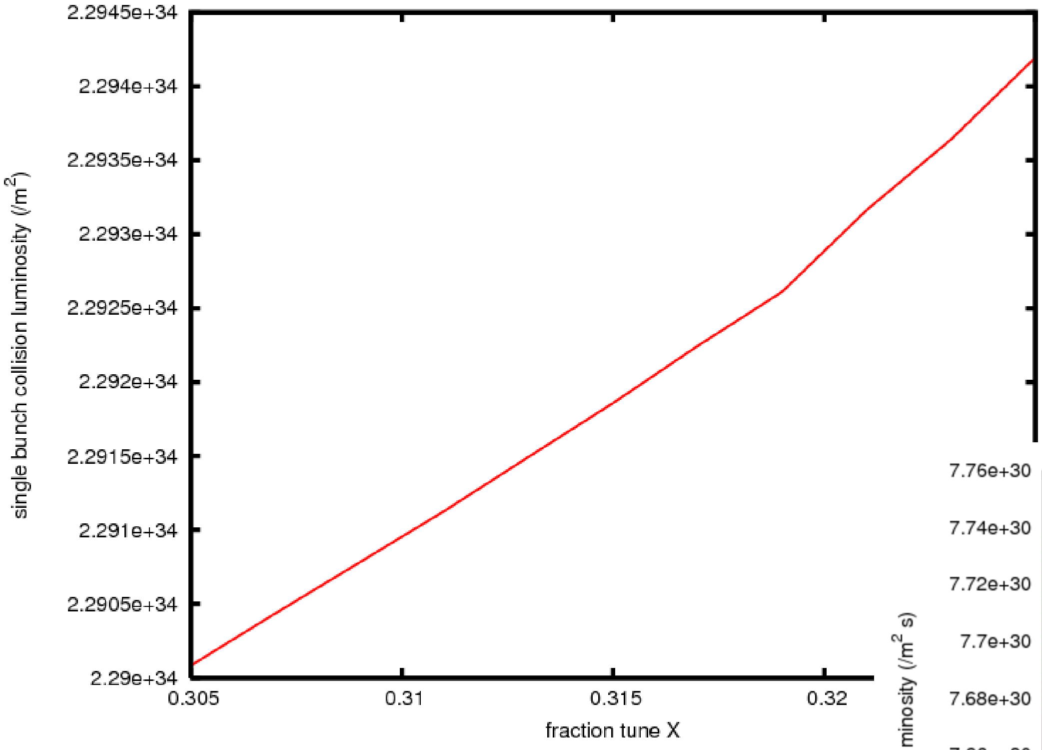


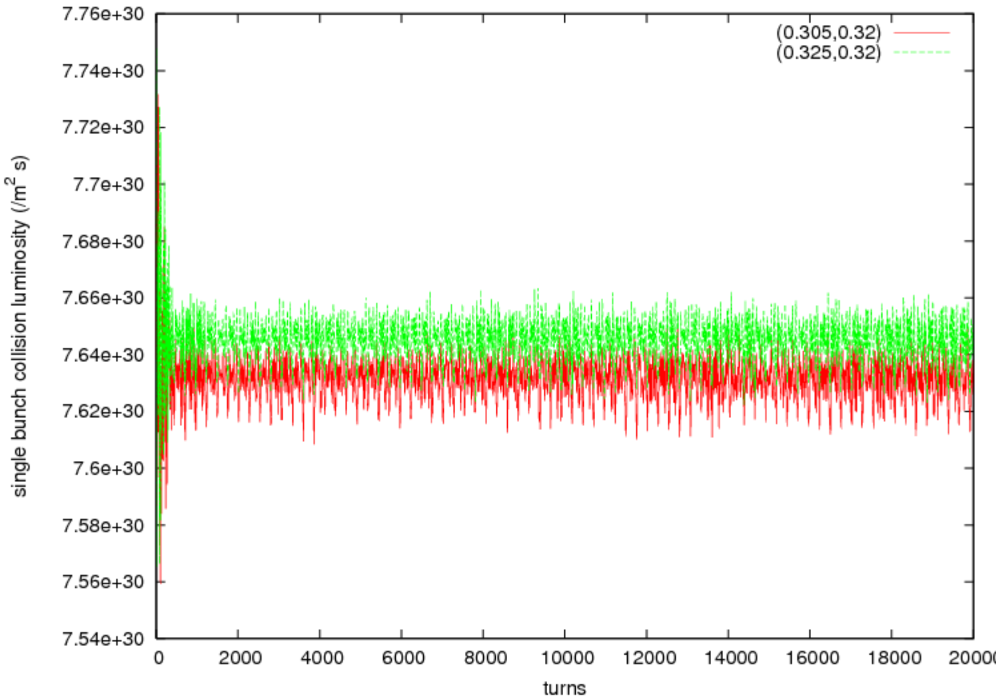


Preliminary Beam-Beam Tune Scan Studies with Crab Cavity

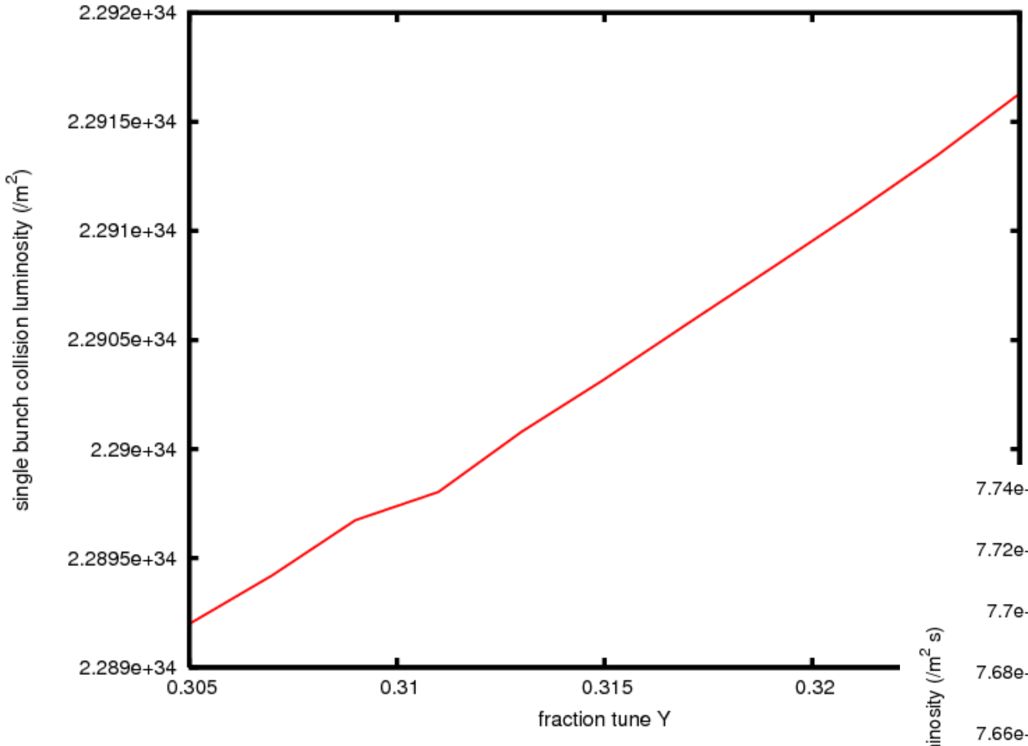
1. Nominal tune work point (0.31,0.32)
2. Horizontal tune scan for 400 MHz crab cavity
3. Vertical tune scan for 400 MHz crab cavity
4. Horizontal tune scan for 800 MHz crab cavity
5. Vertical tune scan for 800MHz crab cavity

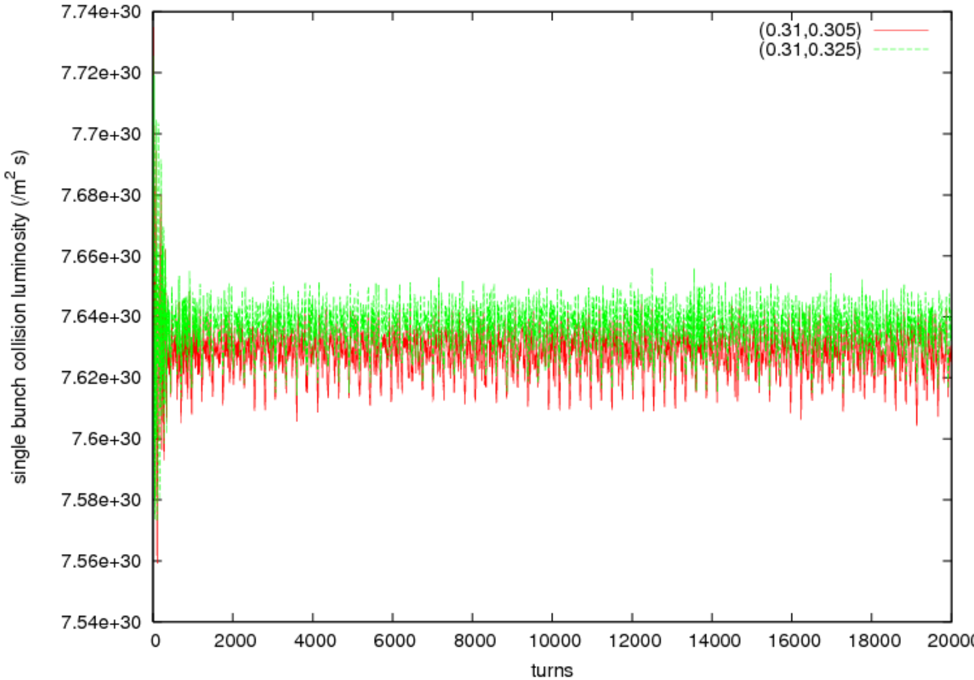
Integrated Lum. (5k-20k Turns) vs. Horizontal Tune
400 MHz Crab Cavity



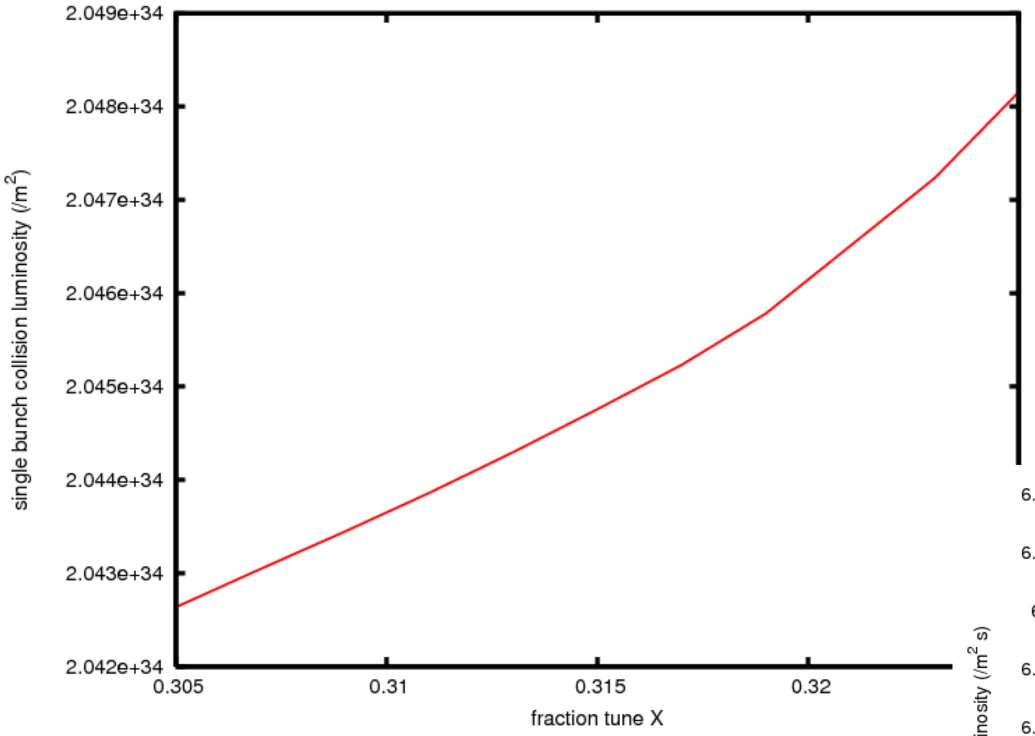


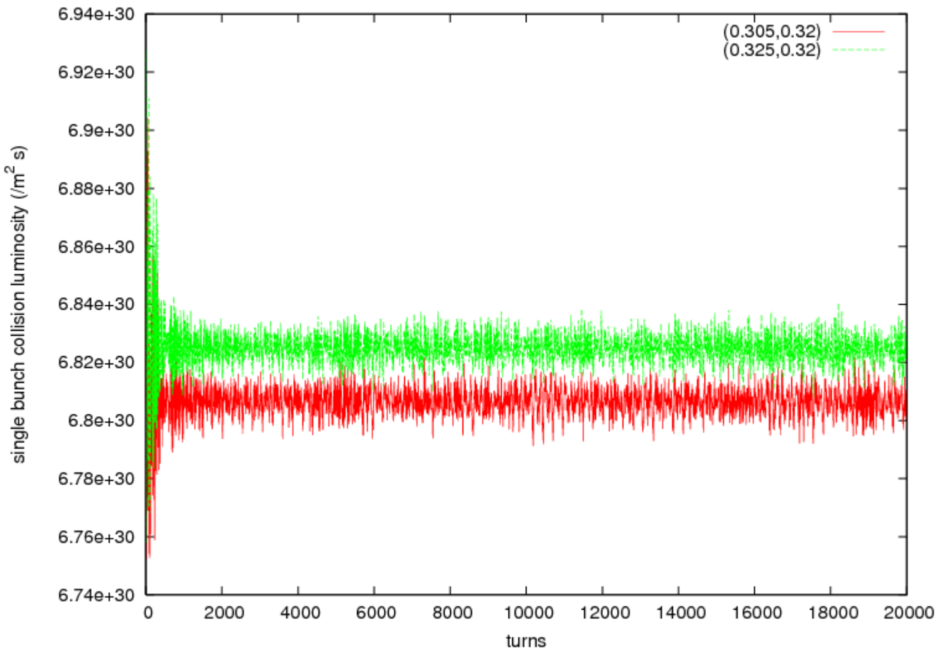
Integrated Lum. (5k-20k Turns) vs. Vertical Tune
400 MHz Crab Cavity



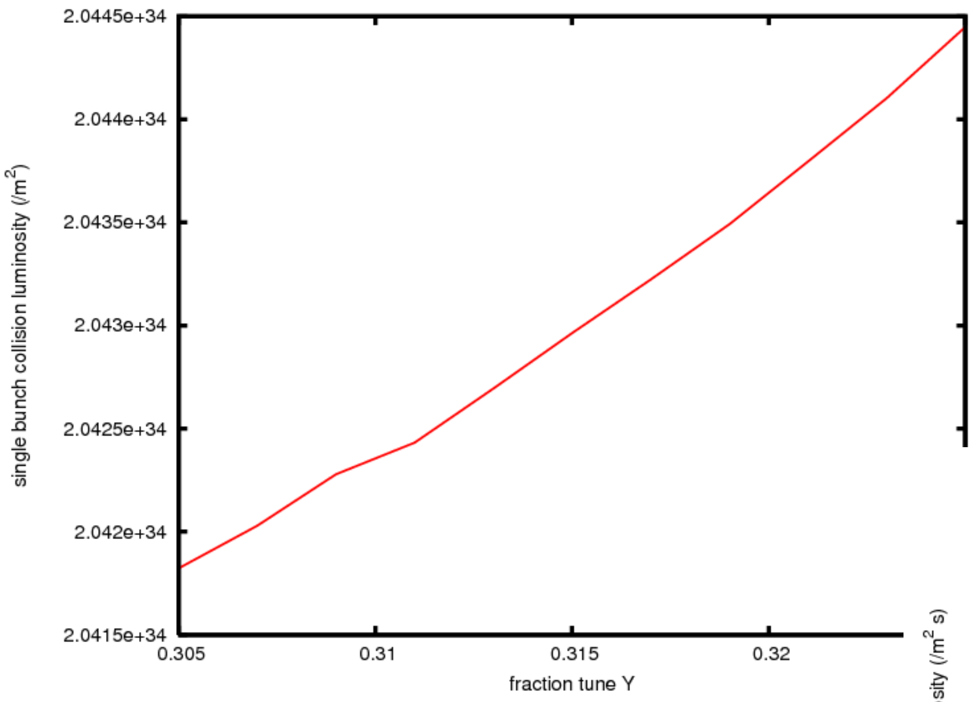


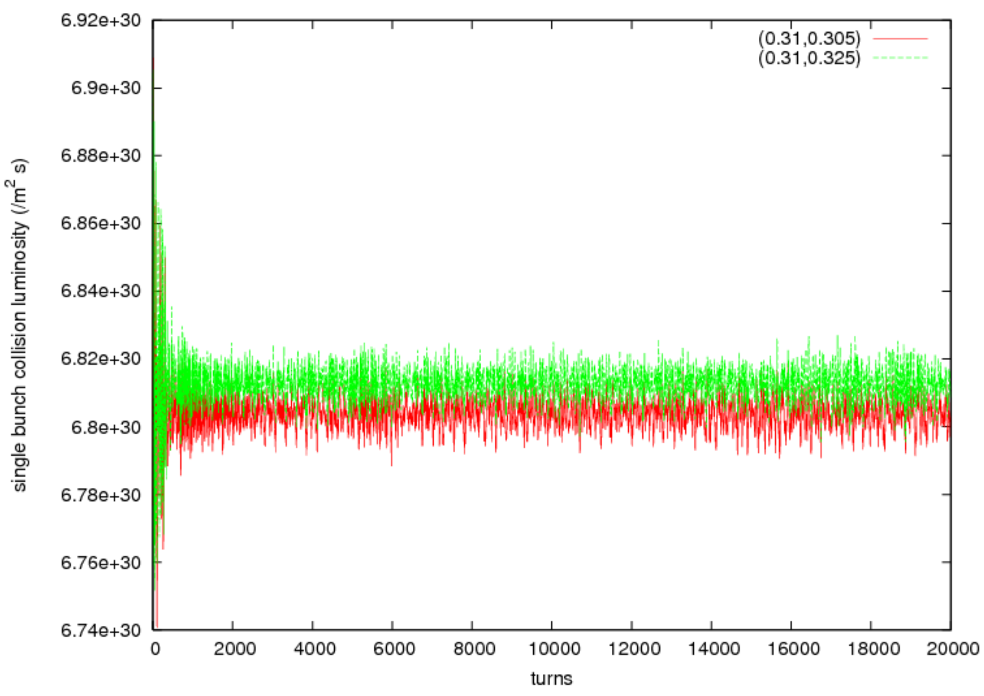
Integrated Lum. (5k-20k Turns) vs. Horizontal Tune
800 MHz Crab Cavity



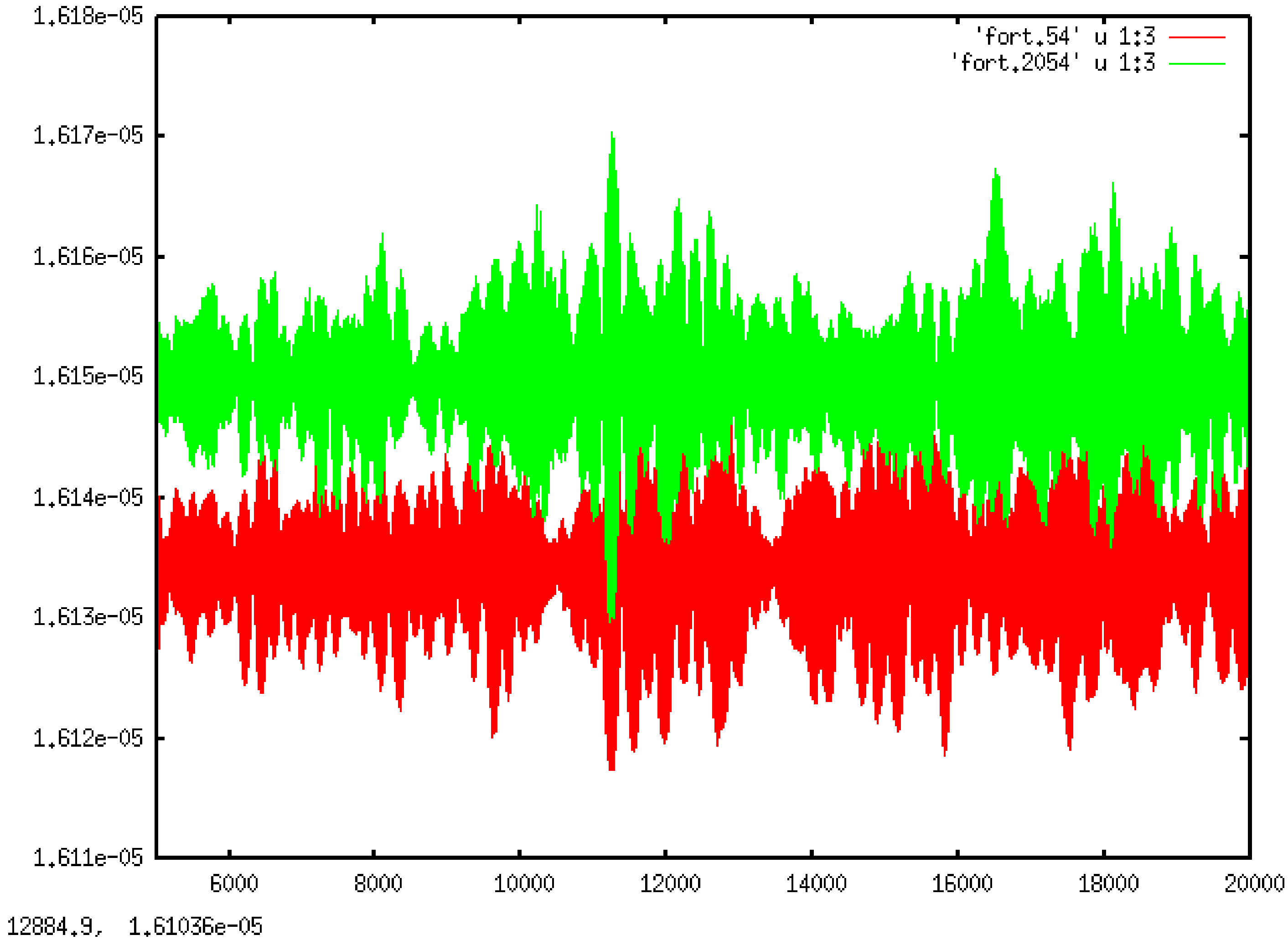


Integrated Lum. (5k-20k Turns) vs. Vertical Tune
800 MHz Crab Cavity





Horizontal Rms Size Evolution with Working Points (0.305,0.32) and (0.325,0.32)



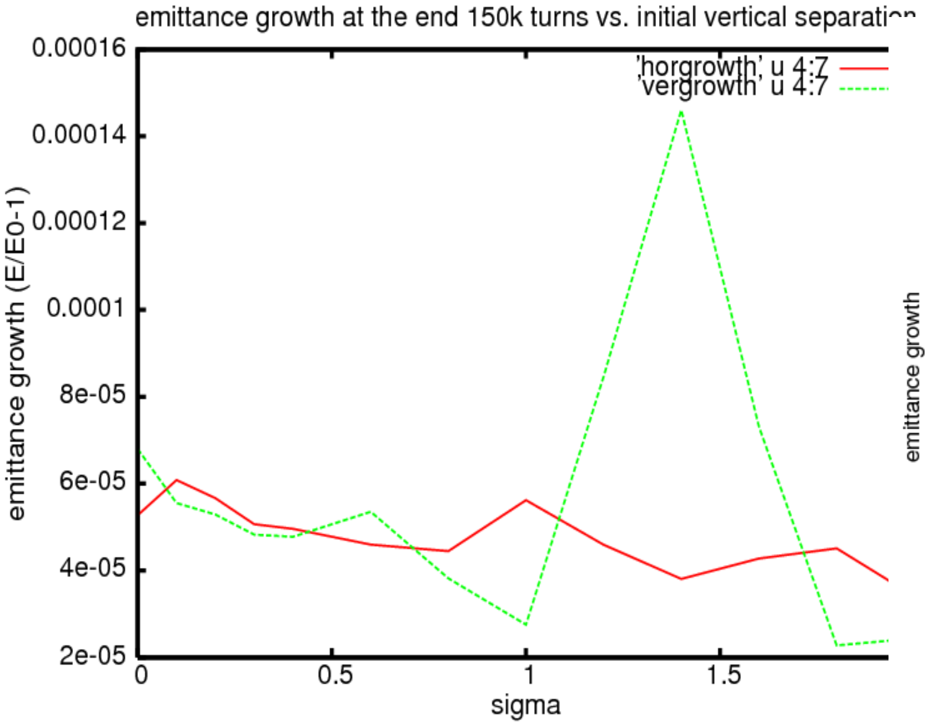
Summary and future work

- crab cavity jitter driven time dependent offset errors could cause significant emittance growth and loss of luminosity under some modulation frequency
- outside modulation resonance frequency, no sigificant emittance growth
- some increase of horizontal and vertical tune helps improve luminosity
- continue the study of the two-dimensional working point scan with crab cavity compensation
- explore the potential frequency bands driving emittance growth
- single crab cavity global compensation

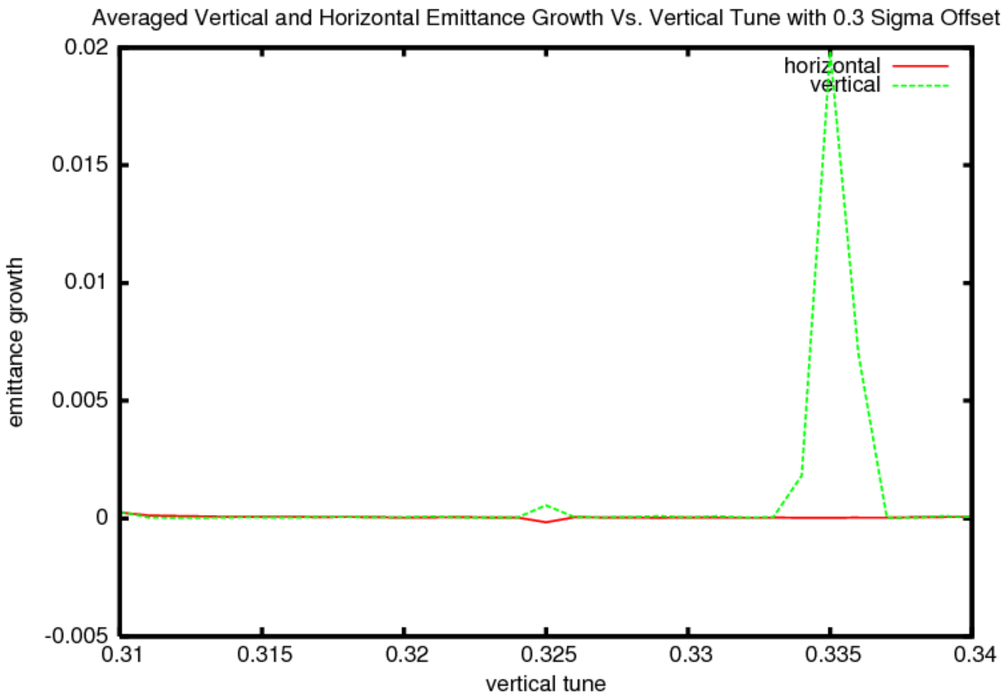
Appendix: LHC Offset Beam-Beam Collision Studies

- The offset collision is unavoidable due to the different bunch collision schemes at LHC
- Such offset collision might cause emittance growth that degrades luminosity lifetime and experimental conditions

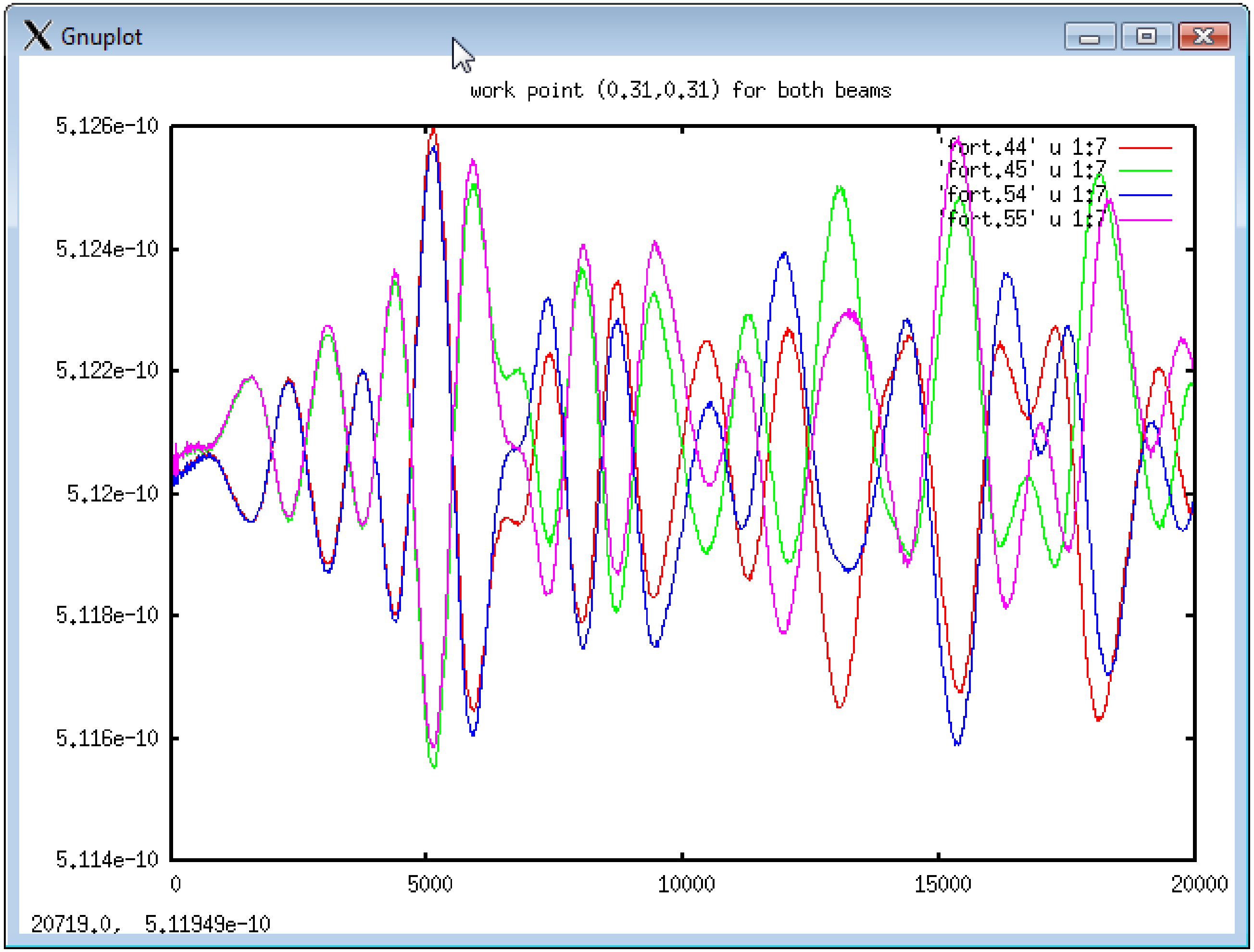
Emittance Growth vs. Offset



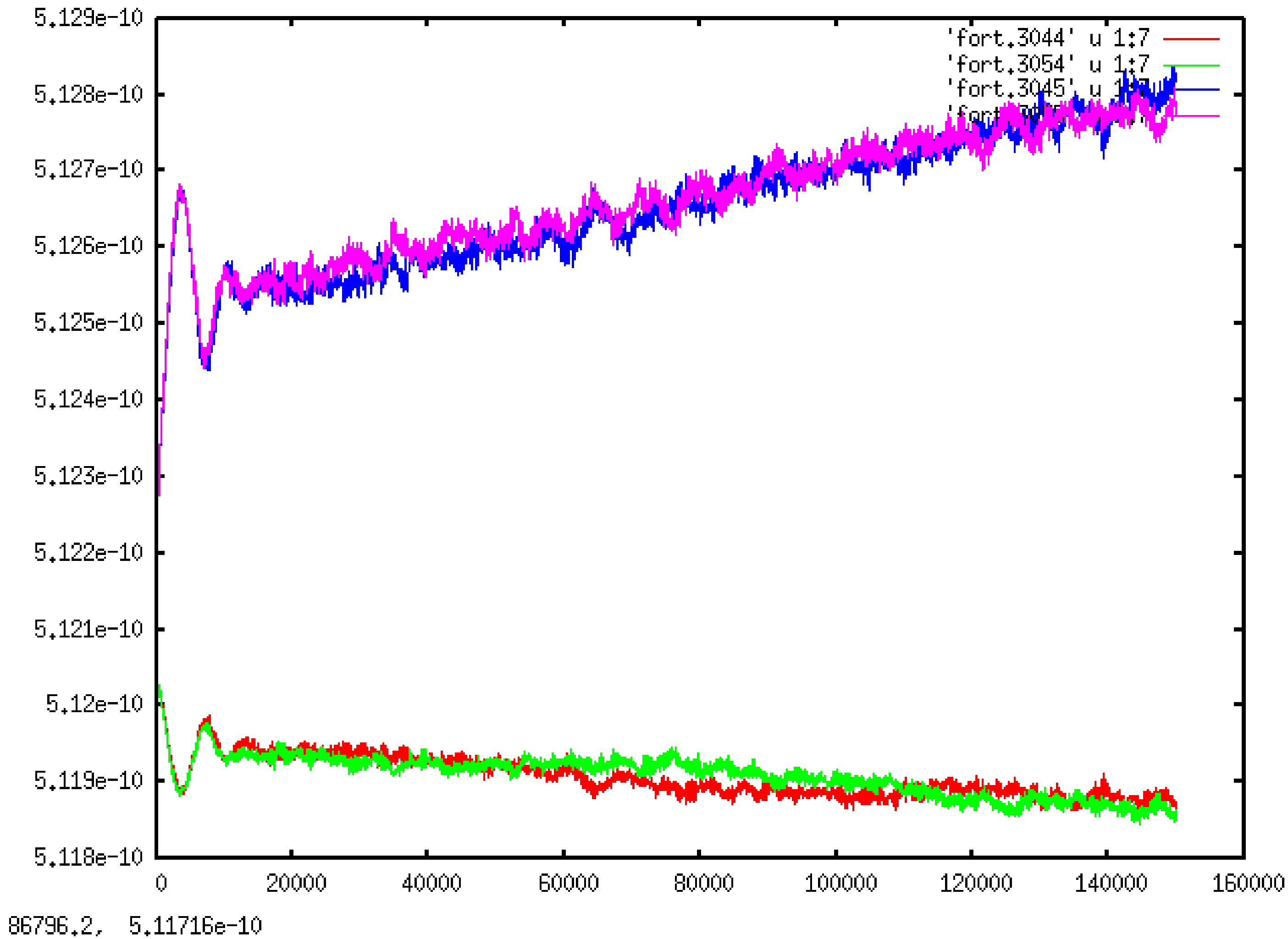
Emittance Growth vs. Tune



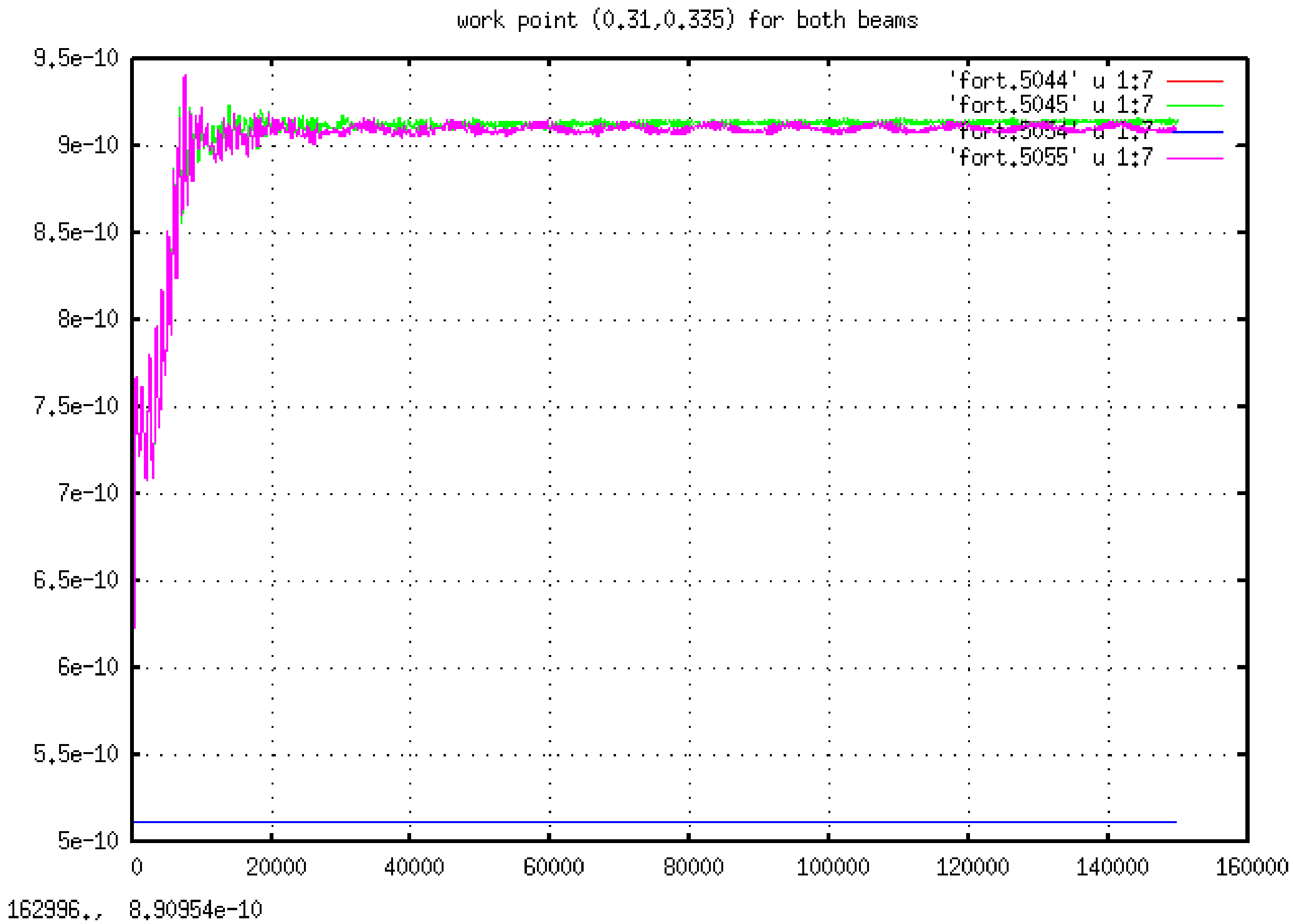
Transverse Emittance Evolution with Working Point (0.31,0.31)



Transverse Emittance Evolution with Working Point (0.31,0.325)



Transverse Emittance Evolution with Working Point (0.31,0.335)



Summary and future work

- offset beam-beam collision could cause emittance growth
- the extent of emittance growth depends on the tune working points and the offset amplitude
- explore the effects of offset collision in horizontal direction
- include the effects of long-range beam-beam
- include the crossing angle collision effects