Self-consistent Simulations of Short- and Long-Range Wakefield Effects in Storage Rings

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Outline

- Self-consistent Parallel Tracking Code SPACE:
  - a) General Description
  - b) Computation of Short- and Long-range Wakes
  - c) Parallel Structure
- Application:
  - Passive Higher-Harmonic Cavity Effects in NSLS-II
  - Performance Reduction from Gap in Uniform Fillings

SPACE*

(Self-consistent Parallel Algorithm for Collective Effects)

- Particle method for the numerical solution of a system of M-coupled Vlasov-Fokker-Planck equations governing the time evolution of M bunches, each with an arbitrary bunch population N_m $(m = 0, \ldots, M-1)$, subject to collective effects driven by wakefields in storage rings. M=h, where h is harmonic number.
- Allows for the simultaneous study of short- and long-range wakefield effects in 6D phase-space.
- General Features and Capabilities:
  - Study of slow head-tail effect + coupled-bunch instabilities for arbitrary fillings.
  - Microwave instability/bunch lengthening/TMCI + passive higher harmonic cavity effects for arbitrary fillings.
  - Chromatic/amplitude dependent decoherence + short-range wakefield effects.
  - Localized impedance effects from arbitrary wakefields.
  - Transient beam loading for arbitrary fillings.
  - Feedback system effects: low level RF + transverse BxB feedback (in progress).
  - Efficient methods for density estimation from simulation particles.

* G. Bassi et al., Phys. Rev. Acc. Beams **19** 024401, 2016.

Computation of Short-range Wake Force: Fourier Method

The short range wake force F_x^S, for example, from the horizontal dipole wake function W_1 in $4D$ phase space (longitudinal + horizontal)

$$F_x^S(\tau,t) = A_x \int_{-\infty}^{\tau} d\tau' W_1(\tau-\tau') d_x(\tau',t), \quad d_x(\tau,t) = \int_{-\infty}^{+\infty} dx\, d\delta\, dp_x\, x\, \Psi(\tau,\delta,x,p,t), \; A_x = \text{const.}$$

is calculated via Fourier inversion: $\hat{F}_x^S(\omega,t) = \int_{-\infty}^{\infty} d\tau\, e^{-i\omega\tau} F_x^S(\tau,t) = iA_x Z_1^{\perp}(-\omega)\hat{d}_x(\omega,t)$,

where $Z_1^{\perp}(\omega) = i\int_{-\infty}^{\infty} d\tau\, e^{i\omega\tau} W_1(\tau)$ and $\hat{d}_x(\omega,t) = \int_{-\infty}^{\infty} d\tau\, e^{-i\omega\tau} d_x(\tau,t)$.

Smoothing: $\hat{F}_x^{S,\text{smooth}}(\omega,t) = \hat{F}_x^S(\omega,t) e^{-\alpha_s\omega^2}$, where α_s is a suitable smoothing parameter.

Computational Load

- With FFT is $\mathcal{O}(N_g \log_2 N_g)$, where N_g is the number longitudinal grid points. Improved estimate: for a DFT of size N^{2m}, the classic ``radix-2'' FFT algorithm of Cooley and Tukey (implemented in SPACE) has a number of flops $\sim 5N\log_2 N$.
- To be compared with $\mathcal{O}(\mathcal{N})$ from particle tracking and particle deposition scheme, where $\mathcal{N}$ is the number of simulation particles.
- Example: high resolution microwave instability simulations for NSLS-II, with $\mathcal{N} = 15M$ distributed over 1000 procs. ⇒ a couple of minutes of CPU time on Cori at NERSC.

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Computation of Long-range Wake Force: Taylor Method

The long-range wake force $F^L_{x,m}$ acting on bunch m for an arbitrary wake function W_1

$$F^L_{x,m}(\tau,t) = A_x \sum_{k=0}^{k_c} \sum_{m'=0}^{M-1} c_{m'k} \int d\tau' W_1\left(\tau - \tau' + a^k_{m'm} T_0\right) d_{x,m'}\left(\tau', t - kT_0\right), \; a^k_{mm'} = k + (m - m')M,$$

is calculated via Taylor expansion, assuming the wake function $W_1(\tau)$ slowly varying within the support of bunch $m' \, (m' \neq m)$

$$F^L_{x,m}(\tau,t) \approx A_x \sum_{k=0}^{k_c} \sum_{m'=0}^{M-1} c_{m'k} \sum_{n=0}^{N_{TL}} \frac{W_1{}^{(n)}(a^k_{m'm} T_0)}{n!} \sum_{l=0}^{n} (-1)^l \binom{n}{l} \tau^{n-l} \langle \tau^l x \rangle^k_{m'}$$

where $\langle \tau^n x \rangle^k_m = \int d\tau \, \tau^n \, d_{x,m}(\tau, t - kT_0)$ $\Rightarrow$ store moments "history".

Computational Load

- Direct computation on the longitudinal grid is $\mathcal{O}(k_c M N_g \log_2 N_g)$ with FFT method.
- To be compared with the computational load of Taylor expansion $\mathcal{O}(k_c M N_{TL} N_g)$, where N_{TL} is the number of terms in the Taylor expansion.
- Using for the FFT method the number of flops $5 N_g \log_2 N_g$, the ratio of the two computational loads is $K = 5 \log_2 N_g / N_{TL}$.
- In many applications of interest $N_{TL} < 10$ thus $K > 3.5$ with $N_g = 128$.

Computation of Long-range Wake Force: Discussion

- Method based on Taylor expansion is general and applicable to arbitrary long-range wake fields.
- For a narrow-band resonator wake, the integration over history can be avoided by the use of invariance properties under translation of the resonator wake function.
- Alternative method: express a general wake function as a sum of resonators (Migliorati et al *, tracking code MuSiC).

*M. Migliorati and L. Palumbo, Phys. Rev. ST Accel. Beams **18**, 031001 (2015).

Parallelization: General Strategy

- M bunches, each with $\mathcal{N}$ simulations particles, are distributed to M processors.
- Short-range (single bunch) wakefield interaction calculated in serial (locally).
- Long-range wakefield calculation done in parallel (globally) via master-to-slave processor communications by storing the ``history" of moments of the bunches.
- For efficient study of microwave instability, the calculation is done in parallel by distributing $\mathcal{N}/M$ simulation particles to M processors.

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Beam Dynamics with a 3rd Harmonic Cavity*
(in the NSLS-II Storage Ring)

* Presented at the:

NSLS-II Beam Intensity Review, 24-25 Jul 2018, BNL.

Beneficial Effects of a 3rd Harmonic Cavity (HC)

- Bunch lengthening:
  - a) bunch lifetime improvement
  - b) heating reduction of vacuum components
- Anharmonic (quartic) potential for small oscillations:
  - synchrotron frequency spread (Landau damping) helpful for suppression of longitudinal coupled bunch instabilities
- No energy spread increase

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Options for a HC System

Options

- Normal-conducting (NC):
  - Optimal operational settings possible, however sensitive to HOM driven longitudinal coupled bunch instabilities
- Super-conducting (SC):
  - Good operational settings possible, less sensitive to HOM driven longitudinal coupled bunch instabilities

Modes of Operation

- Active: HC powered by external generator (expensive)
- Passive: HC powered by the beam (cheaper)

NSLS-II 1500 MHz SC 3RD HC

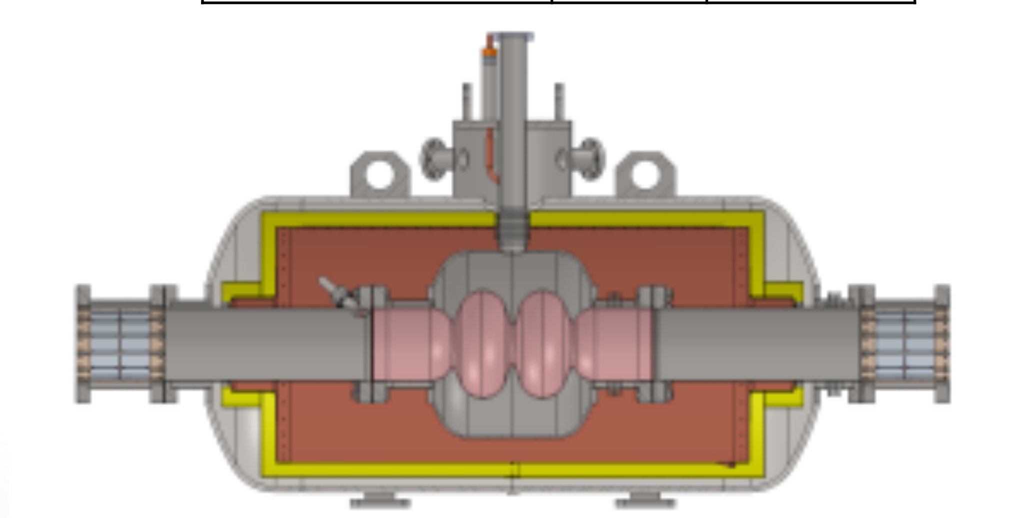
to be* operated in passive mode

*option considered for future operations

Designed by NSLS-II (Jim Rose)
Built by Niowave under an SBIR Phase II Project.

Cavity parameters

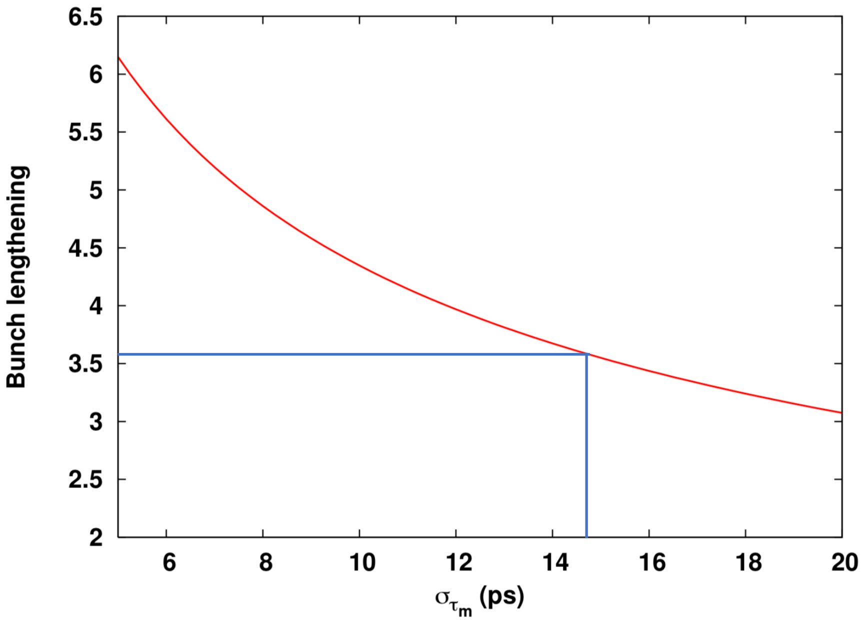
Freq(π-mode)	MHz	1499.25
R/Q (Pi)	Ω	88
Q_0	@4.5K	$2.6*10^8$
Accelerating Voltage	MV	1.0
Freq (0-mode)	MHz	1478.03
R/Q (zero)	Ω	0.15
Q_0	@4.5K	$2.7*10^8$



Theoretical (Maximum) Bunch Lengthening from a 3rd HC

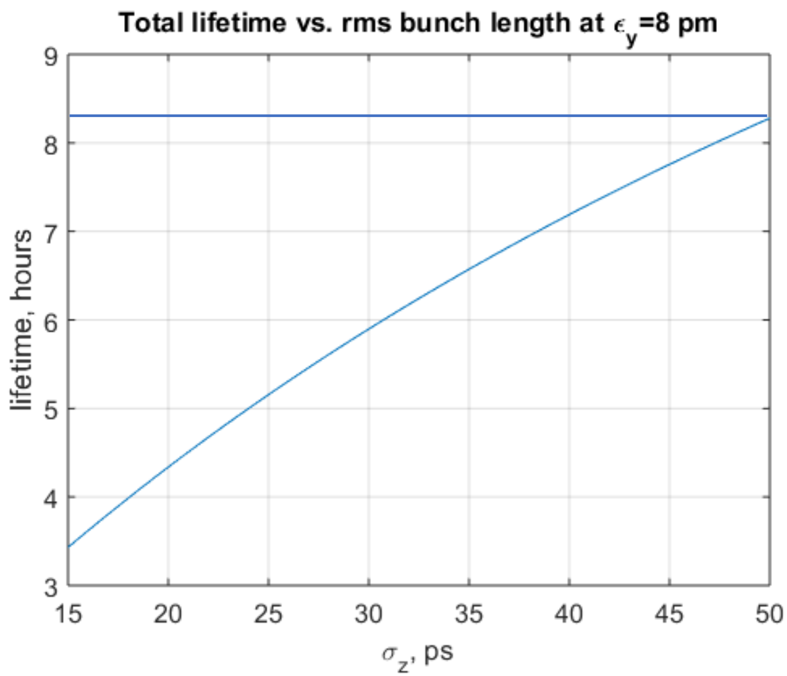
achievable under optimal conditions: NC HC + uniform fillings

$$u := \frac{\sigma_{\tau L}}{\sigma_{\tau m}} = \left(\frac{\Gamma(3/4)}{\Gamma(1/4)}\right)^{1/2} \left(\frac{24\cos\phi_{s0}}{(m^2-1)\omega_{rf}^2\cos\phi_s}\right)^{1/4} \frac{1}{\sqrt{\sigma_{\tau m}}}$$



Beam lifetime (ϵ_y = 8pm)

B. Podobedov



$\sigma_{\tau m}$ = 14.5ps (bunch length w/o HC with present NSLS-II operational settings)

$\sigma_{\tau L}$ = 50ps → Beam lifetime = 8.3 hours

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3RD HARMONIC CAVITY IN NSLS-II

Parameters for the Current Operational 3DWs Lattice

Storage Ring Parameters

Parameter	Value
Beam energy	$E = 3GeV$
Average current	$I = 500mA$
Gap in the uniform filling	$g = 260$
Harmonic number	$h = 1320$
Circumference	$C = 792m$
Bunch length w/o HC	$\sigma_\tau = 14.5ps$
Energy spread	$\sigma_p = 8.7x10^{-4}$
Energy loss per turn	$U_s = 664keV$
Momentum compaction	$\eta = 3.76x10^{-4}$
Long. radiation damping	$\tau_{rad} = 11.9ms$

SC Cavity 2 MAIN cavities

Per cavity parameter	Value
Frequency	$f_{rf} = 499.68MHz$
Voltage	$V = 1.7MV$
Loaded shunt impedance	$R_M = 2.97\ M\Omega$
Loaded quality factor	$Q_M = 66817$

Adding a 3rd HARMONIC cavity

Per cavity parameter	Value
Frequency	$3f_{rf} = 1499.04MHz$
Shunt impedance	$R_H = 22880\ M\Omega$
Quality factor	$Q_H = 2.6x10^8$

- Good bunch lengthening conditions with SC HC are achievable with uniform fillings.
- Performance reduction with a gap in the uniform filling.
- NSLS-II operational mode: 80% fractional filling.

Self-consistent Simulations of HC Effects with SPACE

Equations of motion for particles in bunch m $(0 \le m \le h-1)$ (w/o radiation damping and quantum fluctuations)

$$\dot{\tau} = \eta\delta, \qquad \dot{\delta} = \frac{e}{T_0 E_0}\left[V_{gr}\cos\psi\,\sin(\omega_{rf}\tau + \phi_s + \psi - \theta_L) - V_m(\tau,t) - \frac{U_0}{e}\right], \qquad \dot{} := \frac{d}{dt},$$

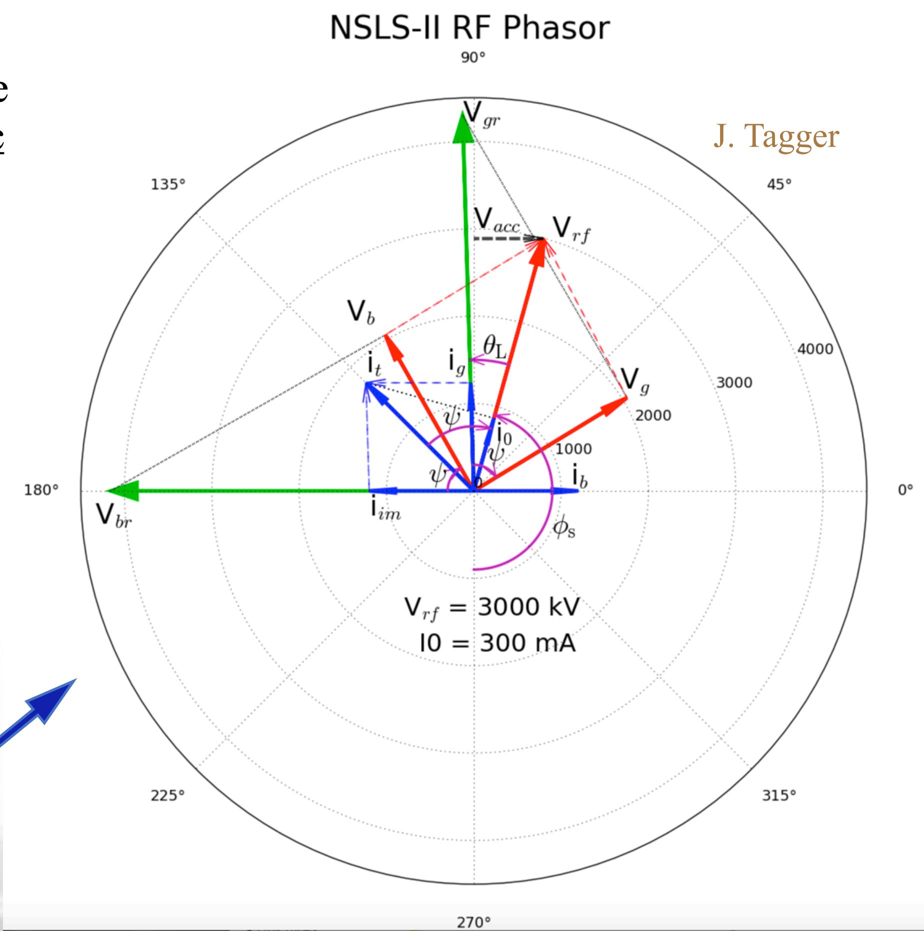
where ϑ_L is the load angle, ψ the detuning angle, ϕ_s the synchronous phase, and V_m is the total collective voltage induced by the beam in the main and harmonic cavities.

V_{gr} and ψ are determined by

$$\tan\psi = \left(1 + \frac{i_{im}}{i_0}\sin\phi_s\right)\tan\theta_L + \frac{i_{im}}{i_0}\cos\phi_s,$$

$$V_{gr} = \frac{V_{rf}}{\cos\theta_L}\left(1 + \frac{i_{im}}{i_0}\sin\phi_s\right).$$

where $i_{im} = 2I_0\tilde{\lambda}(\omega_{rf})$ and $i_0 = V_{rf}/R_L$.



Beam Loading Compensation Scheme

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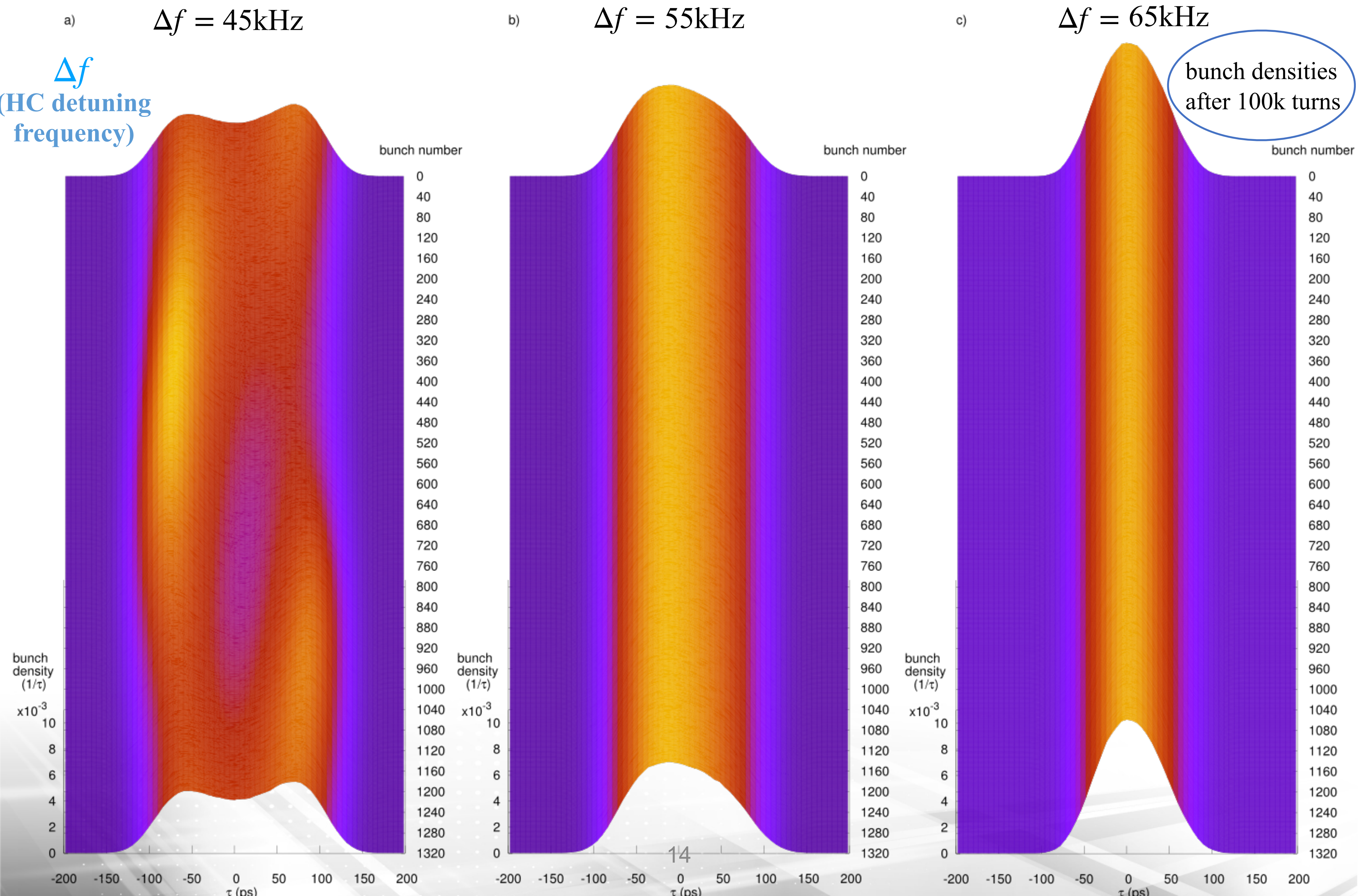
SPACE Simulations with HC: Uniform Filling

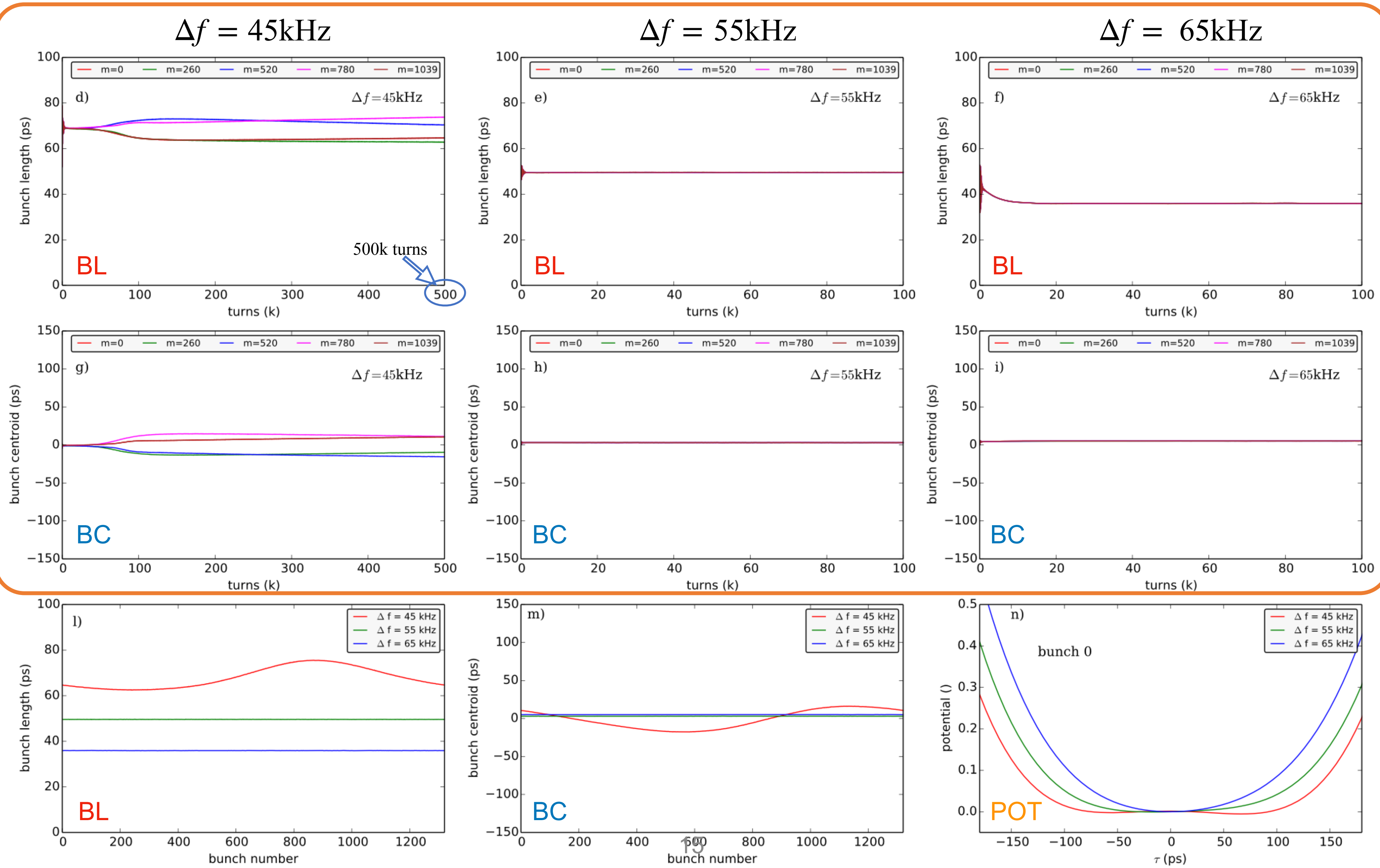
$\theta_L = 0^\circ$



SPACE Simulations with HC: Uniform Filling

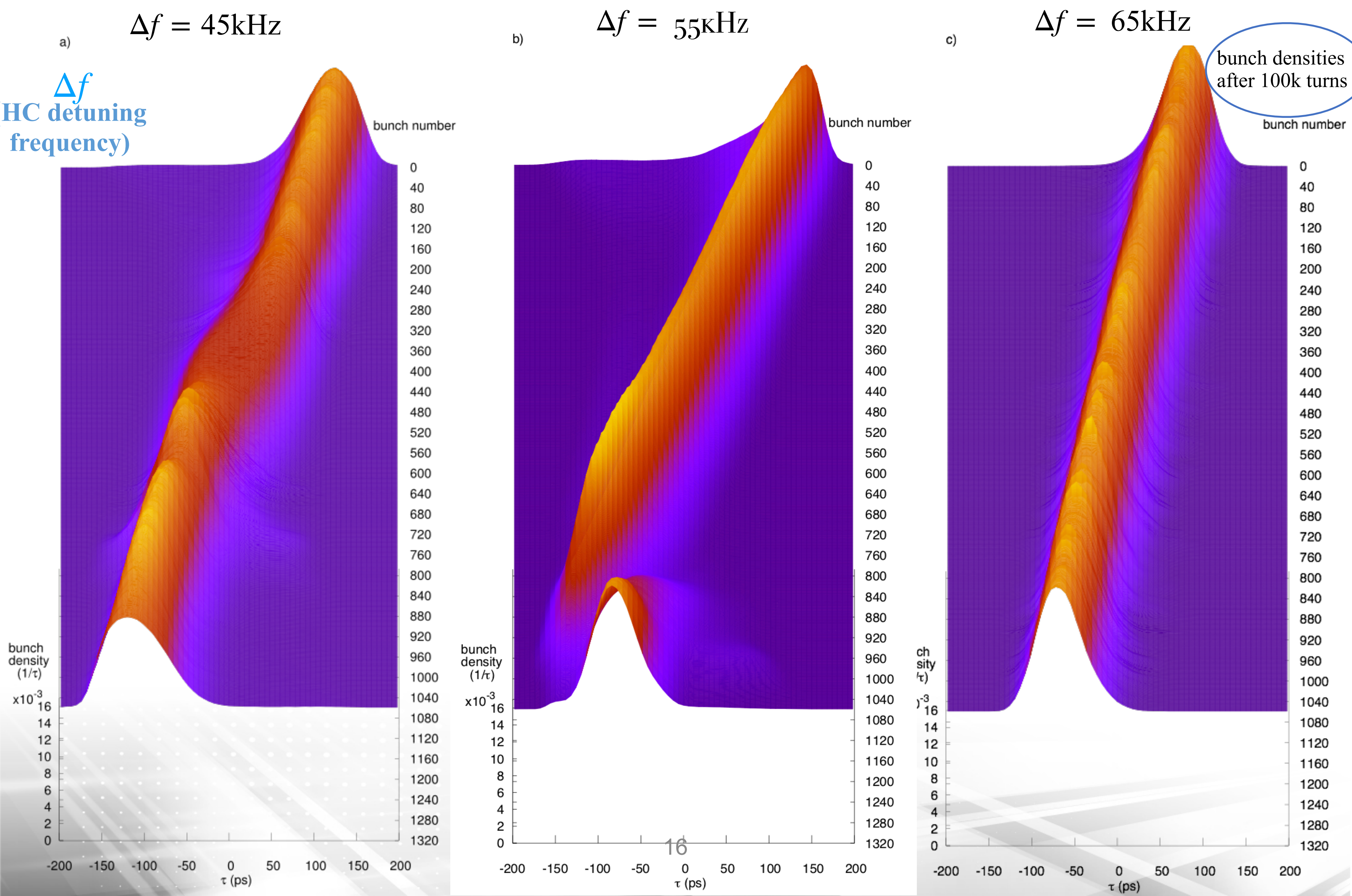
$\theta_L = 0^\circ$

bunch centroid (BC), bunch length (BL), potential (POT)



SPACE Simulations with HC: 80% Filling

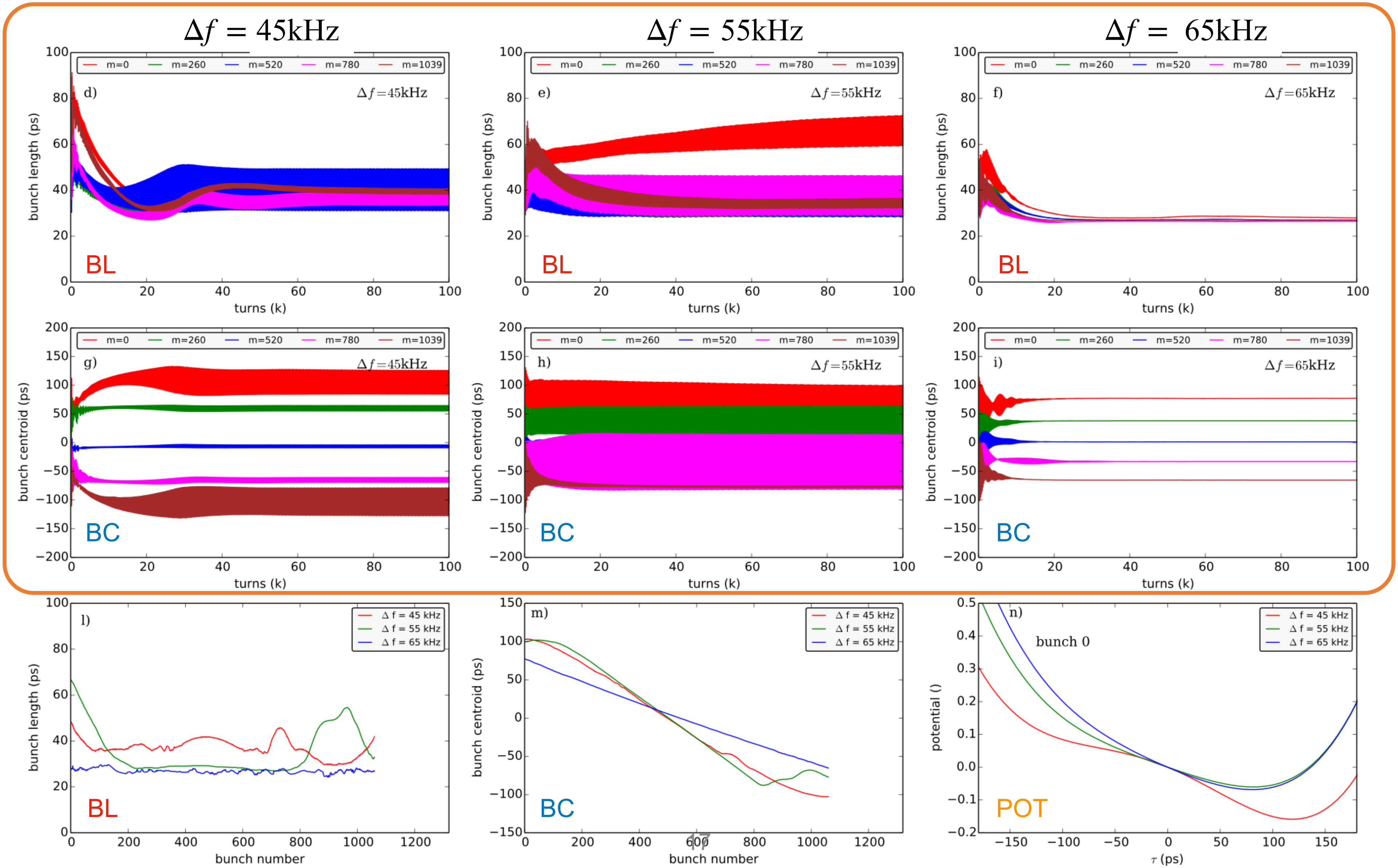
$\theta_L = 0^\circ$



SPACE Simulations with HC: 80% Filling

$\theta_L = 0°$

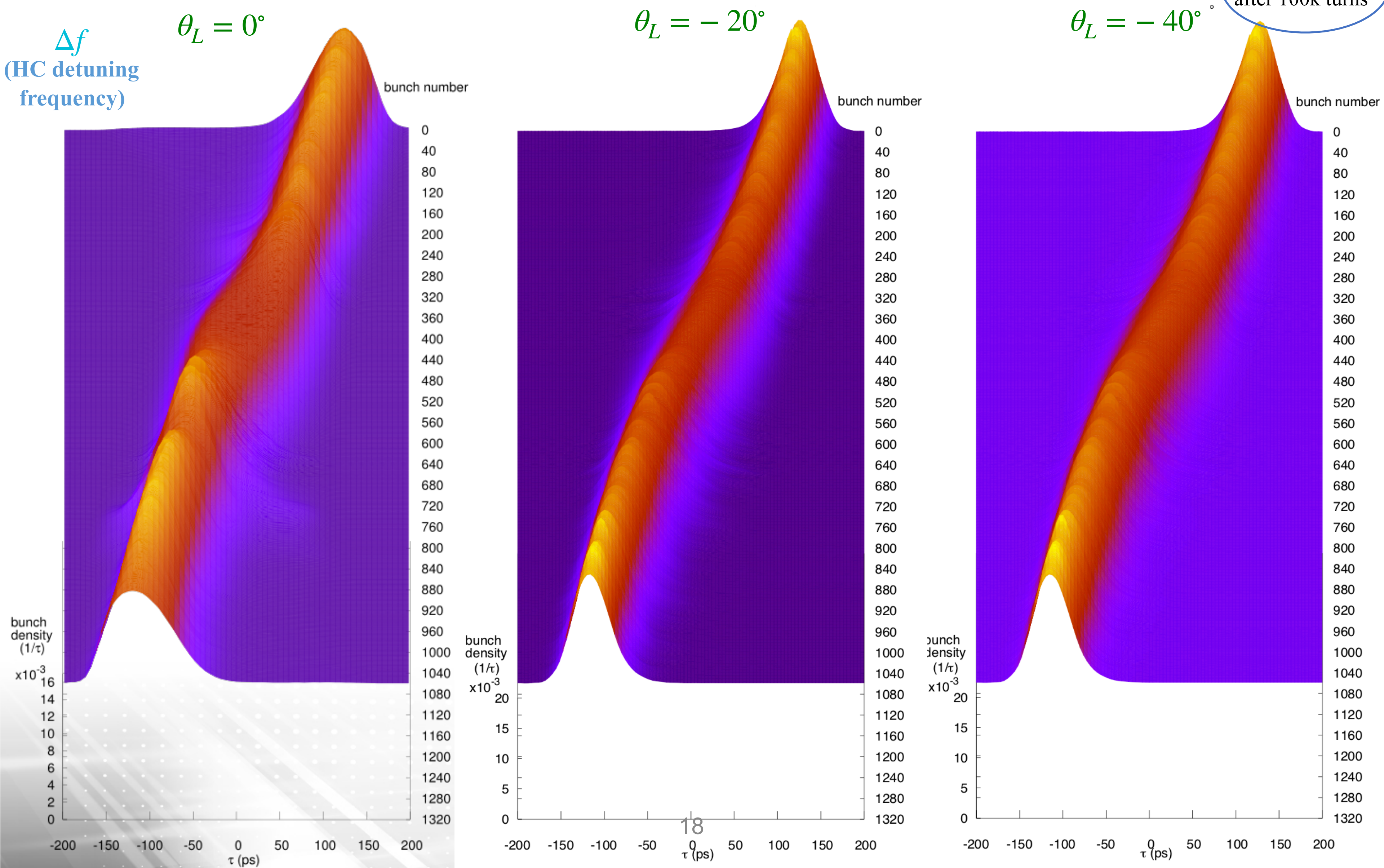
bunch centroid (BC), bunch length (BL), potential (POT)



SPACE Simulations with HC: 80% Filling

$\Delta f = 45\text{kHz}$

varying load angle

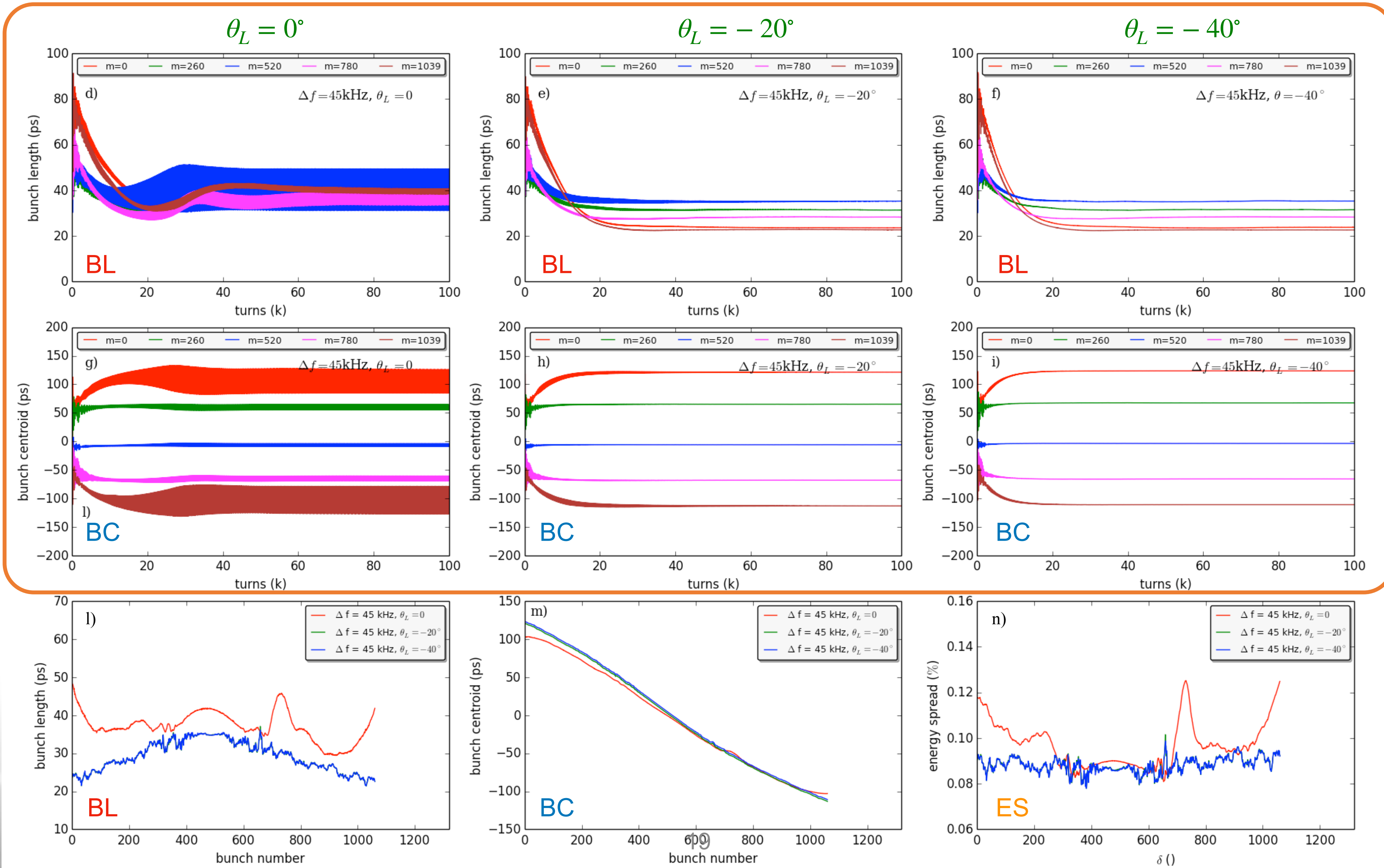


SPACE Simulations with HC: 80% Filling

$\Delta f = 45\text{kHz}$

varying load angle

bunch centroid (BC), bunch length (BL), energy spread (ES)



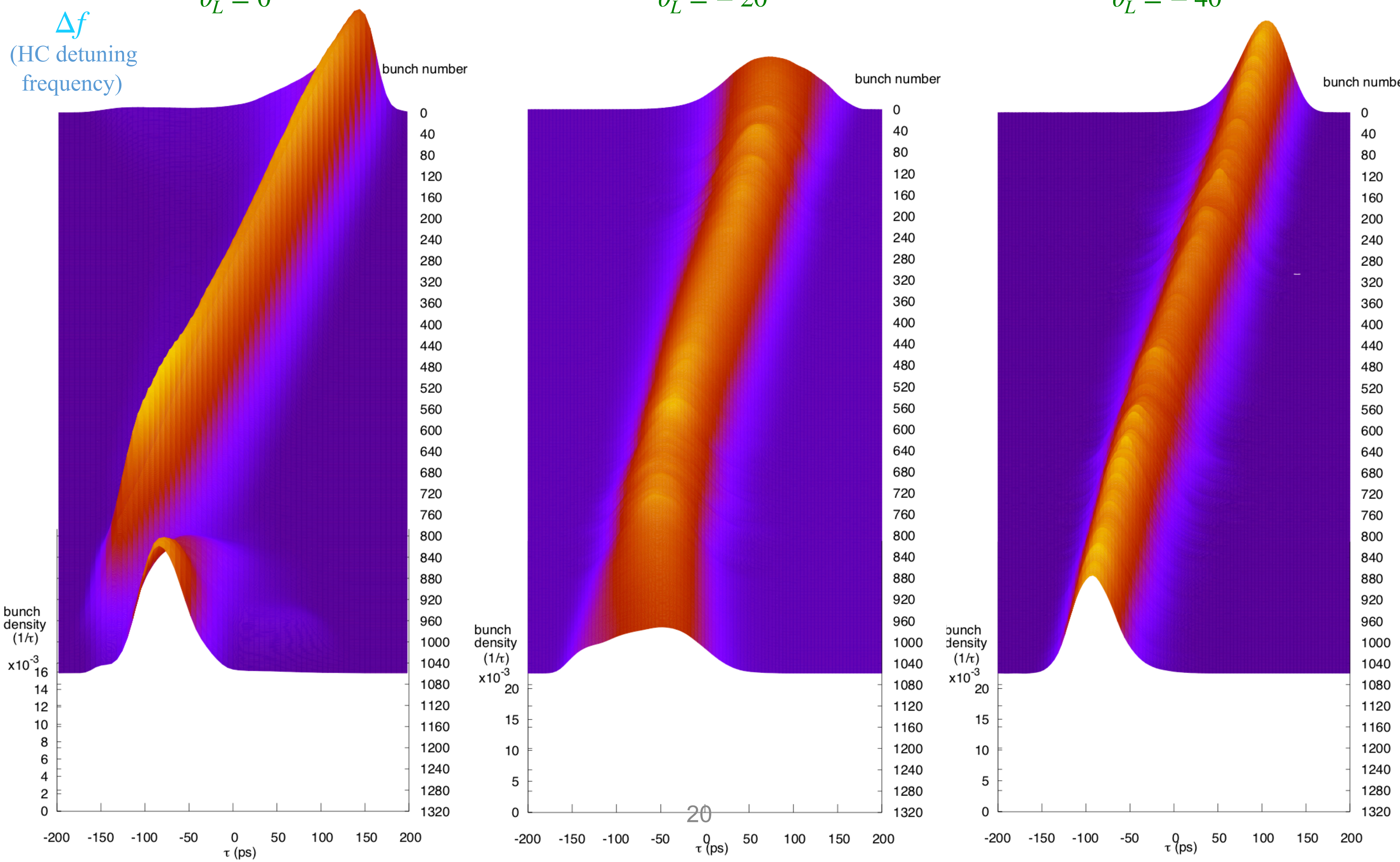
SPACE Simulations with HC: 80% Filling

$\Delta f = \ 55\text{kHz}$

varying load angle

bunch densities after 100k turns

$\theta_L = 0^\circ$ $\theta_L = -20^\circ$ $\theta_L = -40^\circ$



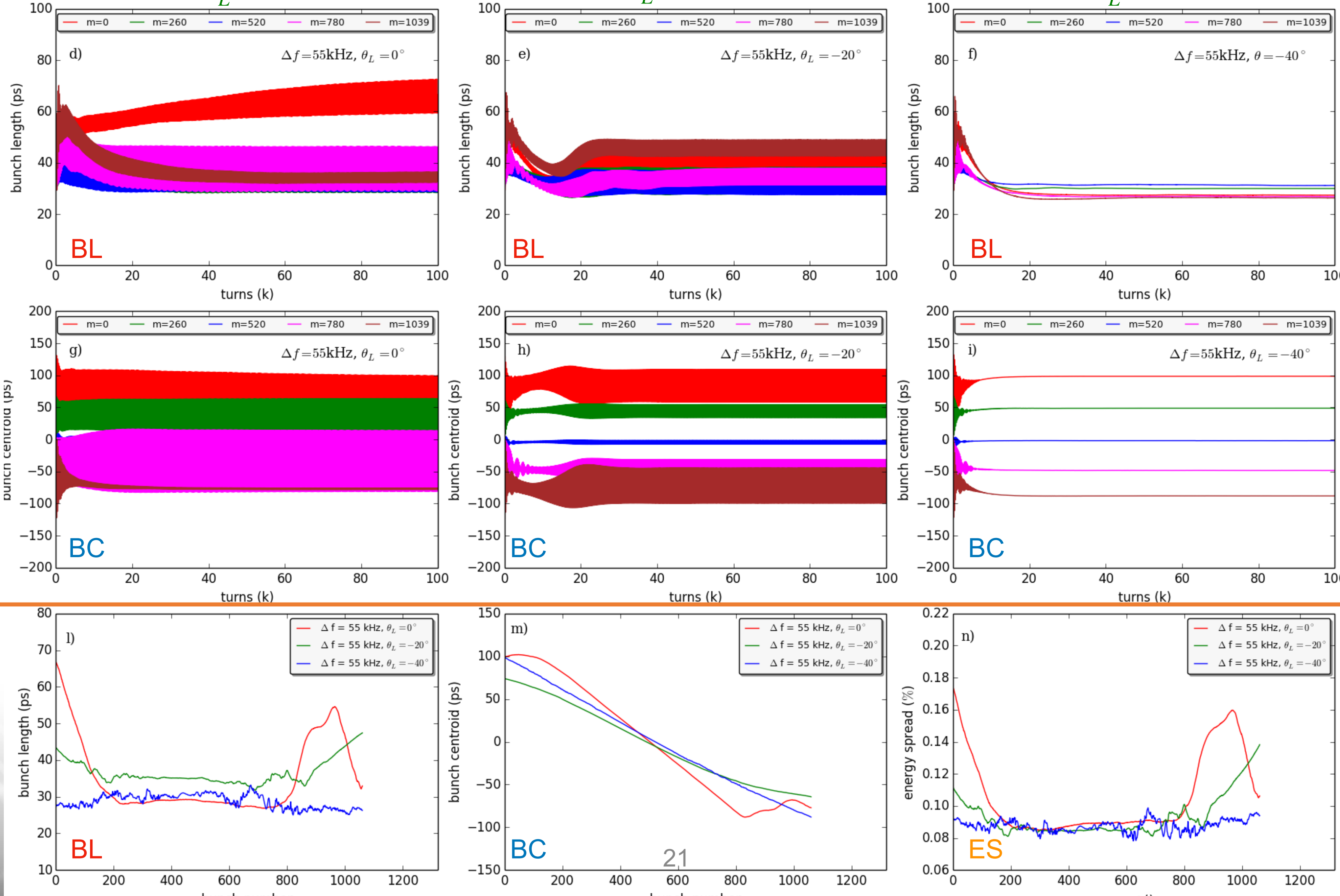
SPACE Simulations with HC: 80% Filling

$\Delta f = 55\text{kHz}$

varying load angle

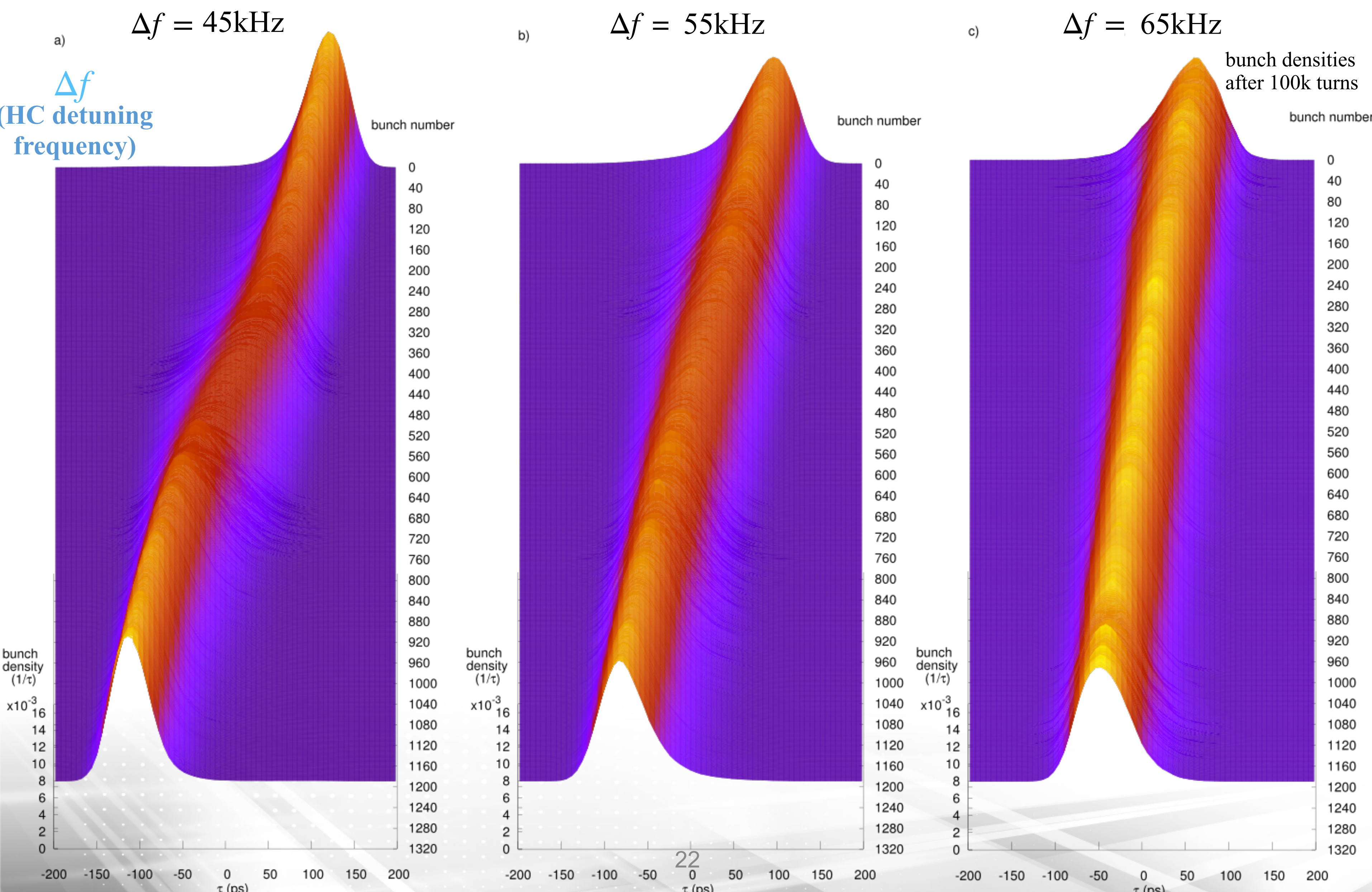
bunch centroid (BC), bunch length (BL), energy spread (ES)

$\theta_L = 0°$ | $\theta_L = -20°$ | $\theta_L = -40°$



SPACE Simulations with HC: 90% Filling

$\theta_L = 0°$

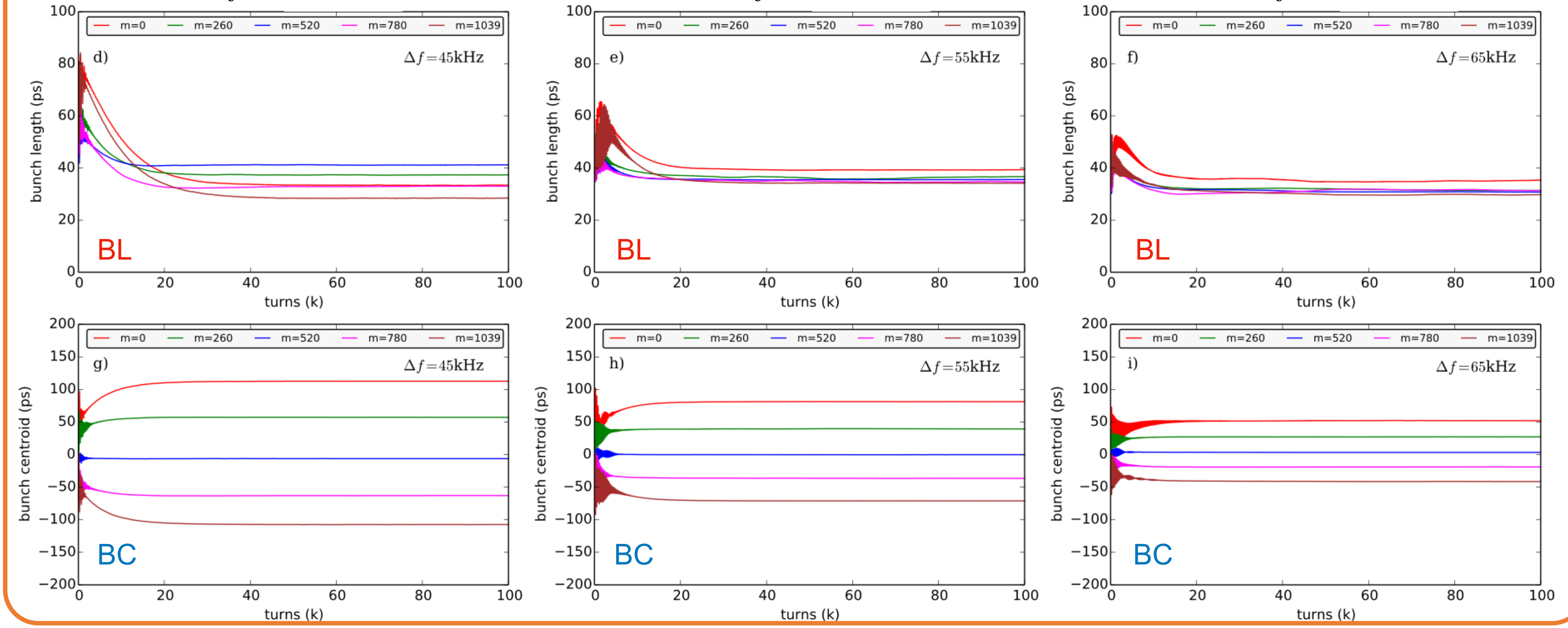


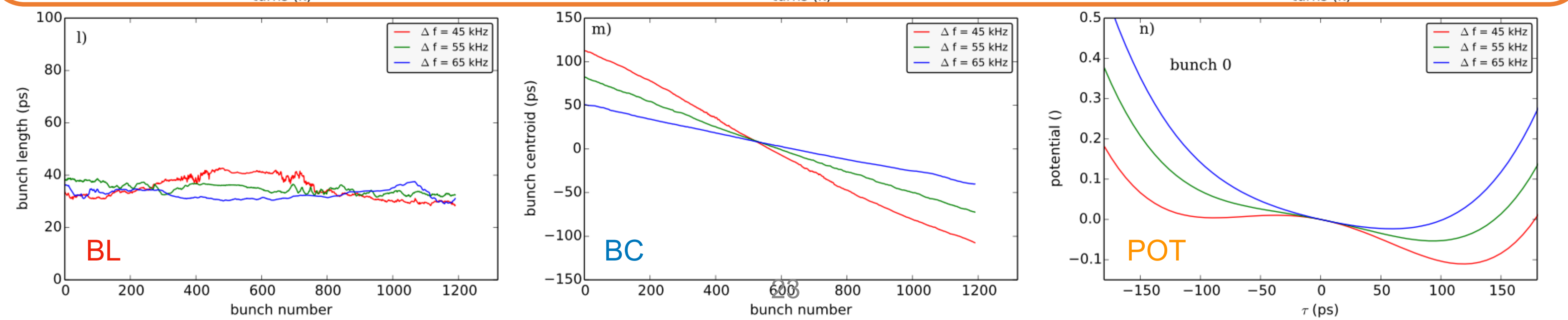
SPACE SIMULATIONS WITH HC: 90% FILLING

$\theta_L = 0^\circ$

bunch centroid (BC), bunch length (BL), potential (POT)

$\Delta f = 45\text{kHz}$ $\Delta f = 55\text{kHz}$ $\Delta f = 65\text{kHz}$





Voltage Induced By Stationary Bunches with Same Symmetric Distribution Density and Arbitrary Bunch Charge

$$\rho_n(\tau,t) = q_n \lambda(\tau), \quad \lambda(-\tau)=\lambda(\tau), \quad \int d\tau \lambda(\tau) = 1, \quad \int d\tau\, \tau\, \lambda(\tau) = 0, \quad \sum_{n=0}^{h-1} q_n = Q_T = I_{av} T_0 .$$

Total voltage acting on bunch $n\,(n=0,\cdots,h-1)$

$$V_n^T(\tau) = V_{gr}\cos\psi_M \sin(\omega_{rf}\tau + \phi_s + \psi_M - \theta_L) - V_n^M(\tau) - V_n^H(\tau) - \frac{U_0}{e},$$

where $(x = M, H)$ M main cavity, H harmonic cavity

$$V_n^x(\tau) = \alpha_{1,n}^x \cos(m(x)\omega_{rf}\tau) + \alpha_{2,n}^x \sin(m(x)\omega_{rf}\tau),$$ ⇐ beam loading voltage

and

$$\alpha_{1,n}^x = \frac{R_s^x}{Q^x}\frac{i_b m(x)}{D^x}(A_1^x f_{1,n}^x - A_2^x f_{2,n}^x), \quad \alpha_{2,n}^x = -\frac{R_s^x}{Q^x}\frac{i_b m(x)}{D^x}(A_1^x f_{2,n}^x + A_2^x f_{1,n}^x),$$

where $m(x) = 1$ if $x = M, m(x) = 3$ if $x = H$.

Here

$$A_1^x = 1 - e^{-\frac{\omega^x T_0}{2Q^x}}\cos\omega^x T_0, \quad A_2^x = e^{-\frac{\omega^x T_0}{2Q^x}}\sin\omega^x T_0, \quad D^x = A_1^{x2} + A_2^{x2},$$

and $f_{1,n}^x = \mathrm{Re}\{Z_n^x\}, \quad f_{2,n}^x = \mathrm{Im}\{Z_n^x\}$, where

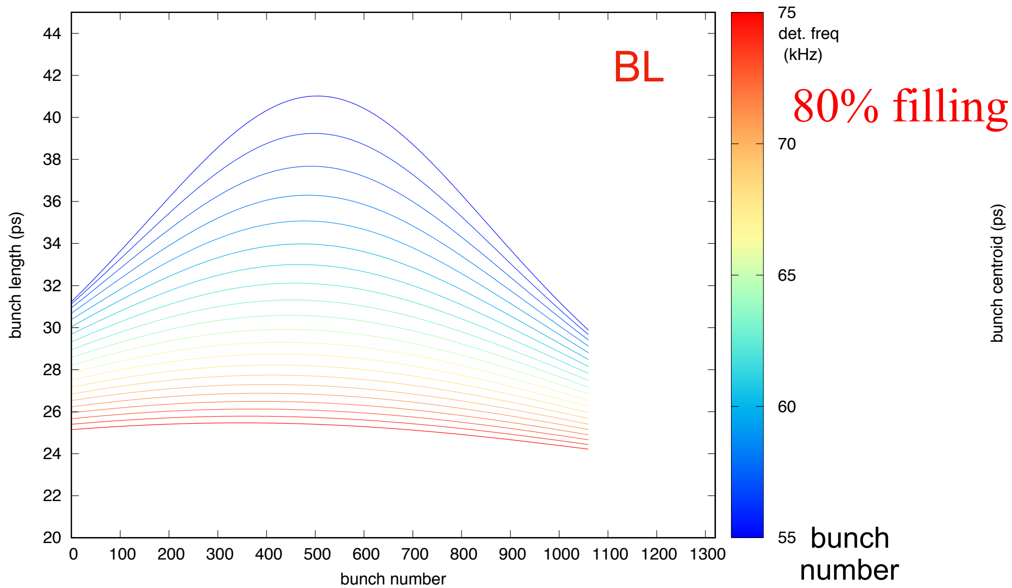
$$Z_n^x = \sum_{p=0}^{h-1}\frac{q_{a(p+n)}}{q_b} i_b(m(x)\omega_{rf}) e^{\frac{\omega^x T_0 p}{2Q^x h}(i2Q^x - 1)}, \quad a(n) = n - h\mathscr{H}(n-h),$$

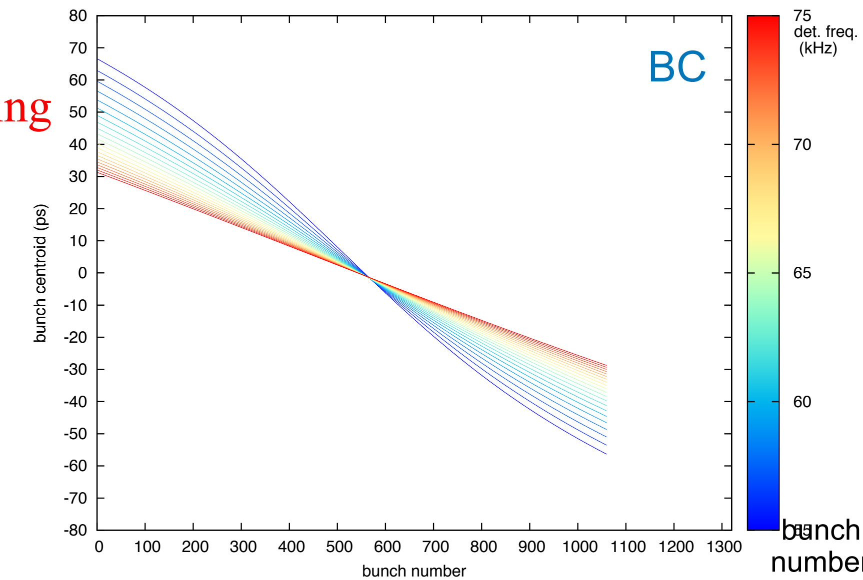
$$i_b(\omega) = 2I_{av}\mathrm{Re}\tilde{\lambda}(\omega), \quad q_b = \frac{Q_T}{h},$$

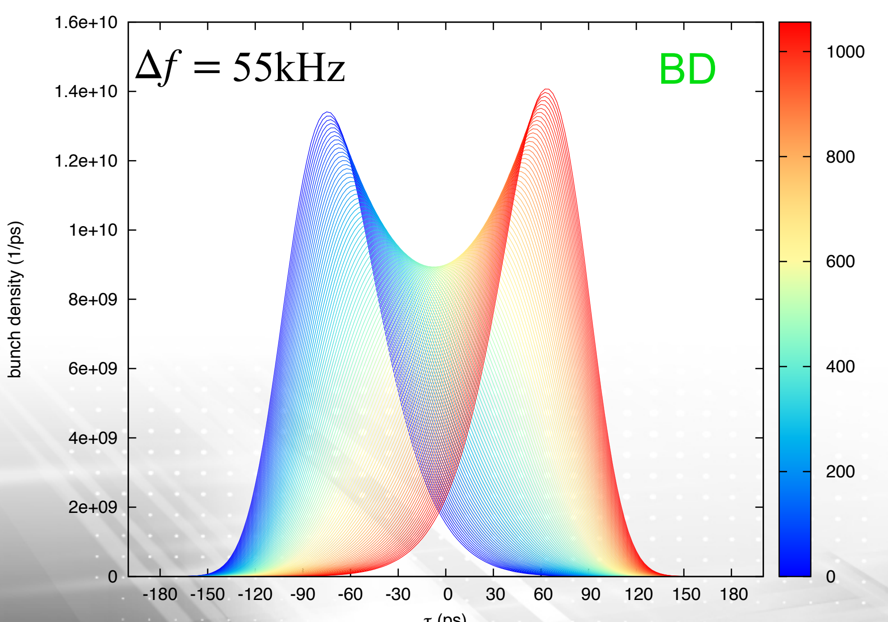
and $\mathscr{H}$ is the Heaviside step function.

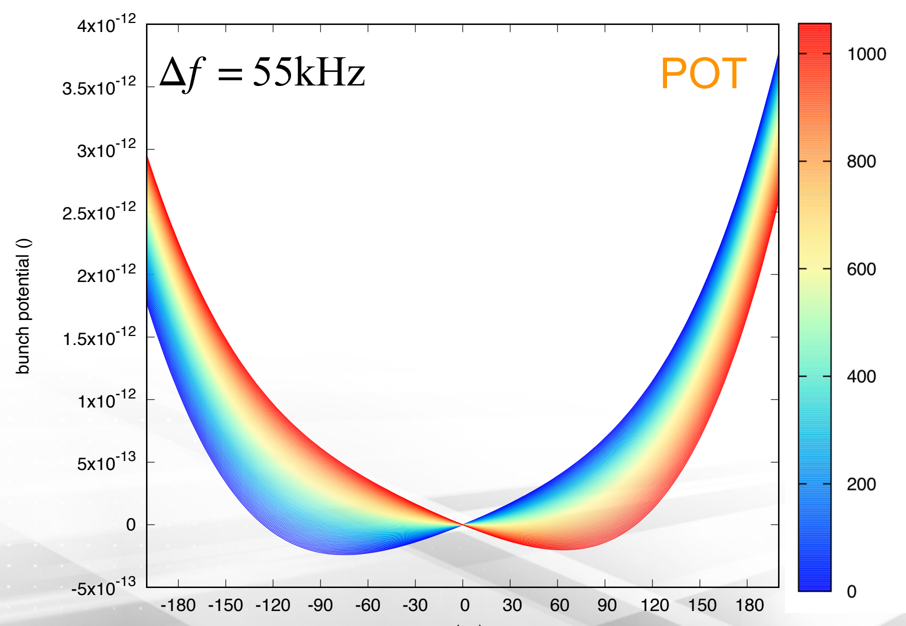
Voltage Induced By Stationary Bunches with Same Symmetric Distribution Density and Arbitrary Bunch Charge

bunch density (BD)

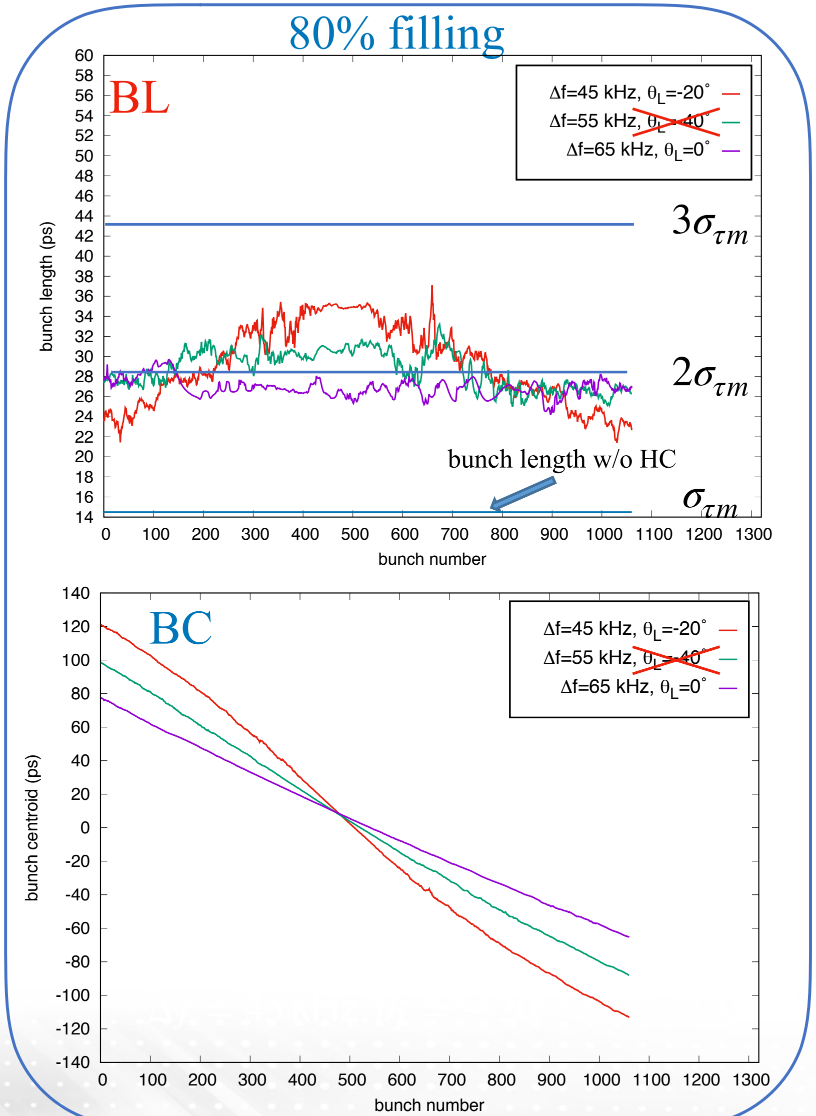


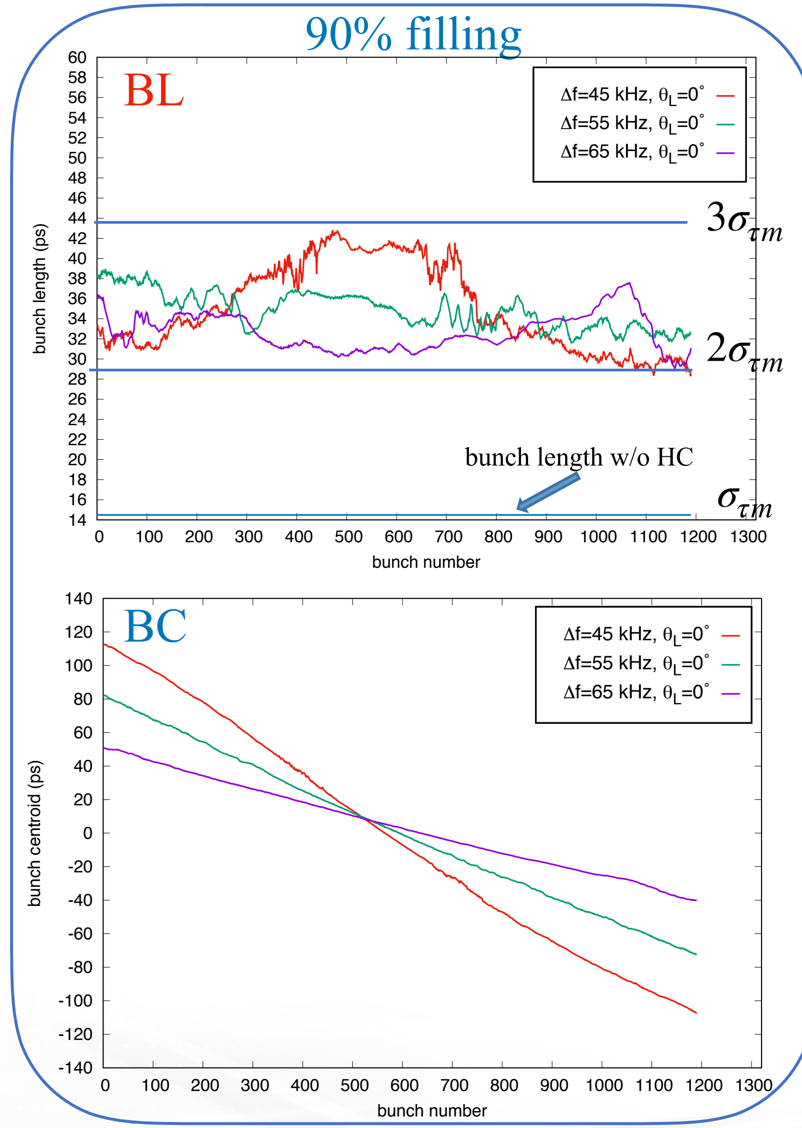






Performance of Stable 3rd HC settings for NSLS-II





90% filling a better choice both in terms of average bunch lengthening and uniformity (BL + BC) across the train

Discussion*

- A gap in the uniform filling reduces the performance of the HHC.
- Do we need to operate with the nominal 80% fractional filling?
- Can the performance of the HC be improved with a "clever" choice of filling patterns/bunch charge configurations, without affecting the need for ion clearing?

* NSLS-II Beam Intensity Review, 24-25 Jul 2018, BNL.

Future Work

- SPACE simulations will be done with arbitrary multi-bunch configurations, including (simultaneously) the effect of bunch lengthening induced by short-range wakefields (neglected so far).
- A systematic comparison will be done with simulations/ measurements done at other light sources:
  - Elettra (first to operate with SC third HC)
  - ALS (NC third HC)
  - Aladdin (NC fourth HC)
  - MAX-IV (NC third HC)

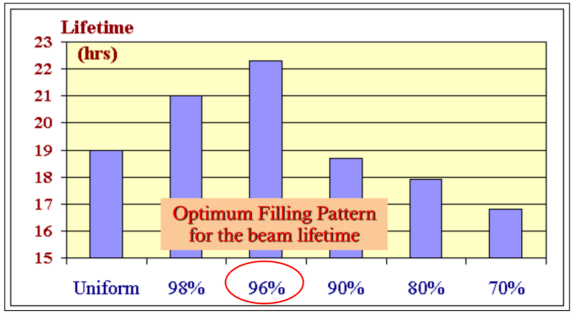
Operations at Elettra with a Superconducting 3rd HC

Elettra Sincrotrone Trieste

Giuseppe Penco - Valencia 5-6 May 2014

ALERT 2014

Beam Lifetime improvements



* Measurements taken during a vacuum conditioning time. The present lifetime at 320mA, 2.0GeV, 96% fractional filling is **27h** (nominal is 7.7h without 3HC)

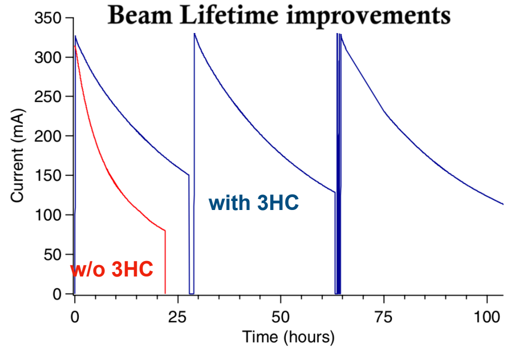


FIG. 19. (Color) Current decay comparison between ELETTRA operation with 3HC not active (red line) and with 3HC tuned (blue line). In this second case the interval between two subsequent injection is about 36 h.

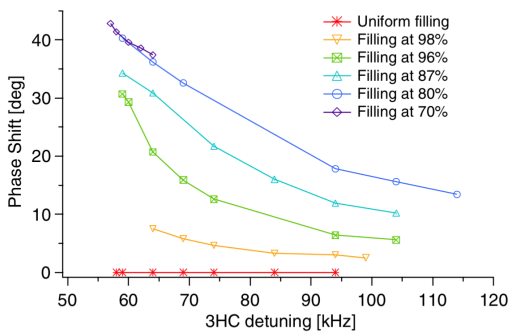


FIG. 7. (Color) Phase difference between the head and the tail of the bunch train vs the 3HC detuning, for several fractional fillings; $I_{beam} = 315$ mA, $E = 2.0$ GeV.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **9**, 044401 (2006)

Experimental studies on transient beam loading effects in the presence of a superconducting third harmonic cavity

Giuseppe Penco and Michele Svandrlik

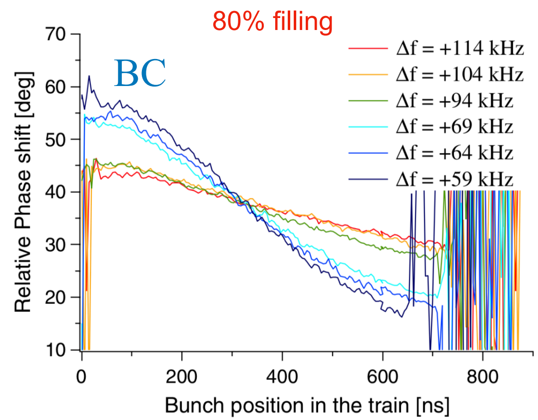


FIG. 6. (Color) Relative stable phase along the bunch train vs the 3HC detuning, for a 80% filling; $I_{beam} = 315$ mA, $E = 2.0$ GeV.

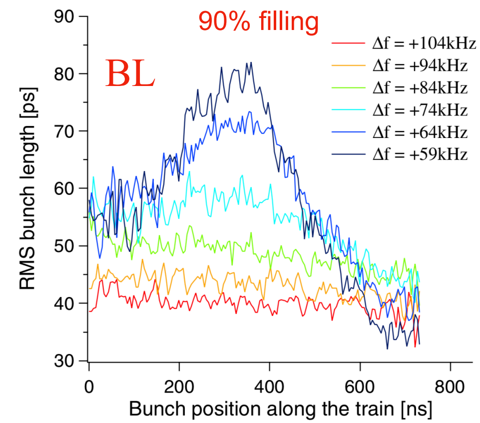


FIG. 10. (Color) rms bunch length along the bunch train for several 3HC tuning for a filling of 90%; $I_{beam} = 315$ mA, $E = 2.0$ GeV.

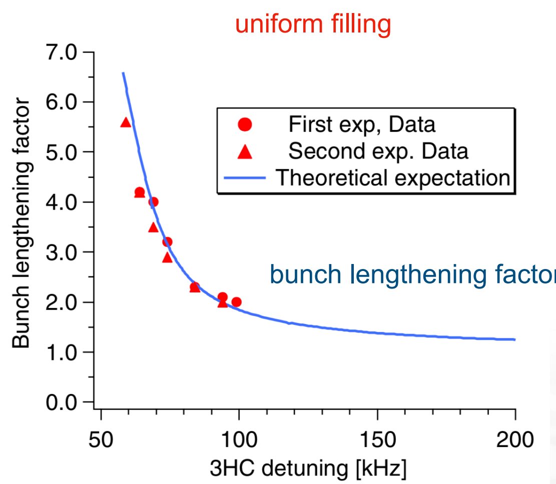


FIG. 12. (Color) Comparison between two set of experimental data, obtained in the same machine condition, and theoretical calculation for a uniform filling pattern, at 315 mA, 2.0 GeV.

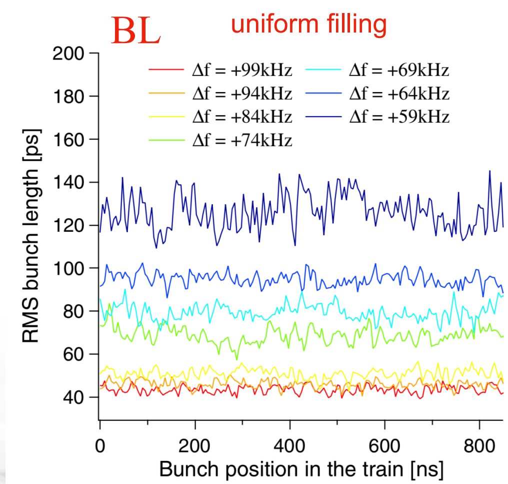
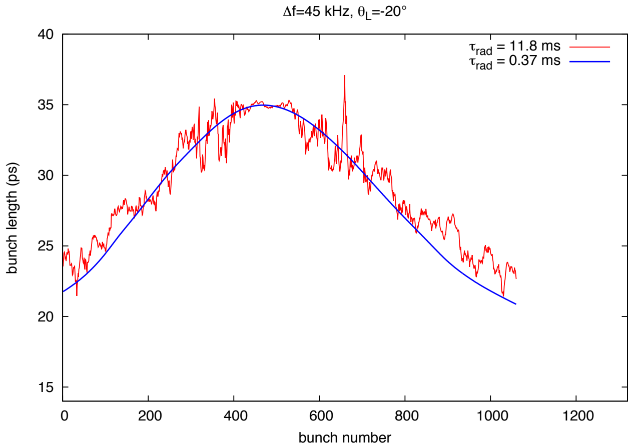


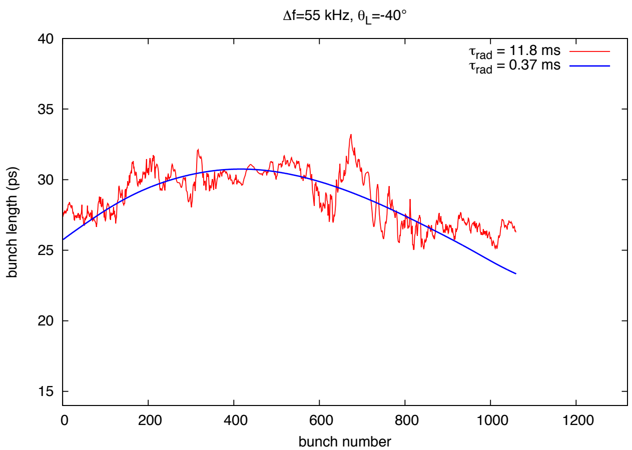
FIG. 11. (Color) rms bunch length along the bunch train for several 3HC tuning for uniform filling; $I_{beam} = 315$ mA, $E = 2.0$ GeV.

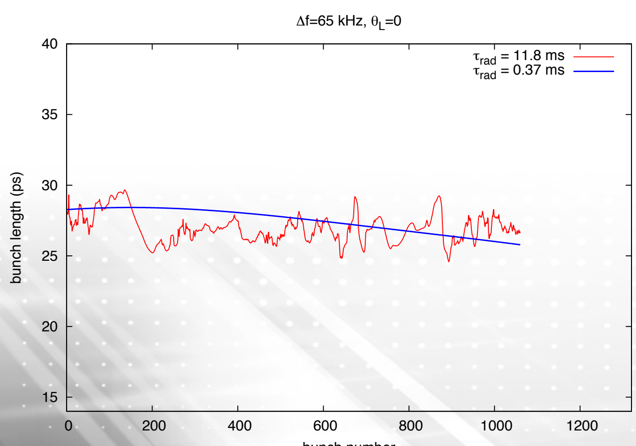
Thank You For Your Attention!

Back Up Slides

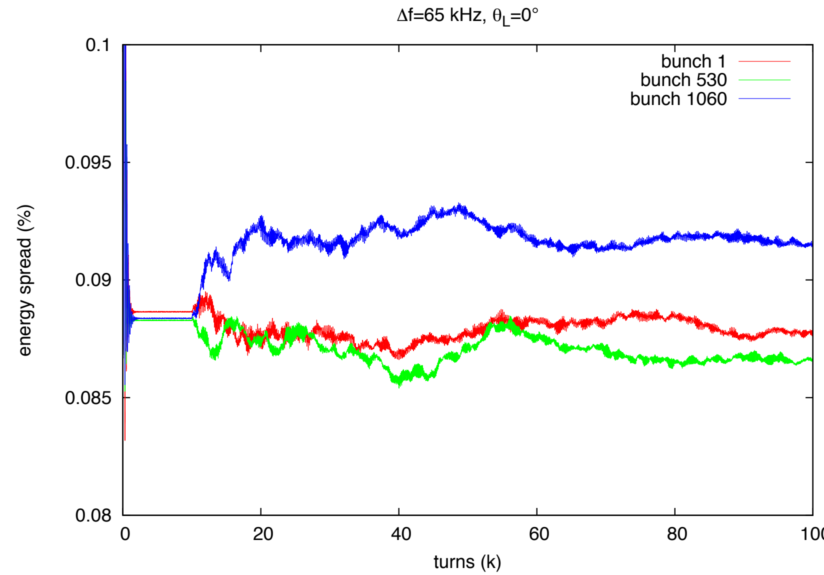
Forcing Equilibrium by Decreasing Radiation Damping Time







Energy spread



Bunch length