Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA
Managed by the Jefferson Science Associates, LLC for the U.S. Department of Energy Office of Science

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Linear Vlasov Solver for Microbunching Gain Estimation with Inclusion of CSR, LSC, and Linac Geometric Impedances

Cheng-Ying Tsai, (*Virginia Tech, Blacksburg, VA*), D. Douglas, R. Li, C. Tennant (*Jefferson Lab, Newport News, VA*)

ABSTRACT

As is known, microbunching instability (MBI) has been one of the most challenging issues with the designs of magnetic chicanes for short-wavelength free-electron lasers or linear colliders, as well as those of transport lines for recirculating or energy recovery linac machines. To more accurately quantify MBI in a single-pass system and for more complete analyses, we further extend and continue to increase the capabilities of our previously developed linear Vlasov solver [1] to incorporate more relevant impedance models into the code, including transient and steady-state free-space and/or shielding coherent synchrotron radiation (CSR) impedances, the longitudinal space charge (LSC) impedances, and the linac geometric impedances with extending the existing formulation to include beam acceleration [2]. Then, we self-consistently solve the linearized Vlasov equation for microbunching gain amplification factor. With application of this code to a beamline lattice of transport arc [3] with a section of linac upstream, the resultant gain functions and spectra are presented and some results are compared with particle tracking simulation by ELEGANT [4]. We also discuss some underlying physics with inclusion of these collective effects and the limitation of the existing formulation. It is anticipated that this more thorough analysis can further improve the understanding of MBI mechanisms and shed light on how to suppress or compensate MBI effects in lattice designs.

NUMERICAL METHODS

➢ **Linear Vlasov solver [2,5,6]**

$$g_k(s)=g_k^{(0)}(s)+\int_0^s K(s,s')g_k(s')ds'$$

$$K(s,s')=\frac{ik_0C(s)}{\gamma_0}\frac{I_0(s)C(s')}{I_A}\hat{R}_{56}(s'\to s)Z\left(kC(s'),s'\right)\times[\text{Landau damping}]$$

$$[\text{Landau damping}]=\exp\left\{\frac{-k^2}{2}\left[\begin{array}{l}\varepsilon_{x0}\left(\beta_{x0}\hat{R}_{51}^2(s,s')+\dfrac{\hat{R}_{52}^2(s,s')}{\beta_{x0}}\right)\\+\varepsilon_{y0}\left(\beta_{y0}\hat{R}_{53}^2(s,s')+\dfrac{\hat{R}_{54}^2(s,s')}{\beta_{y0}}\right)+\sigma_\delta^2\hat{R}_{56}^2(s,s')\end{array}\right]\right\}$$

$$\hat{R}_{56}(s'\to s)=\hat{R}_{55}(s')\hat{R}_{56}(s)-\hat{R}_{55}(s)\hat{R}_{56}(s')+\hat{R}_{51}(s')\hat{R}_{52}(s)-\hat{R}_{51}(s)\hat{R}_{52}(s')+\hat{R}_{53}(s')\hat{R}_{54}(s)-\hat{R}_{53}(s)\hat{R}_{54}(s')$$

$$\hat{R}_{5i}(s,s')=C(s)\hat{R}_{5i}(s)-C(s')\hat{R}_{5i}(s') \qquad C(s)=\frac{1}{\hat{R}_{55}(s)-h_0\hat{R}_{56}(s)}$$

$$G(s)\equiv\left|g_k(s)/g_k^{(0)}(0)\right| \quad \text{(gain function)}$$

$$G_f(\lambda)\equiv G(s=s_f) \quad \text{(gain spectrum)}$$

COLLECTIVE EFFECTS INCLUDED

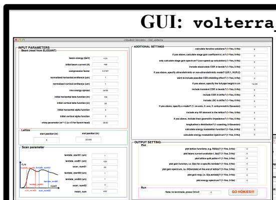
➢ **Free-space CSR Effect (1-D)**
- ❑ Steady-state (non-ultrarelativistic [7] & ultrarelativistic [8, 9])
- ❑ Entrance transient [10, 11]
- ❑ Exit transient [12]

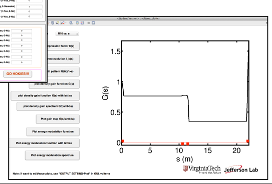
➢ **Parallel-plate shielding CSR Effect**
- ❑ Parallel-plate model [13, 14]

➢ **Free-space LSC Effect** [15, 16]
- ❑ On-axis model
- ❑ Averaged model

➢ **Linac Geometric Effect** [17, 18, 19]

GUI: `volterra_mat_v3.0`



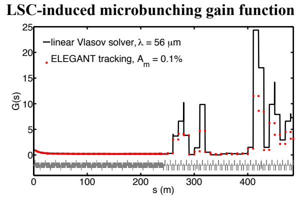


Step-by-step guide user manual: JLAB-TN-15-019

RESULTS OF SEMI-ANALYTICAL VLASOV SOLVER

➢ **Example: 1.3 GeV Linac-Arc** [3]

LSC-induced microbunching gain function



LSC-induced microbunching gain spectrum

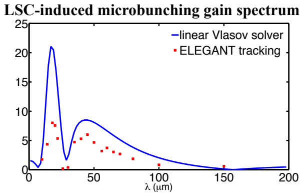
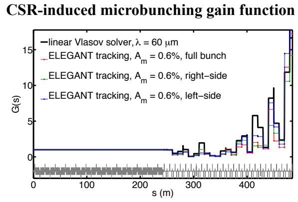


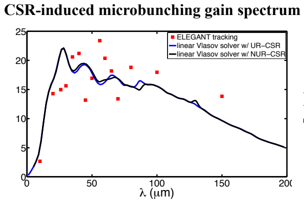
Table 1: Initial beam and Twiss parameters.

Name	Example 1 (large R_{56})	Unit
Beam energy (at linac entrance)	50	MeV
Beam energy (at linac exit)	1.11	GeV
Peak bunch current	88	A
Norm. emittance	0.3	μm
β_{x0}	18	m
α_{x0}	-3.6	
Slice energy spread	3×10^{-4}	

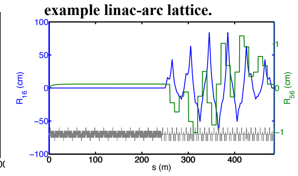
CSR-induced microbunching gain function



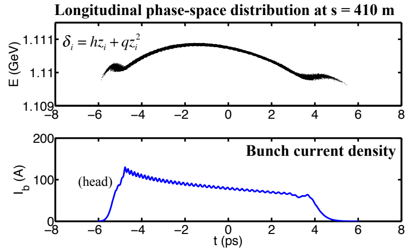
CSR-induced microbunching gain spectrum



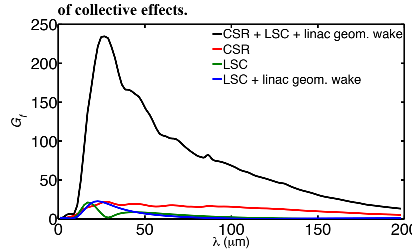
Dispersion (blue) and momentum compaction (green) function of the example linac-arc lattice.



Longitudinal phase-space distribution at s = 410 m



Microbunching gain spectra with various combinations of collective effects.



➢ **Discussion on bulk bunch non-uniformity:**

$$h^{eff}(z_i)\equiv-\frac{\partial\delta_i}{\partial z_i}=-2qz_i\to\begin{cases}<0, \text{ for bunch tail } (z_i<0)\\>0, \text{ for bunch head } (z_i>0)\end{cases}$$

$$C(s,z_i)=\frac{1}{\underbrace{R_{55}(s)}_{\le 1}-h^{eff}(z_i)R_{56}(s)}\to\begin{cases}>1 \text{ (compressed), for bunch head \& } R_{56}(s)>0\\<1 \text{ (de-compressed), for bunch tail \& } R_{56}(s)>0\end{cases}$$

SUMMARY

➢ Developed linear Vlasov solver which is applicable for
- ✓ general linear lattice (from ELEGANT)
- ✓ including beam acceleration (or, deceleration)
- ✓ single-pass or multi-pass beamline (e.g. ERL or recirculating machines)

➢ Relevant collective effects are included
- ✓ CSR effects (steady-state, entrance/exit transients, free-space or parallel-plate shielding)
- ✓ LSC effect
- ✓ linac geometric effect

➢ Demonstrated a linac-arc example for MBI gain estimation

➢ Non-uniformity bunch profile ➔ local bunch compression/decompression
➔ MBI gain reduced at large R_{56}

➢ [CSR + LSC] effects contribute a significant amount of MBI gain

REFERENCES

[1] C. -Y. Tsai et al., FEL'14 (THP022), IPAC'15 (MOPMA028) and ERL2015 (TUICLH2034)
[2] M. Venturini, PRSTAB 10, 104401 (2007)
[3] D. Douglas et al., arXiv: 1403.2318v1 and IPAC'15 (TUPMA038)
[4] M. Borland, APS LS-287 (2000) and PRSTAB 11, 030701 (2008)
[5] S. Heifets et al., PRSTAB 5, 064401 (2002)
[6] Z. Huang and K. Kim, PRSTAB 5, 074401 (2002)
[7] R. Li and C. -Y. Tsai, IPAC'15 (MOPMN004)
[8] J. Murphy et al., Part. Accel. 57 (1997) pp. 9-64
[9] Ya. S. Derbenev et al., TESLA-FEL-Report 1995-05
[10] D. Zhou, IPAC'12 (MOOBB03)
[11] C. Mitchell et al., IPAC'13 (TUPMA057)
[12] R. Bosch et al., PRSTAB 10, 050701 (2007)
[13] R. Warnock, SLAC-PUB-5375 (1990)
[14] T. Agoh and K. Yokoya, PRSTAB 7, 054403 (2004)
[15] M. Venturini, PRSTAB 11, 034401 (2008)
[16] J. Wu et al., PRSTAB 11, 040701 (2008)
[17] R. L. Gluckstern, PRD 39, 2780 (1989)
[18] K. Yokoya and K. Bane, PAC 1999
[19] Z. Huang et al., PAC 2003

JSA · Office of Science, U.S. Department of Energy