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Linear Microbunching Gain Estimation Including CSR and LSC Impedances in Recirculation Machines

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June 9, 2015

Stony Brook University, NY

Outline

- Introduction and Motivation
  - Microbunching instability mechanism
  - What has been done and Why important in ERL
  - MEIC Circulator Cooling Ring (CCR) as an example
- Theoretical formulation
  - (Linear) Vlasov equation
  - Relevant collective effects: CSR and LSC
- Semi-analytical Vlasov solver
- Examples and Results
  - Two comparative high-energy transport/recirculation arcs
  - MEIC Circulator Cooling Ring
- Summary and Future work

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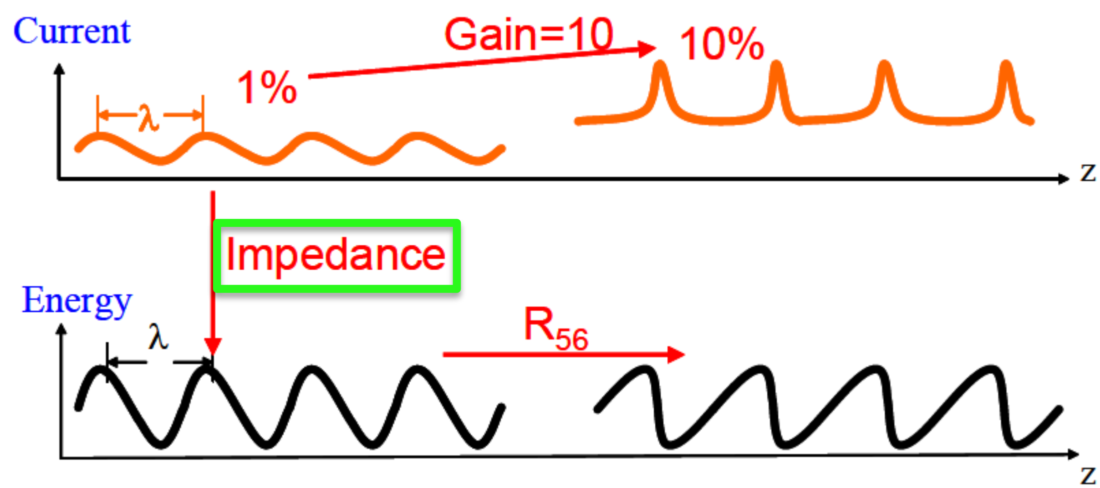
Introduction and Motivation: Microbunching instability mechanism

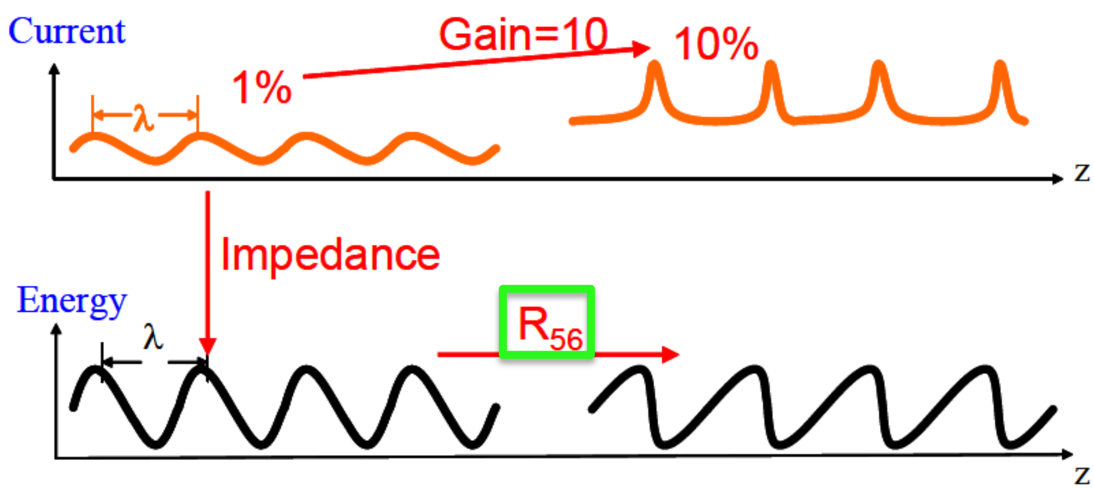
- An initial **density** modulation can induce **energy** modulation due to the presence of (high-frequency) impedance $Z(k)$, e.g. **LSC** or **CSR**.



Z. Huang and J. Wu, Beam Dynamics Newsletter, No. 38

Introduction and Motivation: Microbunching instability mechanism

- An initial **density** modulation can induce **energy** modulation due to the presence of (high-frequency) impedance $Z(k)$, e.g. **LSC** or **CSR**.
- Such **energy** modulation can then convert to further **density** modulation via the momentum compaction $\boldsymbol{R_{56}}$ downstream and possibly induce emittance growth in the dispersive region.



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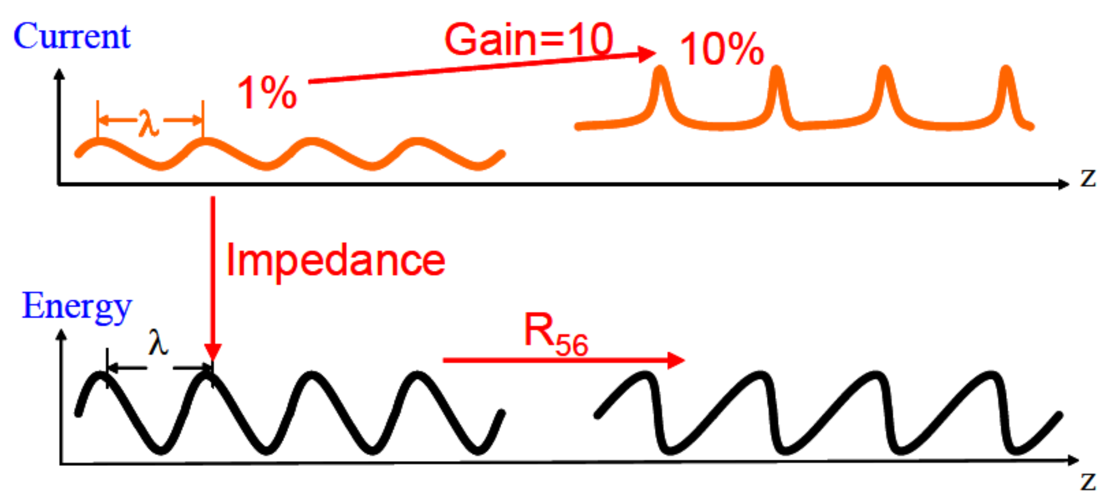
- The above process can accumulate over and over along the beamline, resulting in possible enhancement, called **microbunching instability**.



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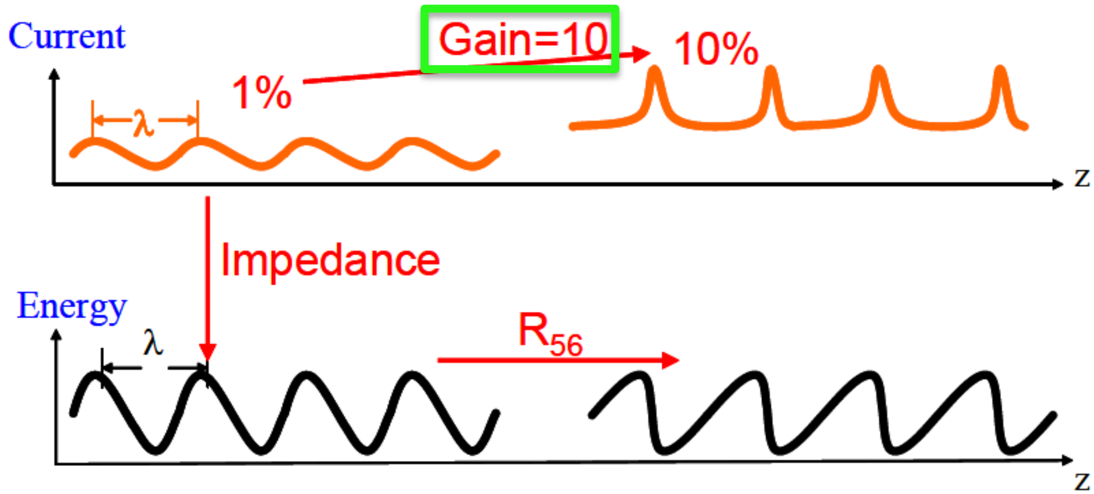

$$G(s) = \left| \frac{g_k(s)}{g_k^{(0)}(s=0)} \right|$$

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What has been done

- Previous studies most focus on microbunching gain analysis for **bunch compressor chicanes**.
  - Heifets, Stupakov, and Krinsly, PRST-AB 5, 064401 (2002)
  - Huang and Kim, PRAT-AB 5, 074401 (2002)
- Vlasov-based analysis
- The **CSR**-induced microbunching gain is (relatively) low
  - e.g. $G_f < 3$, for LCLS BC2

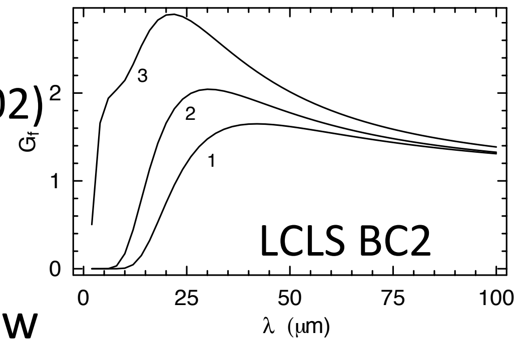
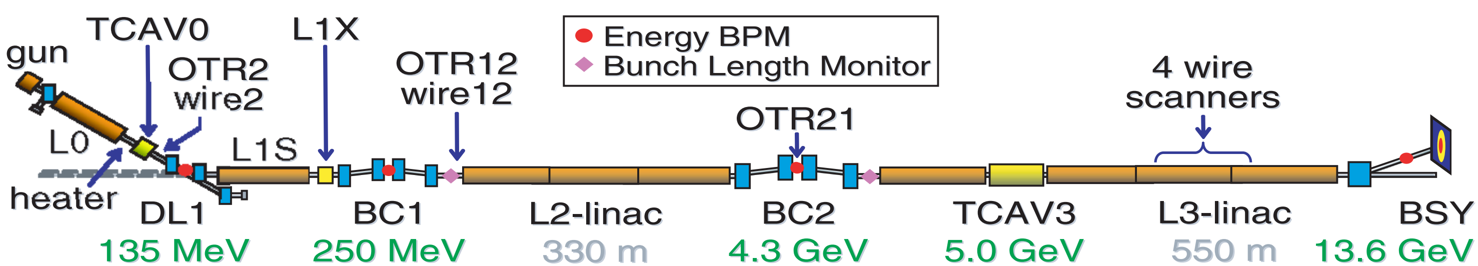


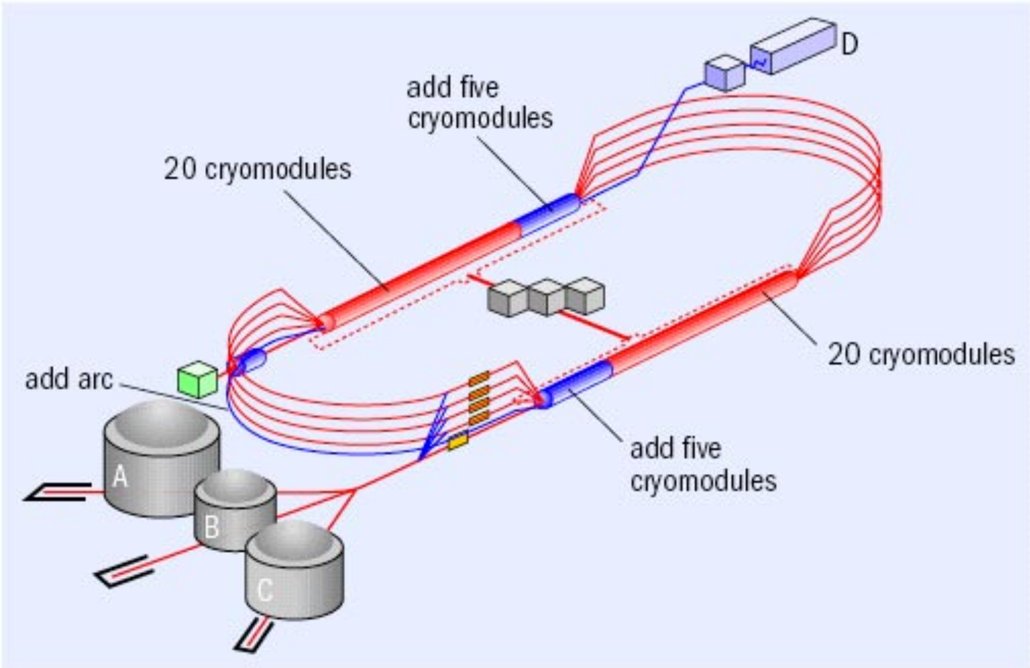
FIG. 3. Amplification factor G_f as a function of wavelength λ of the perturbation at the compressor entrance for various beam emittance and energy spread: (*1*) $\sigma_p = 3.0 \times 10^{-5}$, $\epsilon = 1\ \mu m$; (*2*) $\sigma_p = 3.0 \times 10^{-5}$, $\epsilon = 0$; and (*3*) $\sigma_p = 3.0 \times 10^{-6}$, $\epsilon = 1\ \mu m$.



PRST-AB 12, 030704 (2009)

Why important in ERLs

Even though CEBAF is not an ERL, but a recirculation linac, it is helpful to illustrate the important parts of ERL using this schematic layout.



- However, in Energy Recovery Linac (ERL) or recirculation machines, microbunching instability can be a special concern, because:
  - **low energy merger** (CSR & LSC)
  - **spreaders/recombiners** (CSR)
  - **long transport/recirculation arcs (multiple bends)** (CSR)

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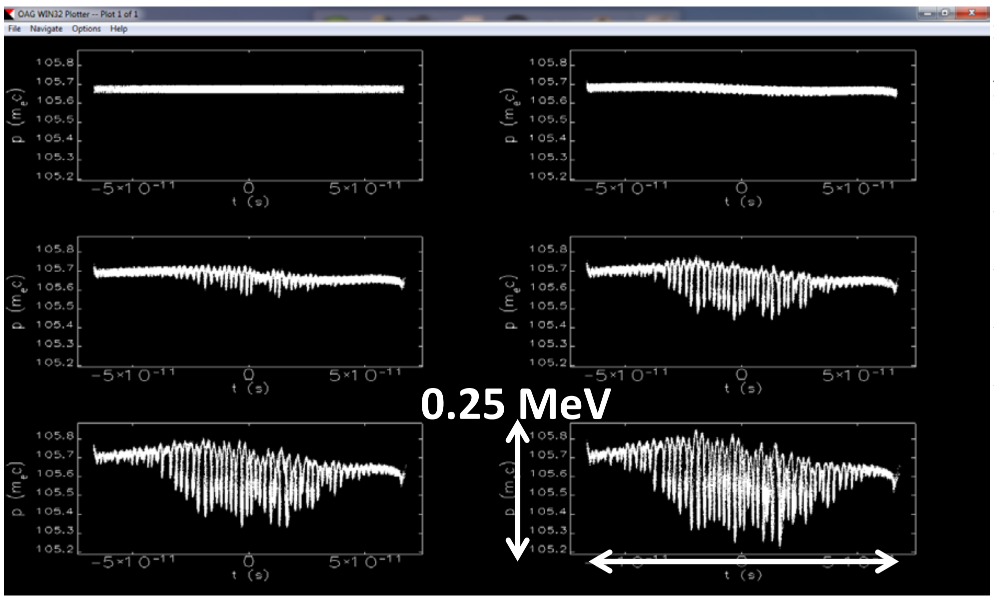
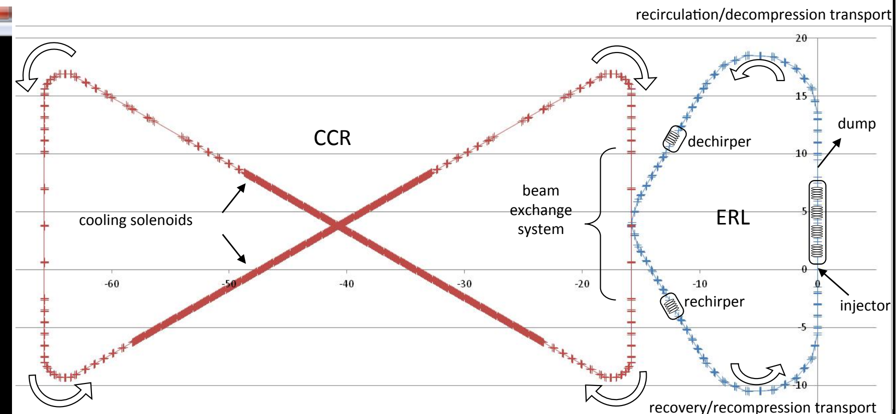
Introduction and Motivation: Microbunching instability in MEIC CCR

- Due to relatively **low energy** (~ 55 MeV) and **high bunch charge** (~ 2 nC), MEIC CCR is potentially subject to CSR-induced microbunching instability.



100 ps (~ 3cm)



MEIC Design Report, 2012

	1 Turn	2 Turns	3 Turns	4 Turns	5 Turns
ε_x (mm-mrad)	2.9	3.1	3.8	4.5	5.1
ε_y (mm-mrad)	2.9	2.9	3.0	3.1	3.2
σ_t (ps)	29.33	29.31	29.28	29.24	29.19
$\sigma_{\Delta E/E}$ (%)	0.012	0.027	0.066	0.096	0.117

C. Tennant and D. Douglas, JLAB-TN-12-027

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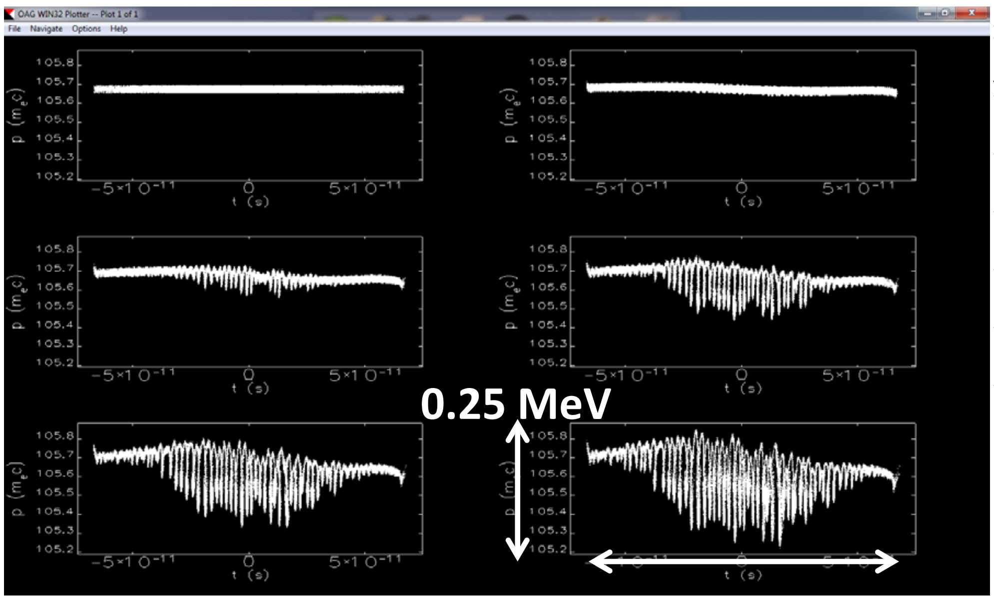

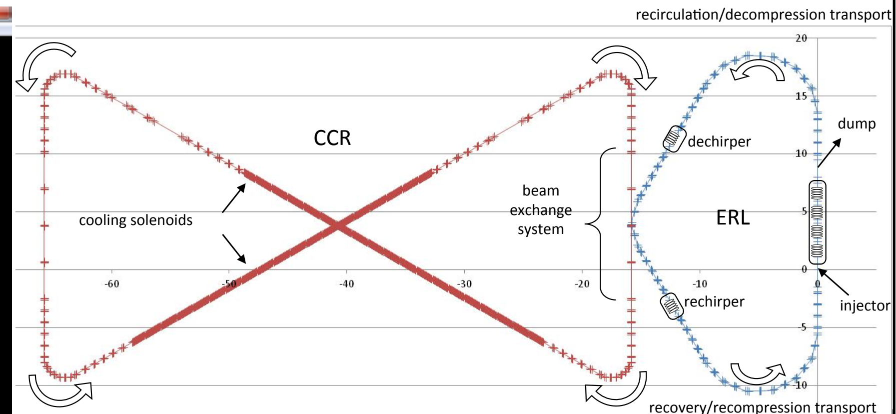

MEIC Design Report, 2012

Note:

◆ In the **ELEGANT** tracking simulation, **100,000** macroparticles with quiet start are used.

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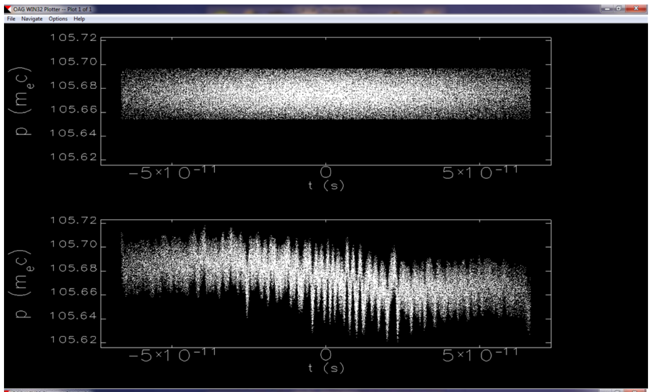
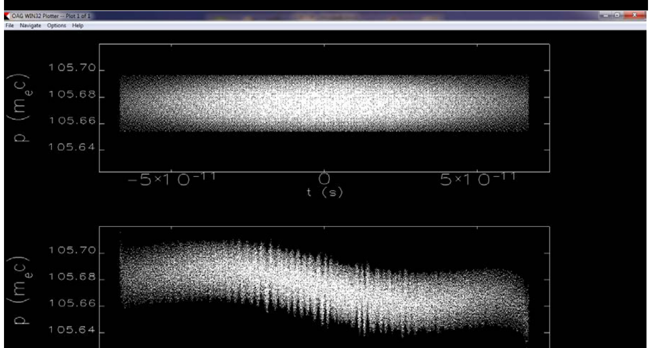
Introduction and Motivation: Numerical challenges from particle tracking



100K macroparticles, **without** quiet start



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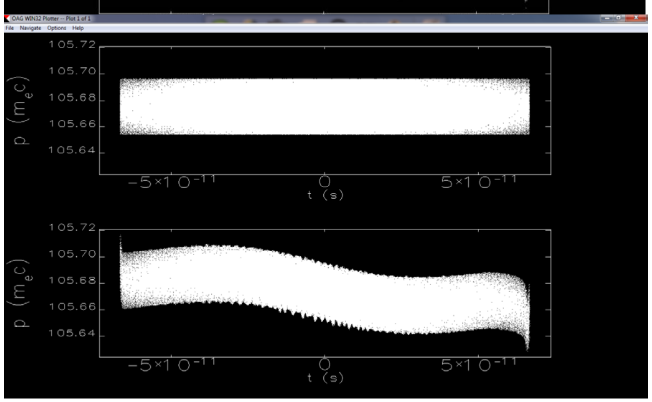

1000K macroparticles, **with** quiet start

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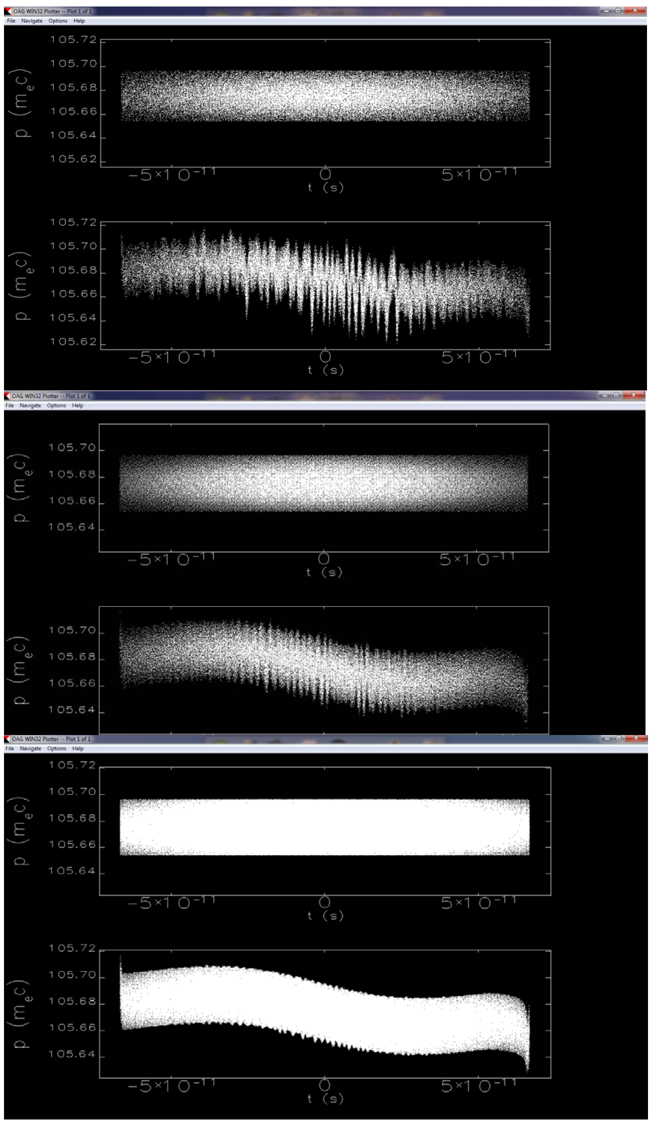

- Particle tracking subject to initial **numerical noise**.
- **Increase** number of particles (with specialized initial quiet start algorithm)
  ➔ **reduce** numerical noise
- How much of the microbunching structure contributed from **numerical** effect? How much from **physical** effect?
- To better design a machine, we would like to know the system **gain** to microbunching effects
- More and more macroparticles
  ➔ more computation **time consuming**
  ➔ difficult to do systematic study and/or lattice design optimization
- Necessary to develop an alternative model for gain analysis that is more robust and also serves to benchmark particle tracking results

C. Tennant and D. Douglas, JLAB-TN-12-027

Introduction and Motivation: Summary of our extended work

- Derived from **Vlasov** equation [Heifets et al. & Huang and Kim, 2002]
- **Extend** to include both **horizontal** and **vertical** bending
  - ➔ spreader/recombiners
- **Extend** to adopt a **general** linear lattice
  - ➔ for generic transport arc design (multiple bends)
- **Extend** to include more relevant collective effects, e.g.
  - ➔ non-ultrarelativistic **CSR** impedance for low energy beamline
  - ➔ transient **CSR** effects
  - ➔ 1-D **(L)SC** effect

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Vlasov formulation and model assumptions

- Linearization of Vlasov equation:
  - Heifets, Stupakov, and Krinsky (HSK), PRST-AB **5**, 064401 (2002); 129902 (2002).
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$$\frac{\partial f}{\partial s}+\left(\frac{dz}{ds}\right)\frac{\partial f}{\partial z}+\left(\frac{d\delta}{ds}\right)\frac{\partial f}{\partial \delta}+\left(\frac{dx}{ds}\right)\frac{\partial f}{\partial x}+\left(\frac{d\theta}{ds}\right)\frac{\partial f}{\partial \theta}=0$$

$$\frac{dz}{ds}=-\frac{x}{\rho}$$

$$\frac{d\delta}{ds}=-\frac{r_e}{\gamma}\int_{\infty}^{\infty}dz' W_{\parallel}(z-z',s)n(z',s)$$

$$\frac{dx}{ds}=\theta$$

$$\frac{d\theta}{ds}=-k_\beta^2(s)x+\frac{\delta}{\rho}$$

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$$\frac{d\delta}{ds}=-\frac{r_e}{\gamma}\int_{\infty}^{\infty}dz'W_{\parallel}(z-z',s)n(z',s)$$

$$\frac{dx}{ds}=\theta_x \qquad \frac{dy}{ds}=\theta_y$$

$$\frac{d\theta_x}{ds}=-k_{\beta x}^2(s)x+\frac{\delta}{\rho_x} \qquad \frac{d\theta_y}{ds}=-k_{\beta y}^2(s)y+\frac{\delta}{\rho_y}$$

Including **vertical** bending is particularly useful for recirculation machines because such lattices usually contain **spreader** and **recombiner** parts.

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- Study this problem **in frequency domain**
  - the modulation of a bunch is characteristic of the (complex) bunching factor, i.e. Fourier spectral component of a bunch distribution
- Track the evolution of the **bunching factor**
- Take into account the relevant collective effects (**impedances**)

$$Z(k,s)=\int_0^\infty d\zeta W_{\|}(\zeta,s)e^{-ik\zeta} \qquad g_k(s)=\int d\mathbf{X} f_1 e^{-ikz}$$

Vlasov equation

↓ standard perturbation technique: $f = f_0 + f_1$

Linearized Vlasov equation

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Linearized Vlasov equation

transform to frequency domain

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

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Vlasov equation

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Linearized Vlasov equation

transform to frequency domain

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

Summary of mathematical formulas

◆ Volterra integral equation:

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

$$K(s,s')=\frac{ik}{\gamma}\frac{I(s)}{I_A}C(s')R_{56}(s'\to s)Z\left(kC(s'),s'\right)\times[\text{Landau damping}]$$

$$[\text{Landau damping}]=\exp\left\{\frac{-k^2}{2}\left[\varepsilon_{x0}\left(\beta_{x0}R_{51}^2(s,s')+\frac{R_{52}^2(s,s')}{\beta_{x0}}\right)+\varepsilon_{y0}\left(\beta_{y0}R_{53}^2(s,s')+\frac{R_{54}^2(s,s')}{\beta_{y0}}\right)+\sigma_\delta^2R_{56}^2(s,s')\right]\right\}$$

$$R_{56}(s'\to s)=R_{56}(s)-R_{56}(s')+R_{51}(s')R_{52}(s)-R_{51}(s)R_{52}(s')+R_{53}(s')R_{54}(s)-R_{53}(s)R_{54}(s')$$

$$R_{5i}(s,s')=C(s)R_{5i}(s)-C(s')R_{5i}(s')\ \text{ for } i=1,2,3,4,6$$

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- Volterra integral equation:

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

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$$R_{56}(s' \to s) = R_{56}(s) - R_{56}(s') + R_{51}(s')R_{52}(s) - R_{51}(s)R_{52}(s') + R_{53}(s')R_{54}(s) - R_{53}(s)R_{54}(s')$$

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Physical meaning of *K*(*s*,*s'*):
initial **density** modulation at *s'* induces **energy** modulation by collective effects
induced **energy** modulation at s' converts to further **density** modulation via R_{56}

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Impedance models

- Coherent synchrotron radiation (CSR) effects:
  - **steady-state** CSR: ultrarelativistic and non-ultrarelativistic
  - **transient** CSR: entrance and exit
  - parallel-plate **shielded** CSR
- Longitudinal space charge (LSC) effects:
  - on-axis model
  - averaged (over radial dependence) model
  - transverse axisymmetric Gaussian model
- Summarized in TUICLH2034 (this workshop)

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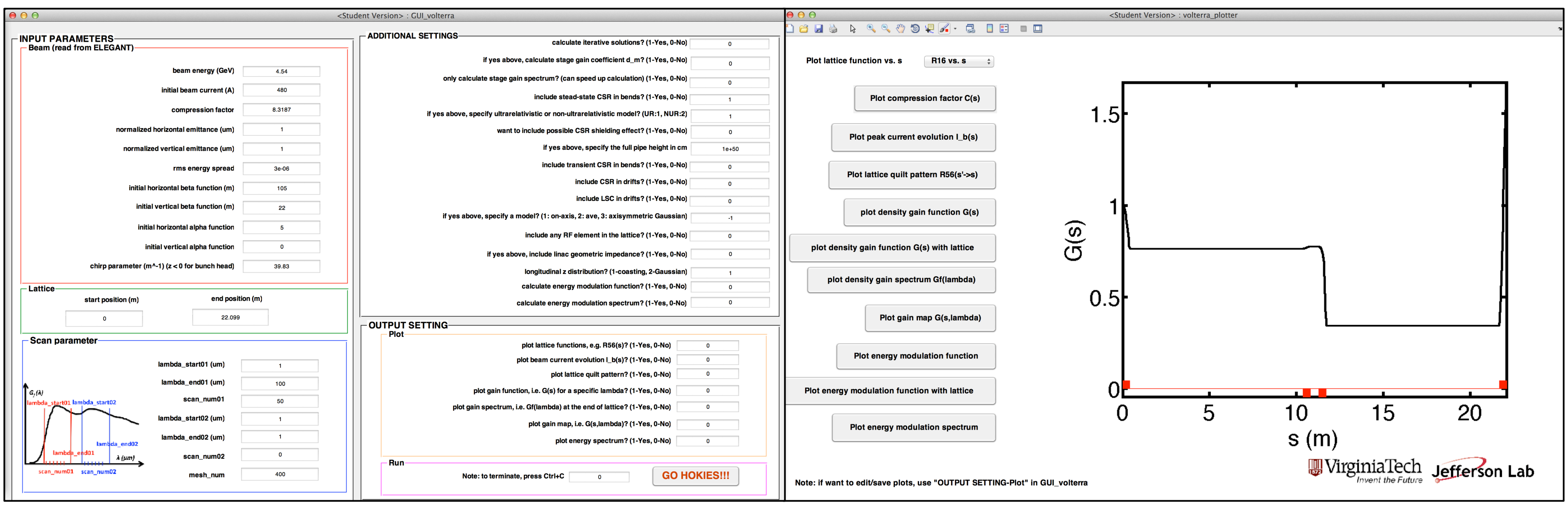
GUI: volterra_mat

- Read input information from **ELEGANT**
- Apply for **general** linear lattice
- Output **gain curves**
- **Fast** (compared with particle tracking)
- **GUI** (graphical user interface)



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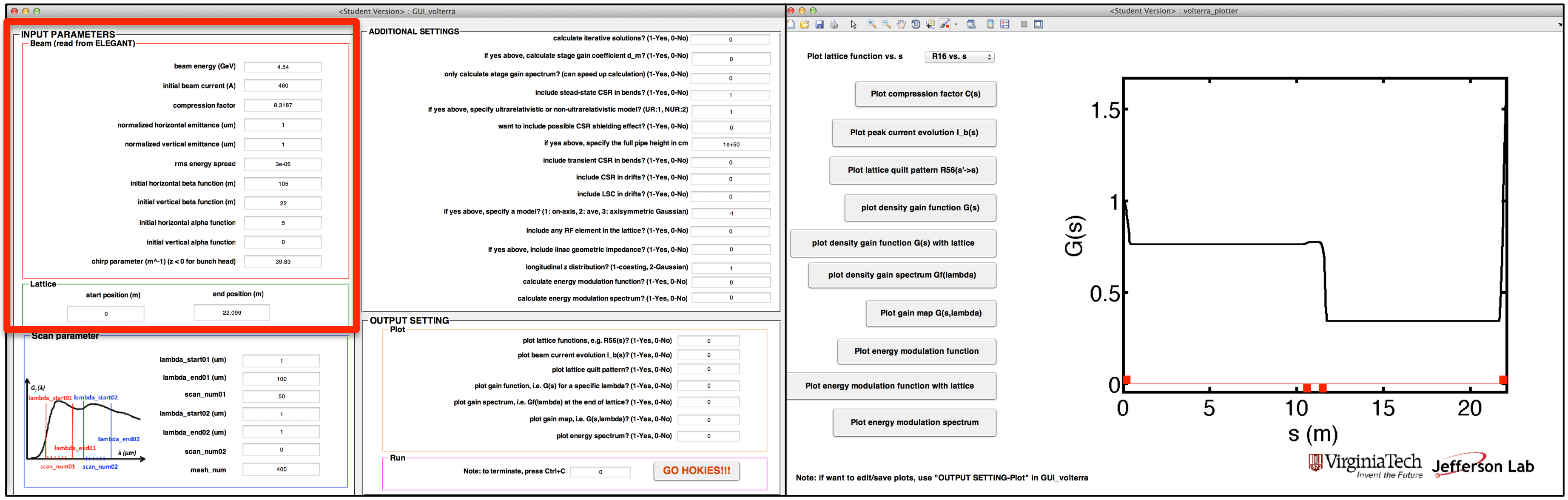

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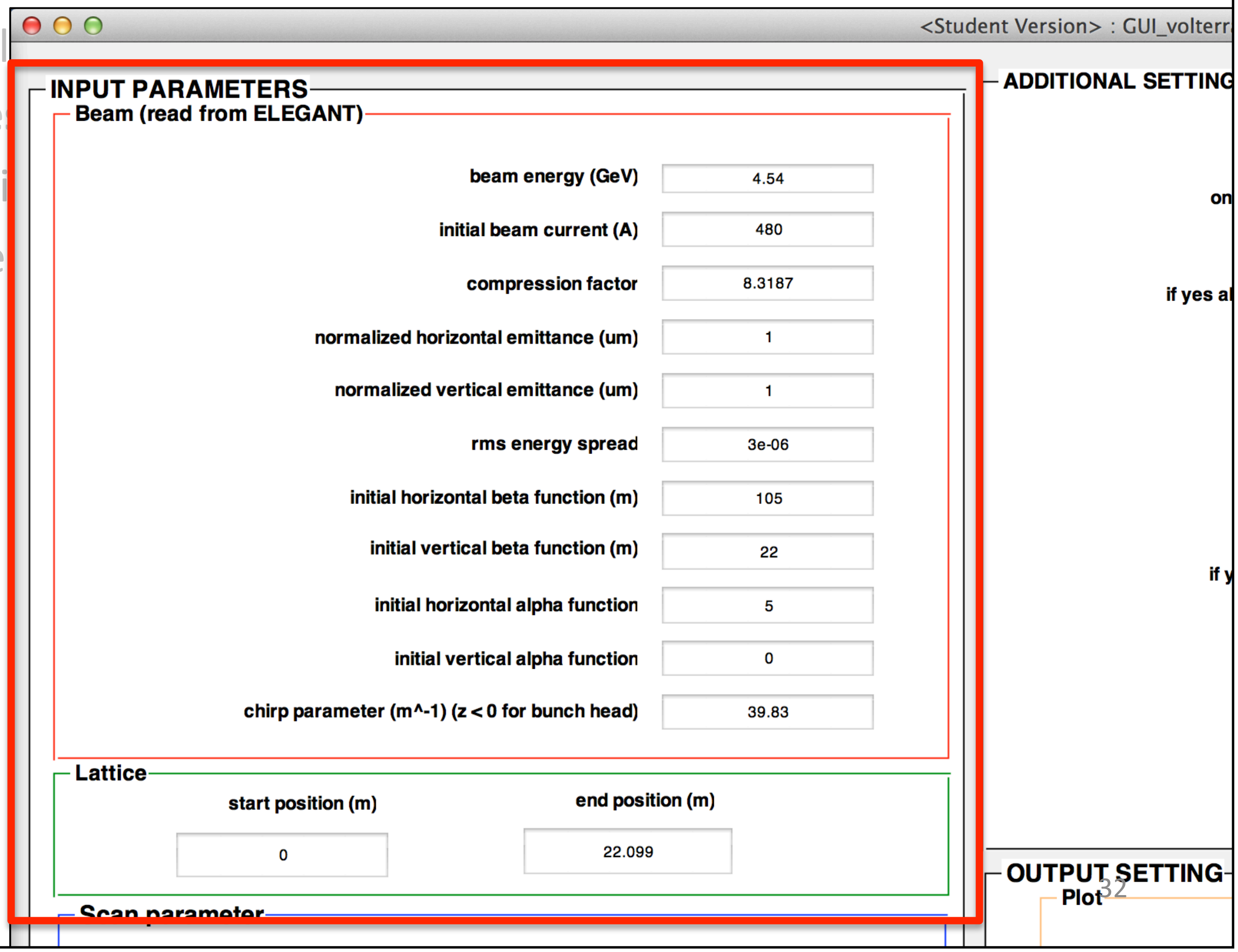

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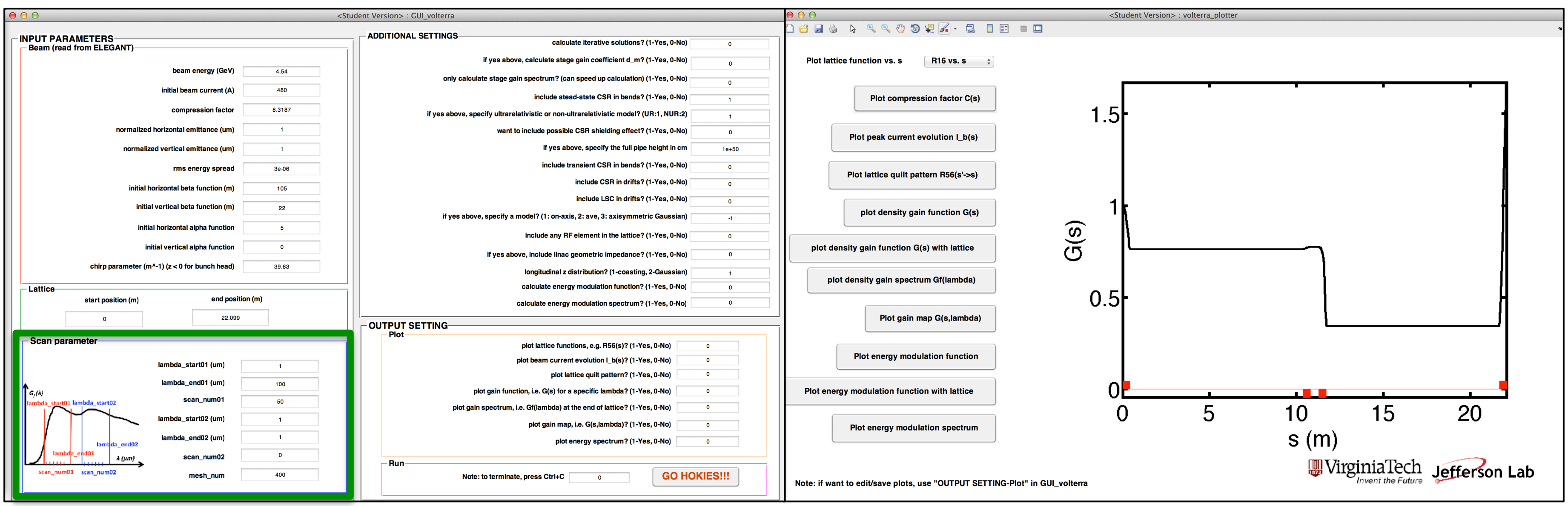
GUI: volterra_mat

- Set up additional numerical parameters
- Apply for **general** linear lattice
- Output **gain curves**
- **Fast** (compared with particle tracking)
- **GUI** (graphical user interface)



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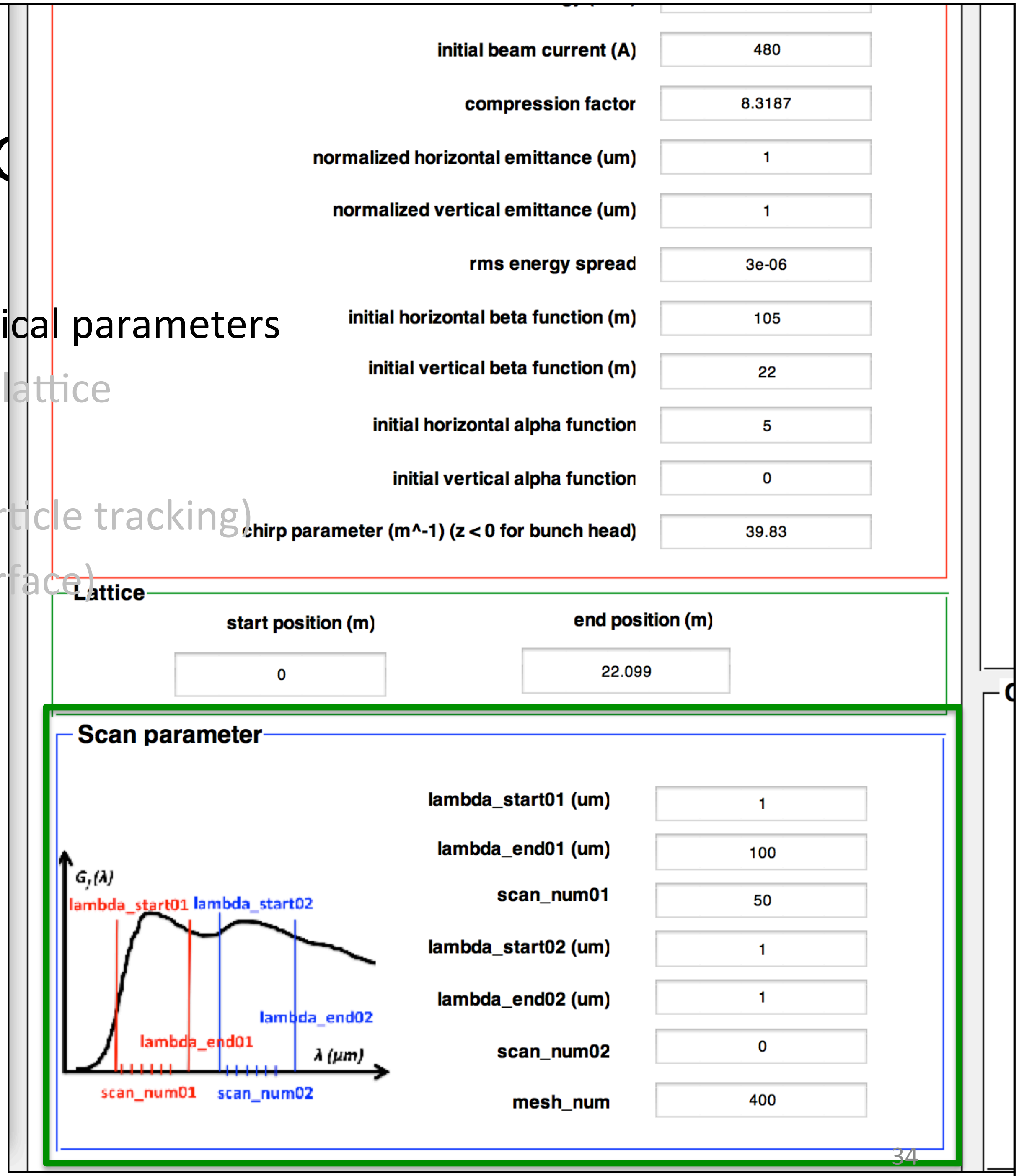
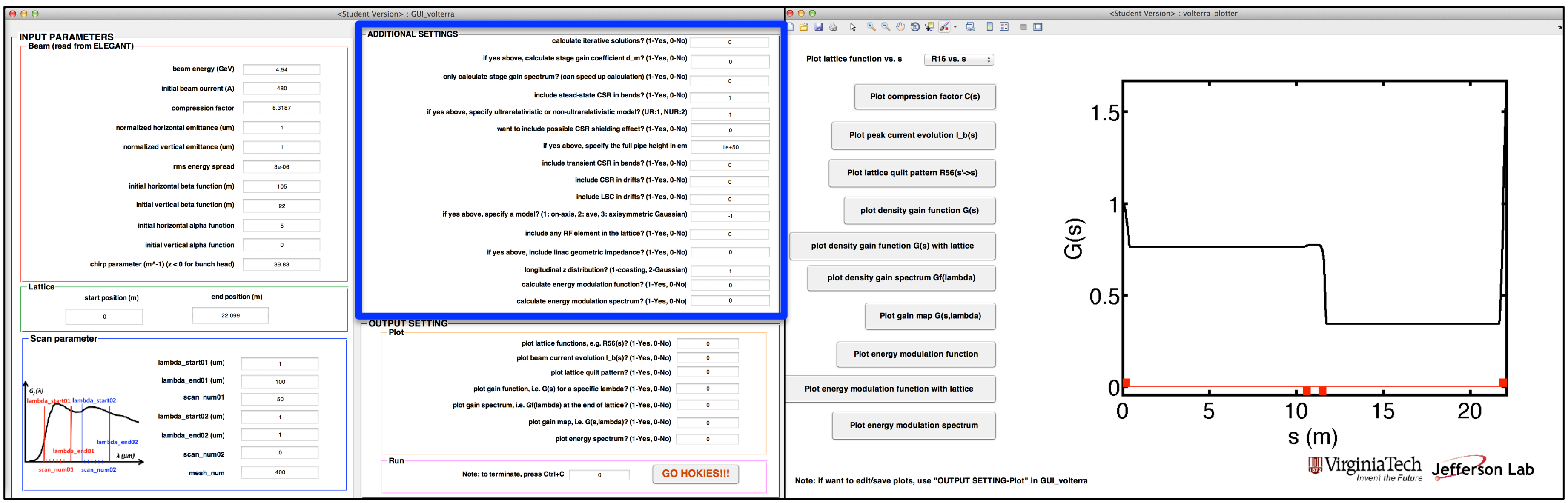


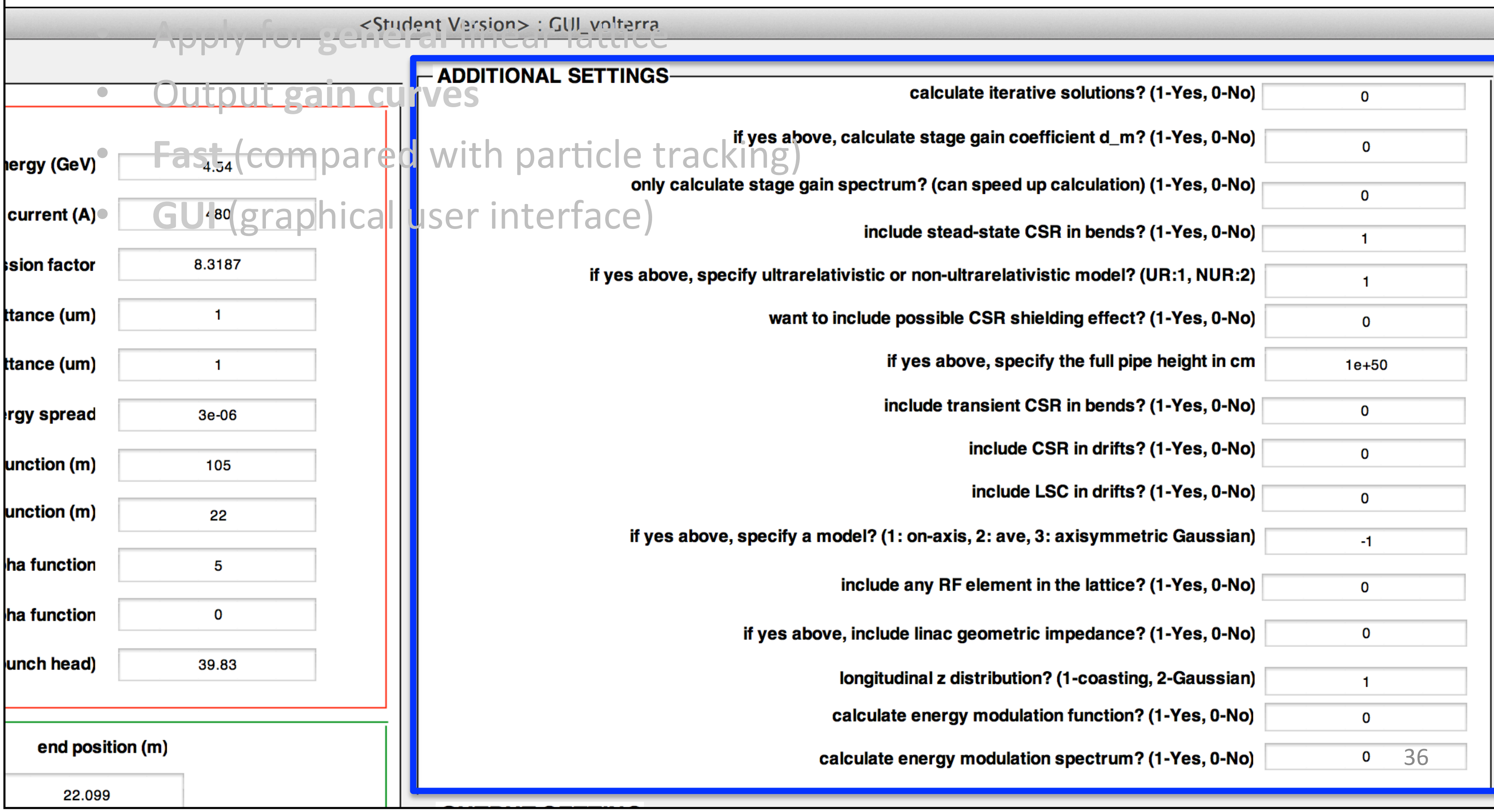
GUI: volterra_mat

- Apply relevant impedance models
- Apply for **general** linear lattice
- Output **gain curves**
- **Fast** (compared with particle tracking)
- **GUI** (graphical user interface)



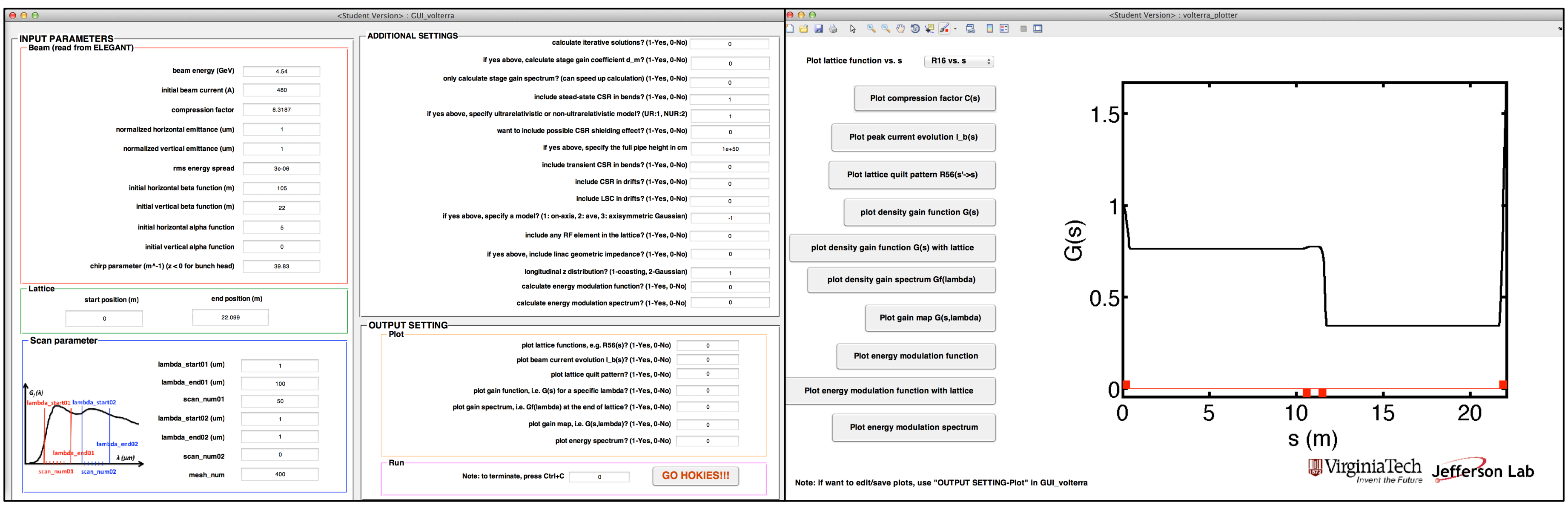
GUI: volterra_mat

- Apply relevant impedance models
- Apply for general linear lattice
- Output gain curves
- Fast (compared with particle tracking)
- GUI (graphical user interface)



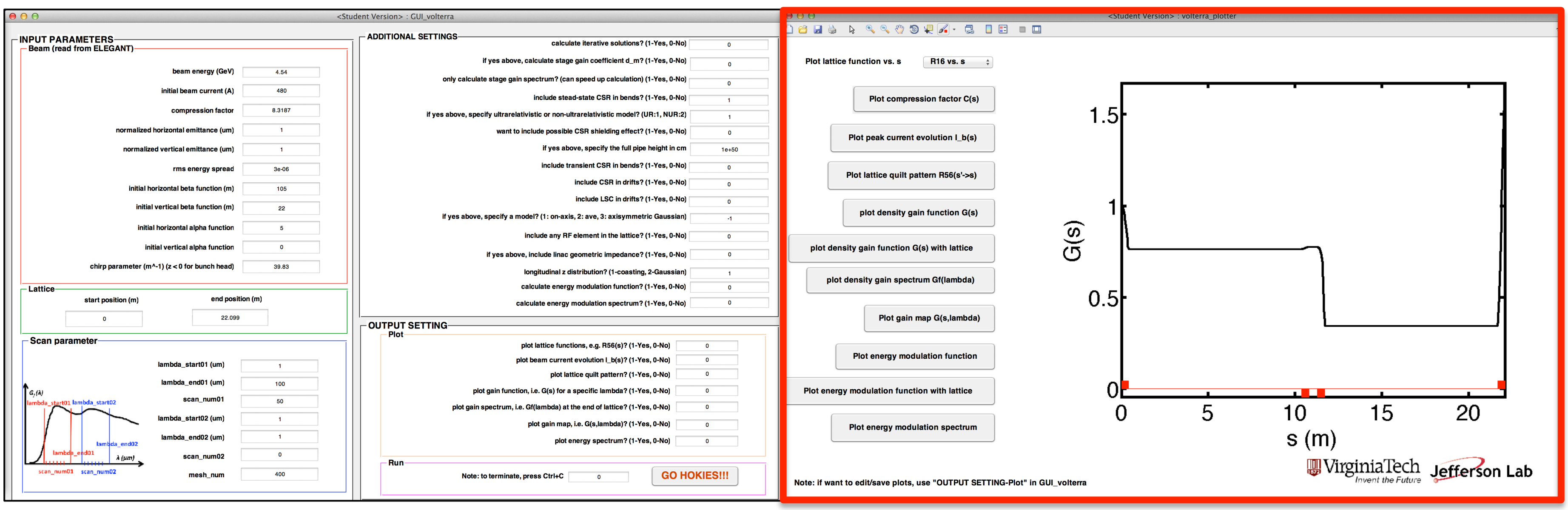
GUI: volterra_mat

- Read input information from **ELEGANT**
- Apply for **general** linear lattice (not shown here)
- Output **gain curves**
- **Fast** (compared with particle tracking)
- **GUI** (graphical user interface)



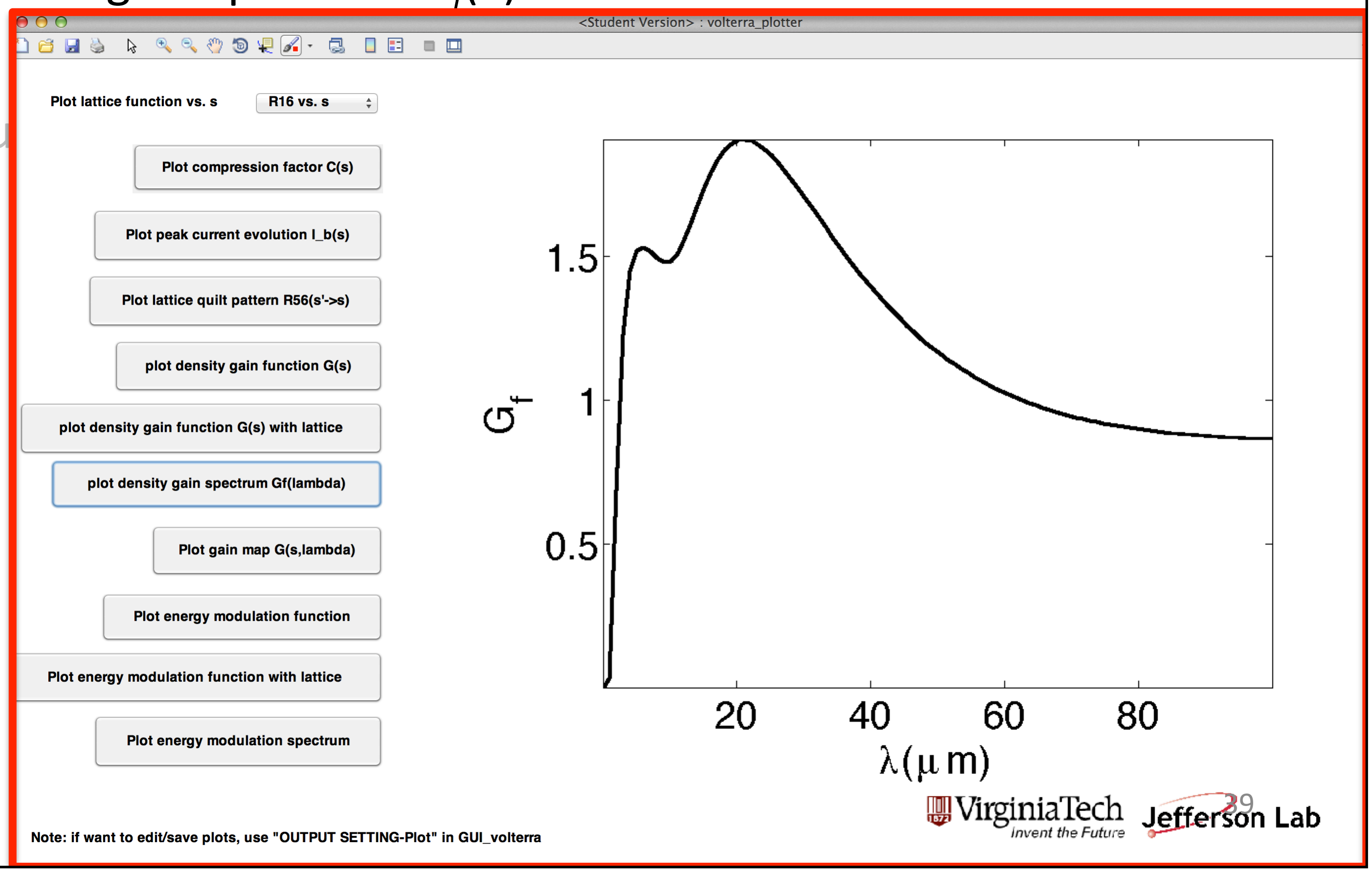
GUI: volterra_mat

- Read input information from **ELEGANT**
- Apply for **general** linear lattice
- Output **capabilities**
- **Fast** (compared with particle tracking)
- **GUI** (graphical user interface)



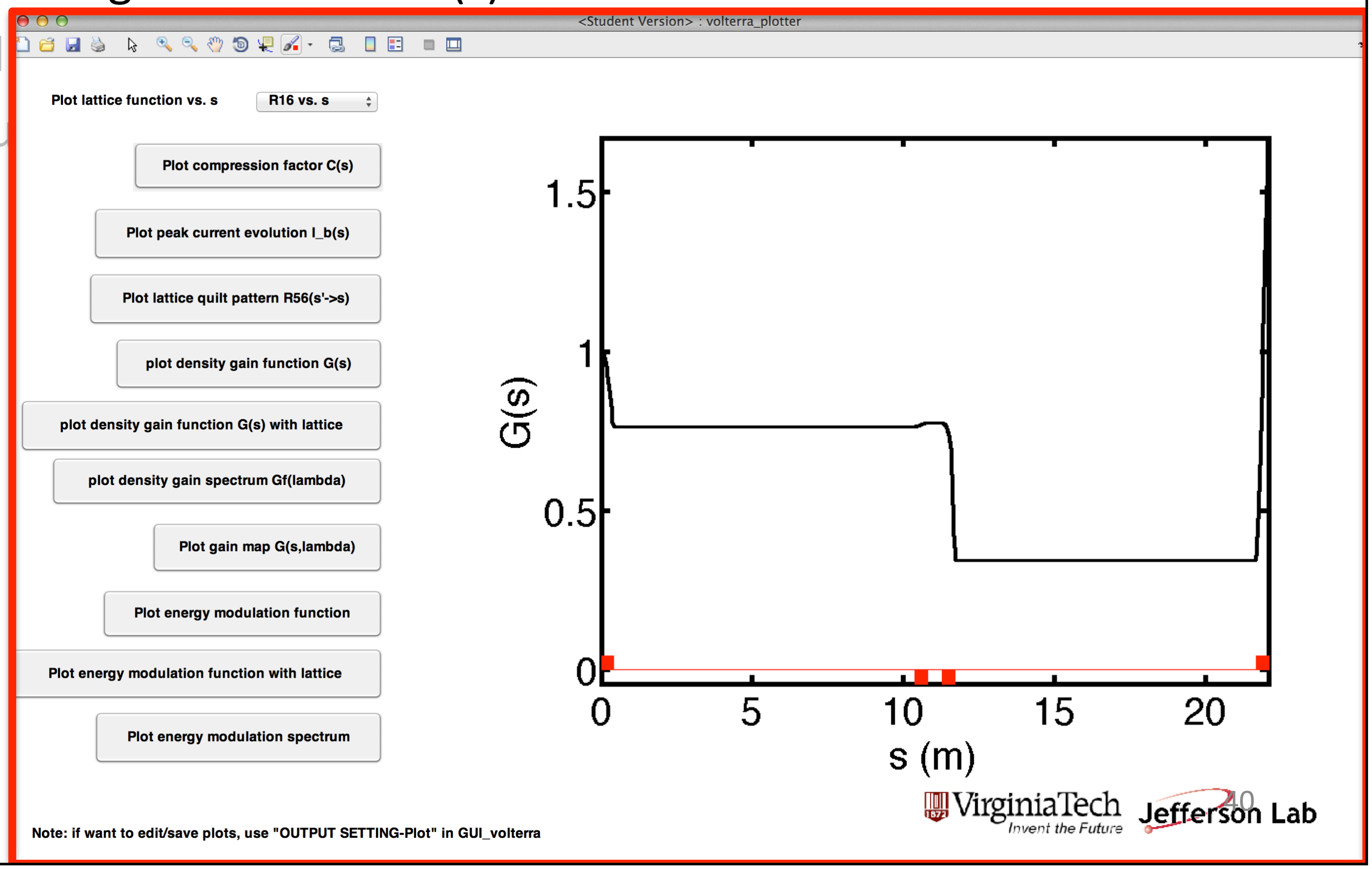
GUI: volterra_mat

- Read input information from **ELEGANT**
- Apply for **general** linear lattice
- Output **capabilities**: gain spectrum $G_f(\lambda)$
- **Fast** (compared
- **GUI** (graphical u



GUI: volterra_mat

- Read input information from **ELEGANT**
- Apply for **general** linear lattice
- Output **capabilities**: gain functions G(s)
- **Fast** (compared
- **GUI** (graphical u



GUI: volterra_mat

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- Apply for **general** linear lattice
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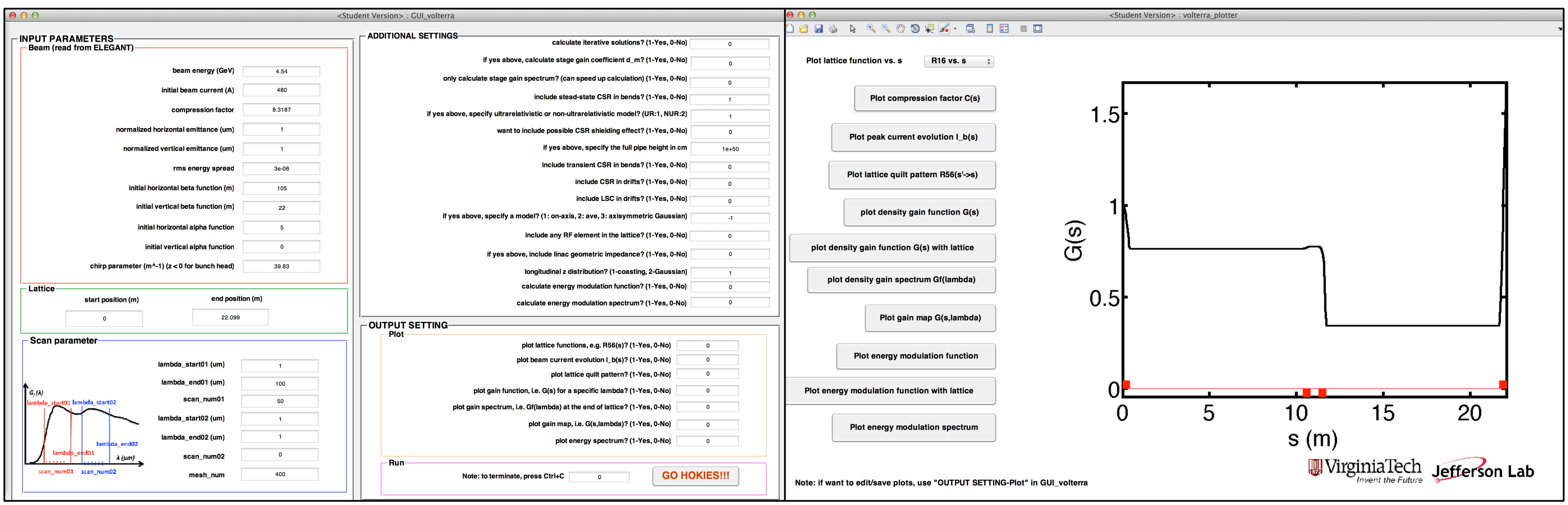

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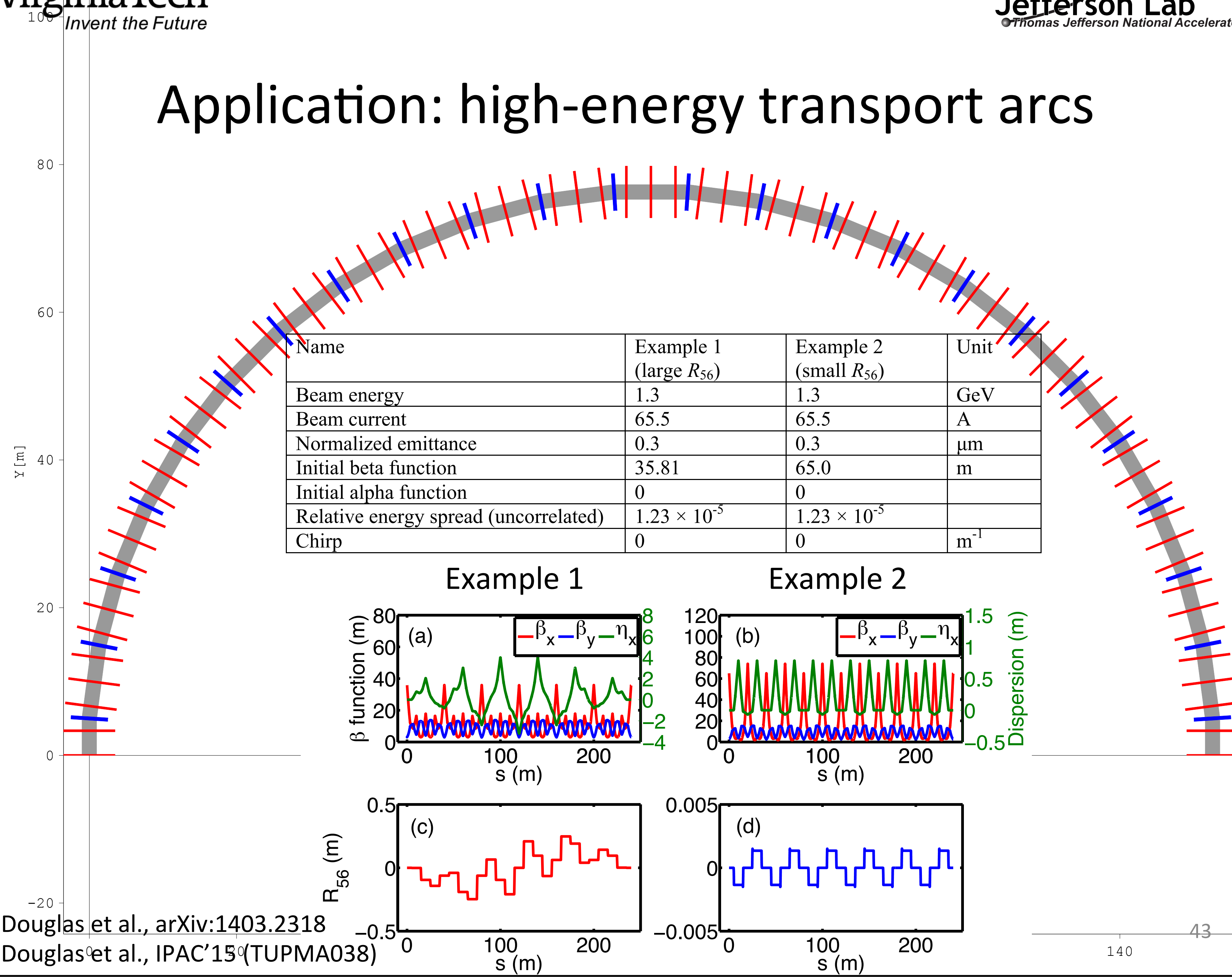
- Examples and Results [$G_f(\lambda)$, $G(s)$]
  - Two comparative high-energy transport/recirculation arcs
  - MEIC Circulator Cooling Ring
- Summary and Future work

Application: high-energy transport arcs



Name	Example 1 (large R_{56})	Example 2 (small R_{56})	Unit
Beam energy	1.3	1.3	GeV
Beam current	65.5	65.5	A
Normalized emittance	0.3	0.3	µm
Initial beta function	35.81	65.0	m
Initial alpha function	0	0	
Relative energy spread (uncorrelated)	1.23×10^{-5}	1.23×10^{-5}	
Chirp	0	0	m^{-1}

D. Douglas et al., arXiv:1403.2318
D. Douglas et al., IPAC'15 (TUPMA038)

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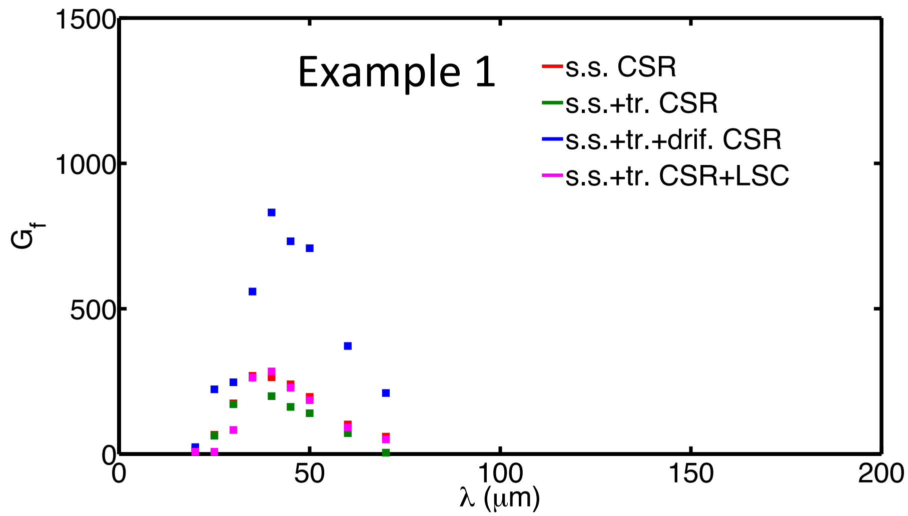
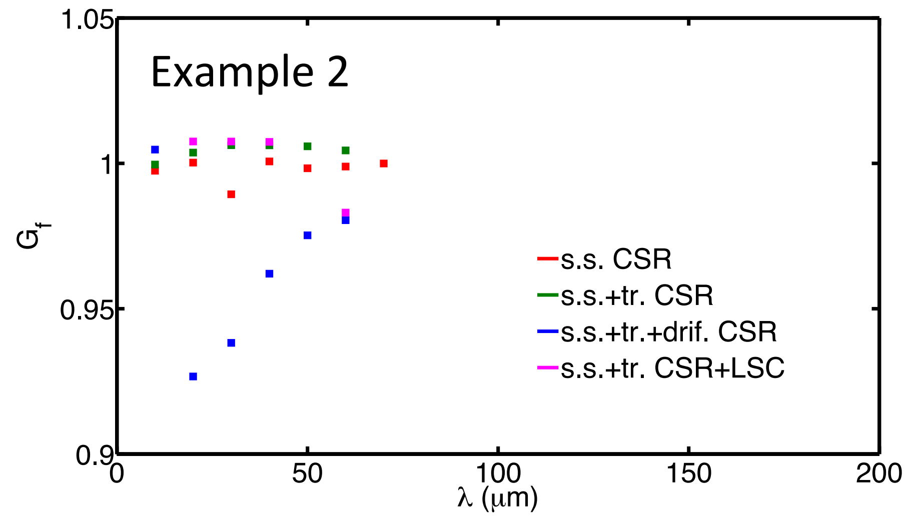
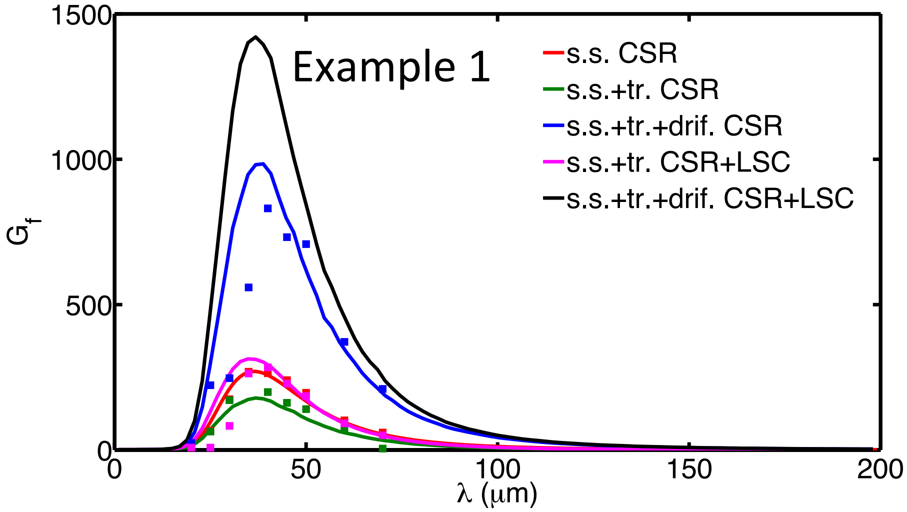
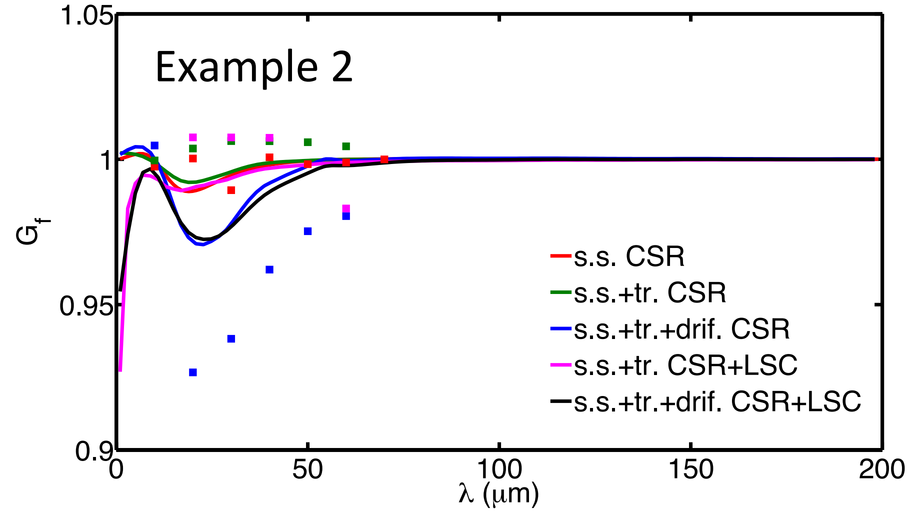




- ❑ For each “dot”, it takes several hours to run ELEGANT tracking, after careful treatment to ensure numerical convergence in linear amplification regime. (particularly for Example 1)
- ❑ Example 1 is subject to microbunching instability; Example 2 not.
- ❑ (**Blue**) adding “CSR drift” increases the overall gain up to 200 %
- ❑ (**Black**) include all CSR and LSC effects





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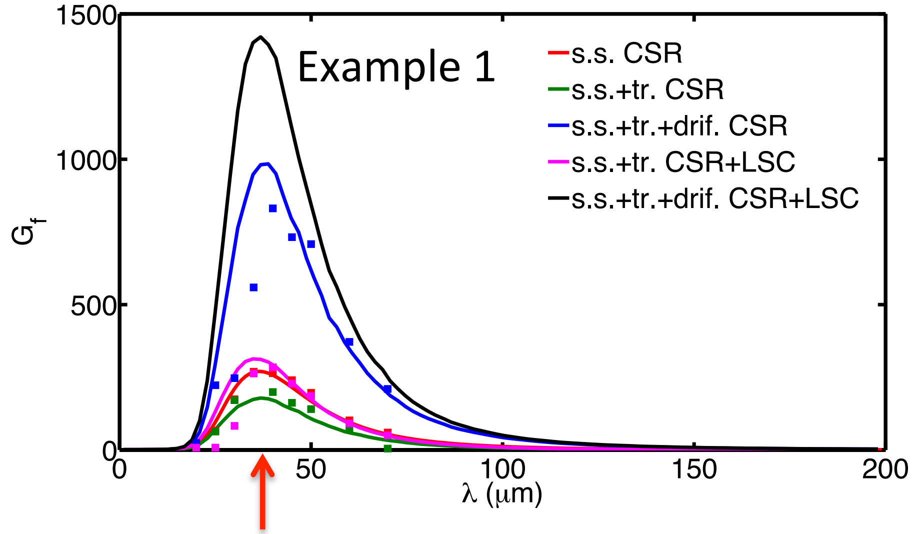

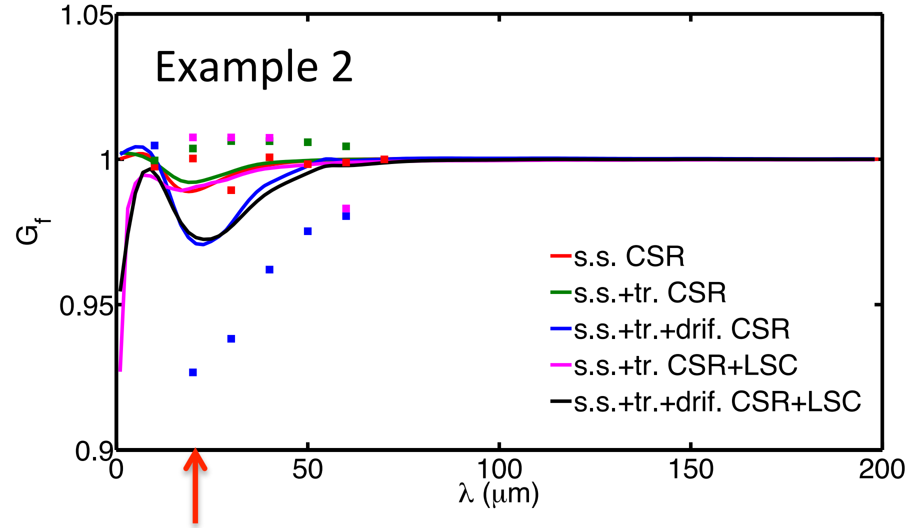

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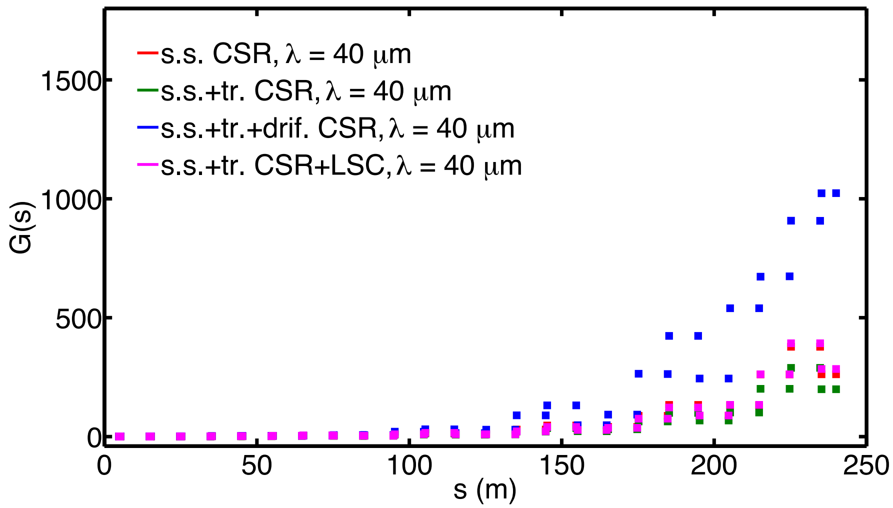
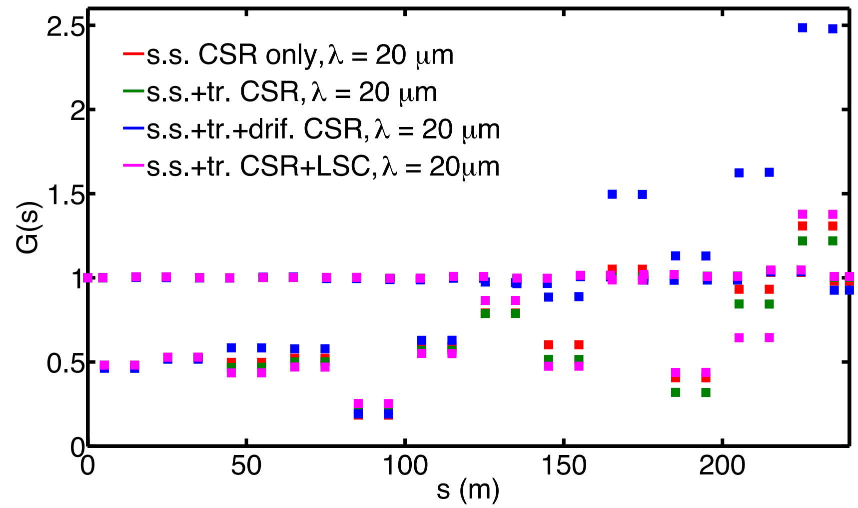
Example 1

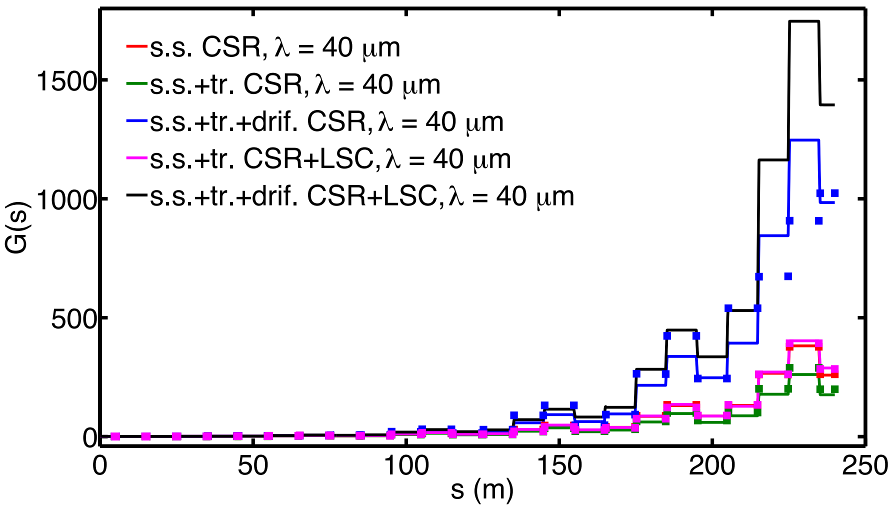


Example 2

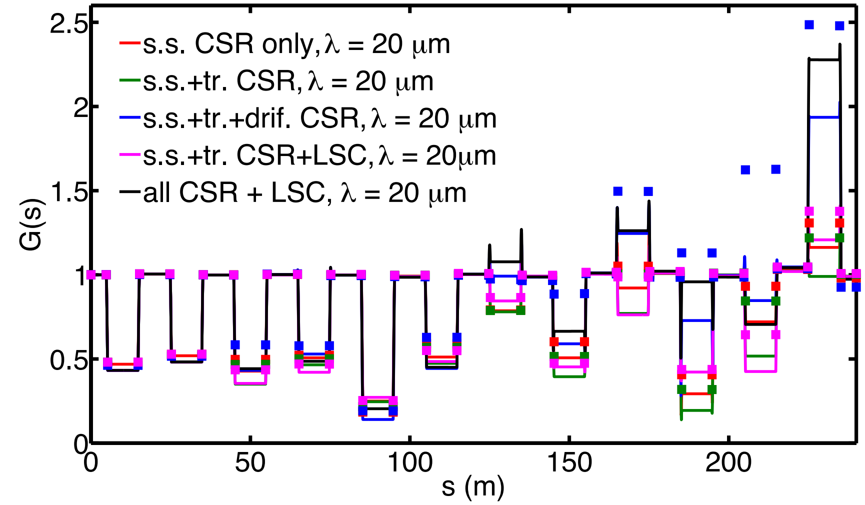


- Because of local achromaticity (η = 0) and isochronicity (R_{56} = 0), CSR effect is much reduced for Example 2 lattice.
- Example 1: **global** isochronous, **large** R_{56} modulation
  Example 2: **local** isochronous, **small** R_{56} modulation
- Overall, microbunching instability can result in a significant effect on the beam quality, depending on lattice design itself.
- For the two cases, the incoming beams have (almost) the same properties.

Example 1



Example 2



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- ❑ Example 1: **global** isochronous, **large** R_{56} modulation
  Example 2: **local** isochronous, **small** R_{56} modulation
- ❑ Overall, microbunching instability can result in a significant effect on the beam quality, depending on lattice design itself.
- ❑ For the two cases, the incoming beams have (almost) the same properties.

ELEGANT numerical parameter setting

Name	Example 1	Example 2	MEIC CCR	Note
Number of macroparticles	50-70 M	50 M	50 M	for initial beam preparation
N_KICKS	400	400	200 (H), 300 (V)	for CSRCSBEND
NONLINEAR	0	0	0	for CSRCSBEND
LINEARIZE	1	1	1	for CSRCSBEND
BINS	12000	20000	10000	for CSRCSBEND
STEADY_STATE	0	0	1*	for CSRCSBEND
HIGH_FREQUENCY_CUTOFF0	0.08	0.1	0.144	for CSRCSBEND
HIGH_FREQUENCY_CUTOFF1	0.08	0.1	0.144	for CSRCSBEND
DZ	0.01	0.01	N.A.	for CSRDRIFT
USE_STUPAKOV	1	1	N.A.	for CSRDRIFT
BINS	12000	20000	N.A.	for LSCDRIFT

Note:
1. Those (any) sextupole fields are turned off to match the theoretical formulation.
2. Details can be found in JLAB-TN-14-016.

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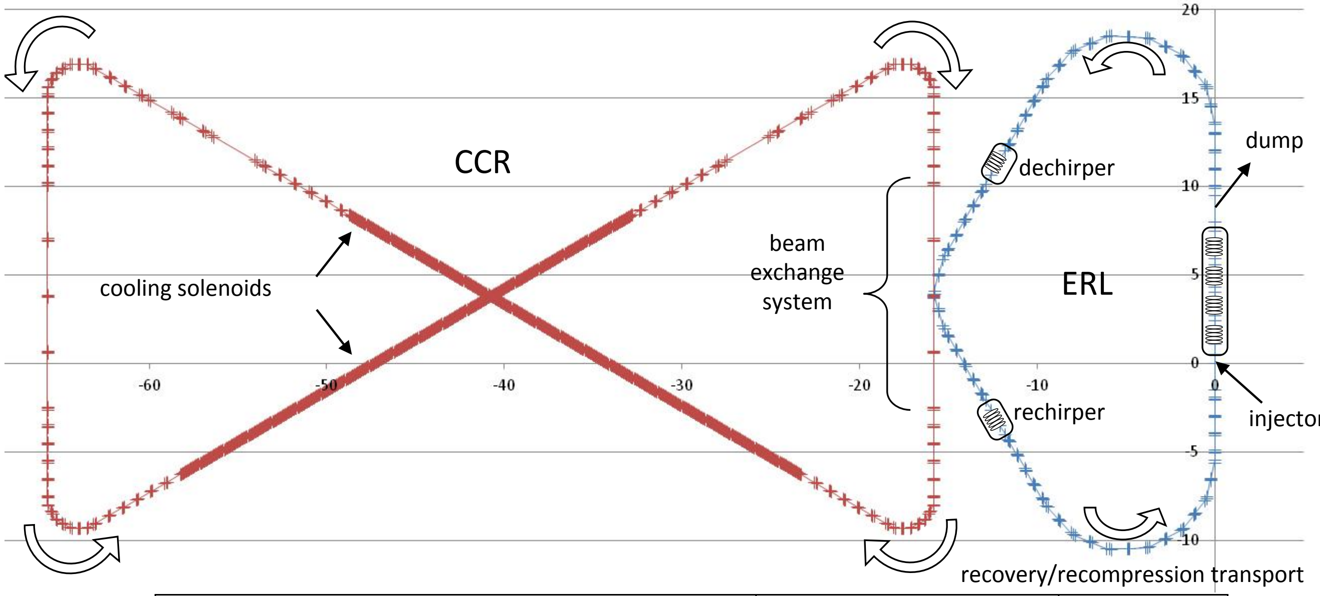
Application: MEIC Circulator Cooling Ring (CCR)

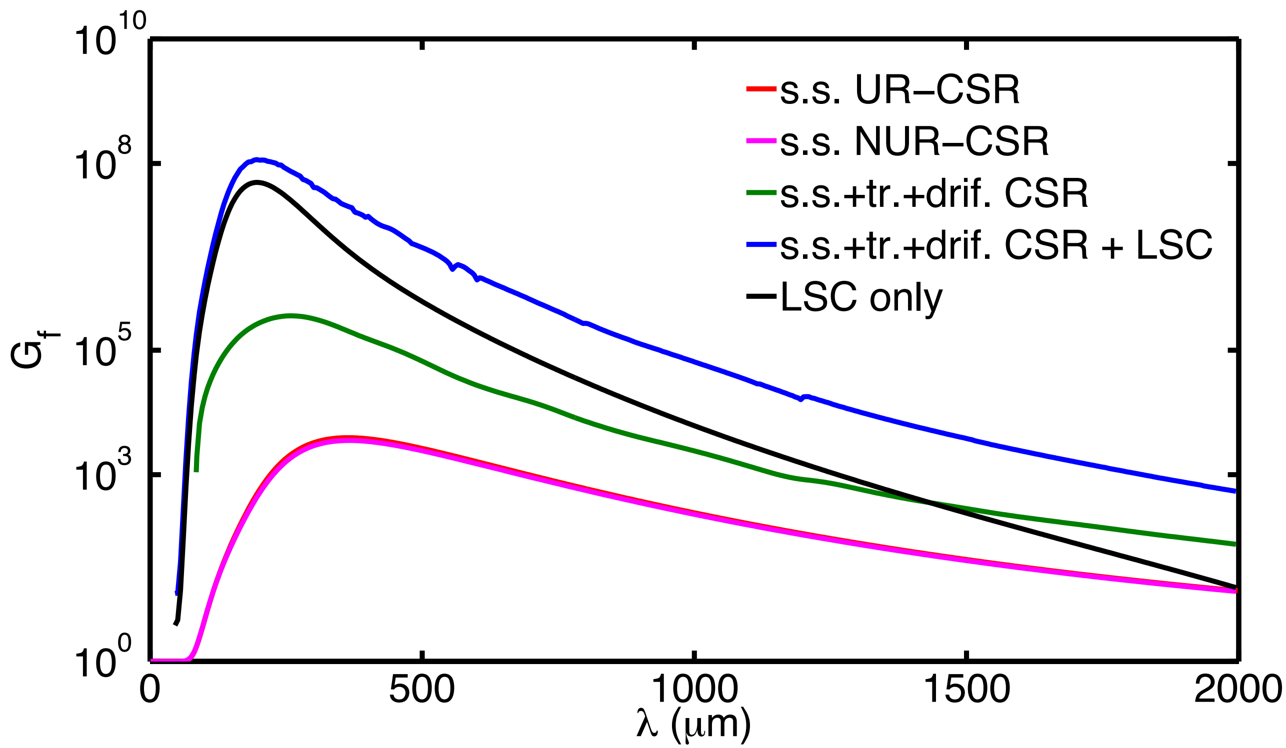


Name	Value	Unit
Beam energy	54	MeV
Beam current	60	A
Normalized emittances	3 (in both planes)	µm
Initial horizontal beta function	10.695	m
Initial vertical beta function	1.867	m
Initial alpha functions	0 (in both planes)	
Relative energy spread (uncorrelated)	1.0×10^{-4}	
Chirp	0	m^{-1}

<u>Note</u>: cooling solenoids have been removed in our simulation.

MEIC Design Report, 2012

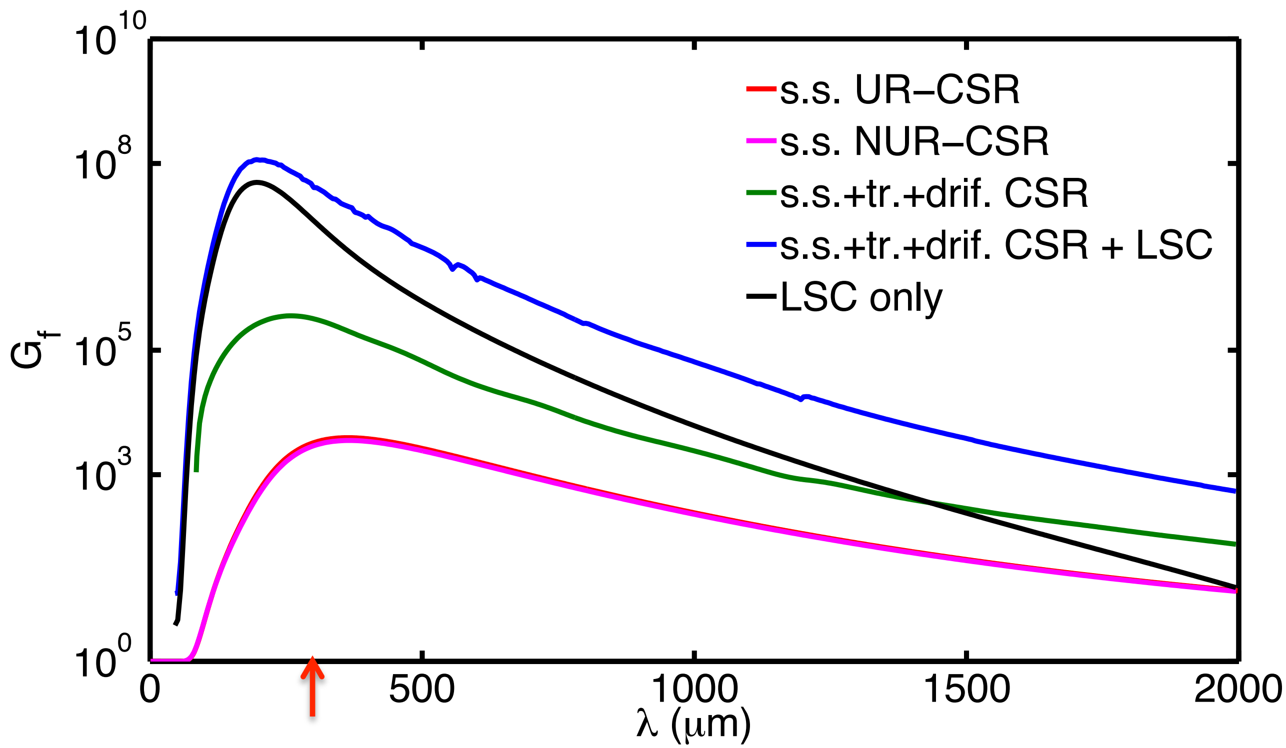
Application: MEIC Circulator Cooling Ring (CCR)



Note:

1. LSC effect can be more severe than CSR on microbunching instability.
2. LSC can be underestimated (because of clipping of solenoid sections).

Application: MEIC Circulator Cooling Ring (CCR)



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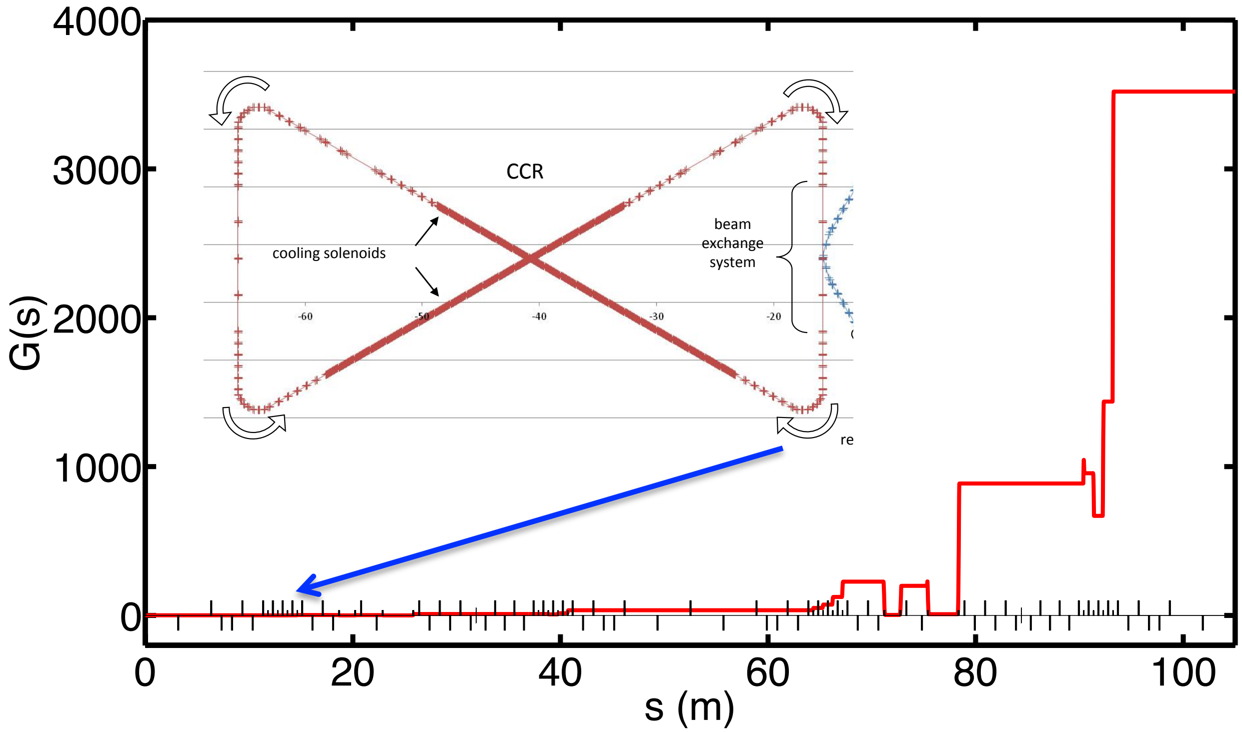
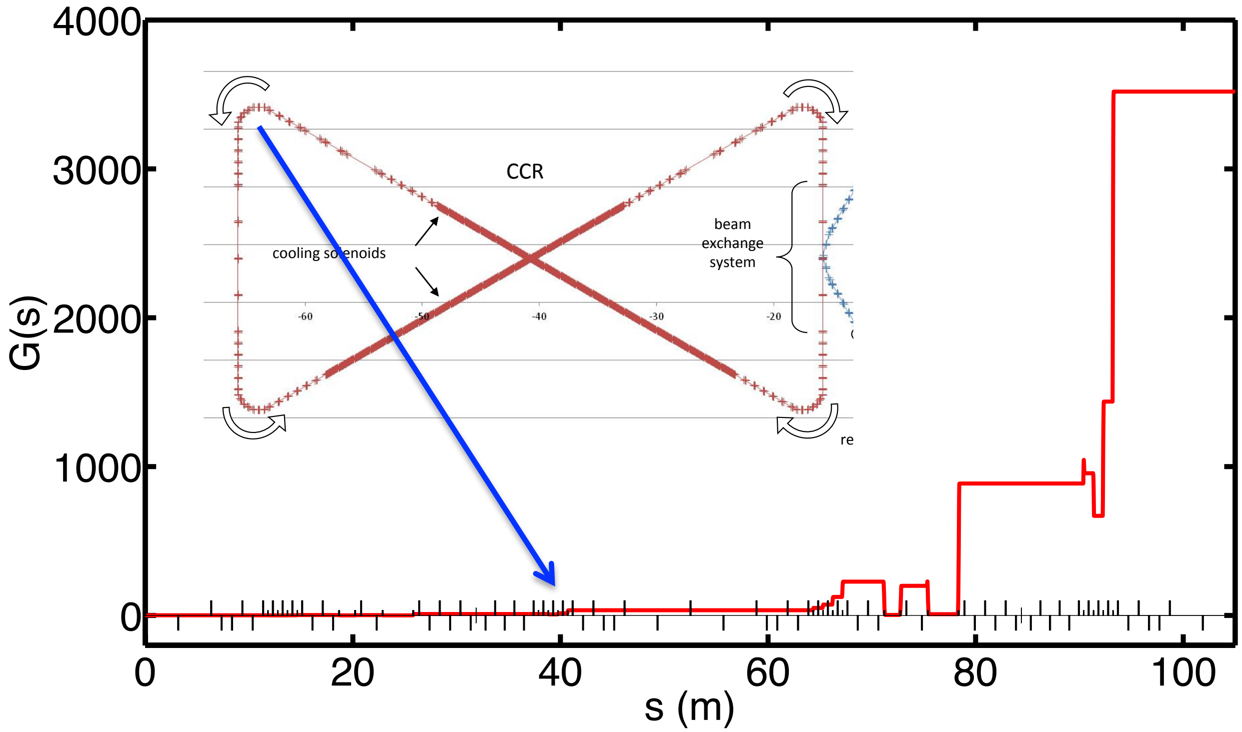


A specific example shows how a "resonant" wavelength (λ = 350 µm) causes microbunching amplification along CCR.

Application: MEIC Circulator Cooling Ring (CCR)



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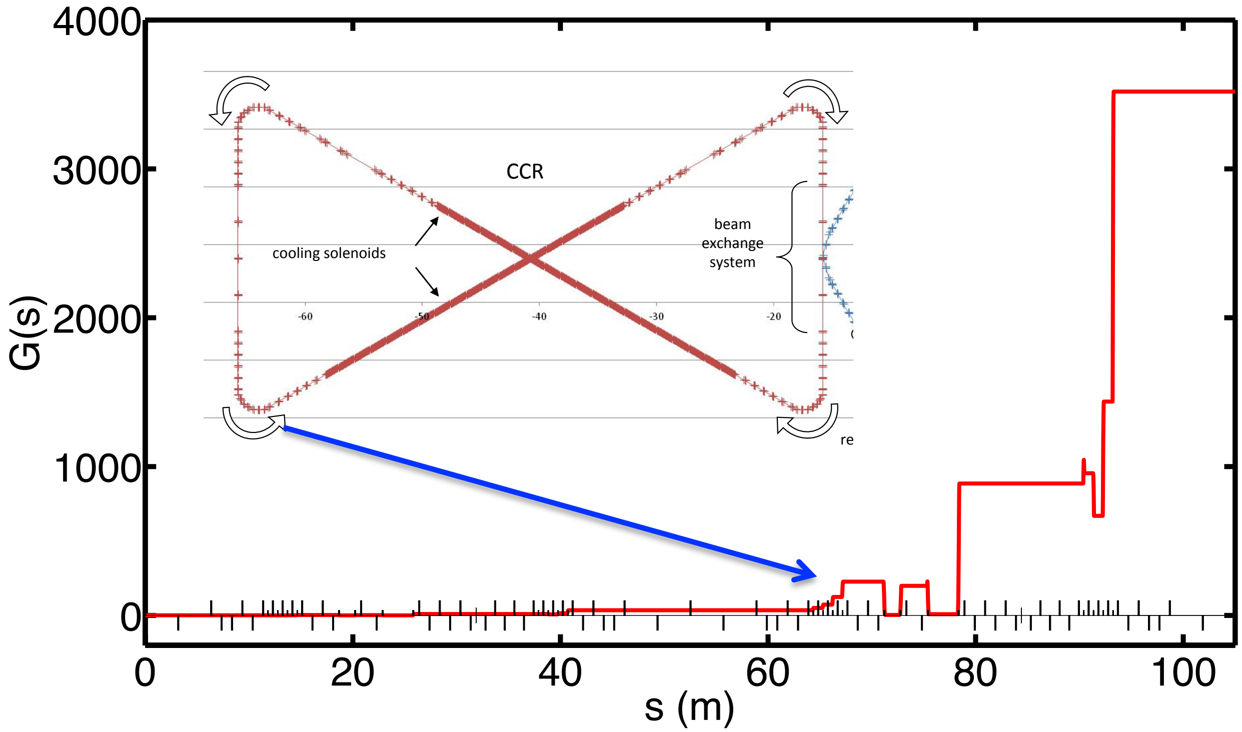

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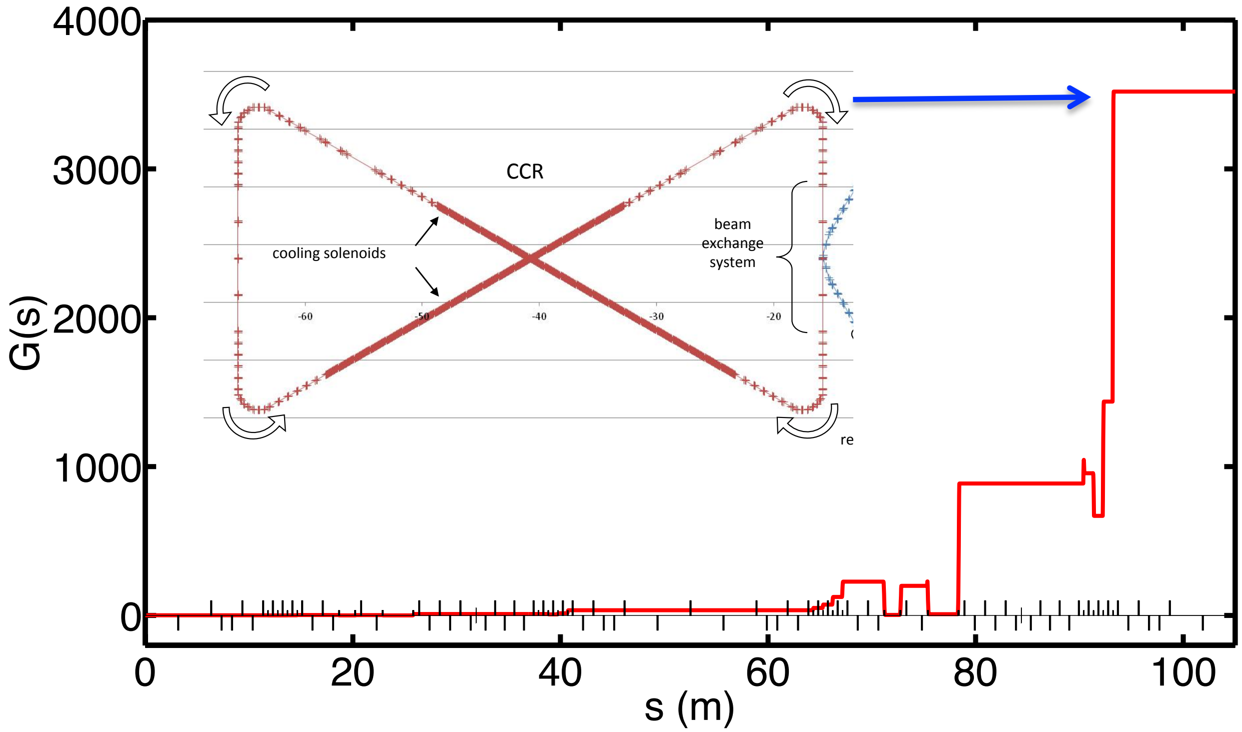
Application: MEIC Circulator Cooling Ring (CCR)



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Summary

- Microbunching instability can be a special concern for ERL or recirculation machines.
- **CSR** and **LSC** can cause severe microbunching instability (e.g. Example 1 and MEIC CCR).
- Impact of **lattice optics** can be significant for ERL-related lattice design (Example 1 vs. Example 2).
- **Quick** estimation of microbunching gain by our developed code.
- Example 2 demonstrates that it is possible to preserve emittance and also suppress microbunching gain at the same time.

Future work

- **Add** more relevant impedance models, including both analytical and numerical impedance models.
- **Extend** the existing (constant-energy) formulation to include a more general case, with beam **acceleration** or deceleration. This is particularly important in recirculation machines.
- Investigate the physical connection between a single-pass or few-pass system and storage-ring system (∞-pass).
- **Experimental** benchmarking of our microbunching studies [JLab LDRDs]

Thank you for your attention

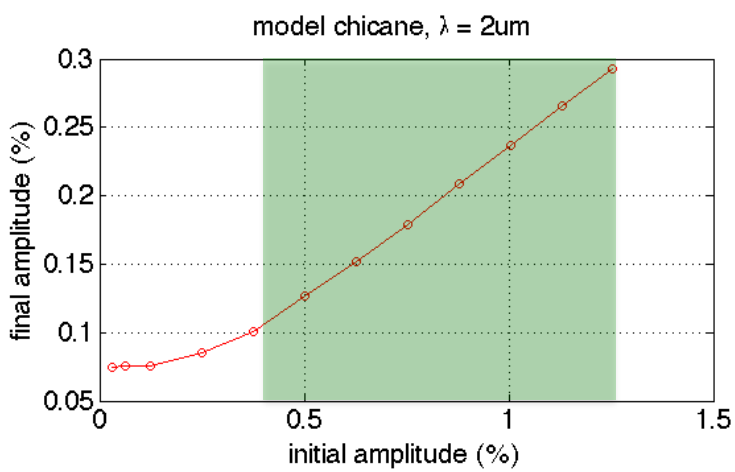
Acknowledgements

- Thanks to my advisors, co-authors for their kind support, insights, discussion and stimulation:
  - Rui Li and Mark Pitt (advisors)
  - Steve Benson, Dave Douglas, Chris Tennant
- Thanks to JSA Graduate Fellowship Program for travel support
- This material is based on work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177.

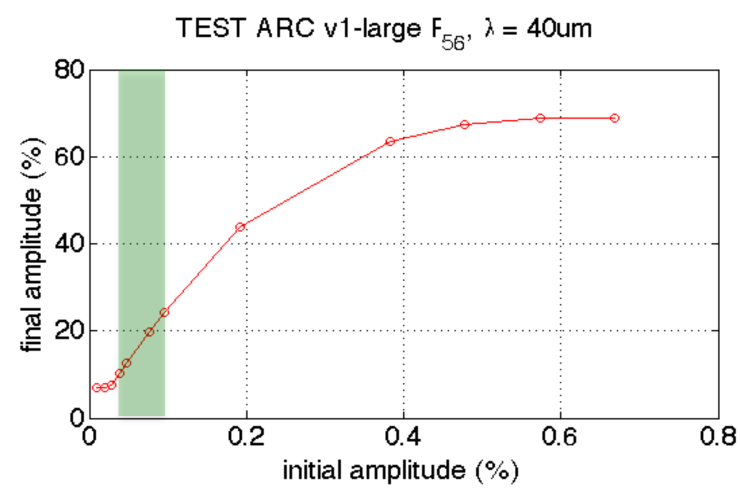
BACKUP SLIDES

Introduction and Motivation: Numerical challenges from particle tracking

- To investigate microbunching gain, we usually impose an initial density modulation, and study how such modulation evolves along the beamline.
- The level of modulation depth should be **small enough** to keep microbunching amplification in linear regime, while **large enough** to surpass (residual) numerical noise.
- For higher gain case, the number of simulation particles becomes more demanding, in order to avoid exaggerated (numerical) fluctuation between the (integration) bins at specific wavelength scale.



(relatively) low-gain case



(relatively) high-gain case

C. -Y. Tsai and R. Li, JLAB-TN-14-016

Introduction and Motivation: Numerical challenges from particle tracking

- It has been known that microbunching instability is **sensitive** to fluctuation/noise in beam phase space density.
- Even if several **specialized** algorithms had been developed to reduce the numerical noise (while to keep the level of physical noise) during particle beam transport subject to microbunching effect, tracking a bunch of several tens of millions of particles (or more) is indeed **time consuming**.
- Instead of doing particle tracking, we can formulate this problem using fluid model, i.e. **Vlasov** equation.
- In this presentation, we shall focus on **linear** regime in particular, i.e. linearized Vlasov equation.

Impedance models: CSR

- **Steady-state ultrarelativistic CSR impedance**: [J. Murphy et al., Part. Accel. 1997, Vol. 57, pp. 9-64]

$$Z_{CSR}^{ss,UR}\left(k(s);s\right)=\frac{-ik(s)^{1/3}A}{\left|\rho(s)\right|^{2/3}},\ k=\tfrac{2\pi}{\lambda}:\ \text{wave number},\ \rho:\ \text{bending radius}\quad A=3^{-1/3}\Gamma\left(\tfrac{2}{3}\right)\left(\sqrt{3}i-1\right)$$

- **Steady-state non-ultrarelativistic CSR impedance**: [R. Li and C. -Y. Tsai, IPAC'15 (MOPMN004)]

$$\mathrm{Re}\left[Z_{CSR}^{s.s.NUR}(k(s);s)\right]=\frac{-2\pi k(s)^{1/3}}{\left|\rho(s)\right|^{2/3}}\mathrm{Ai}'\left(\frac{\left(k(s)\left|\rho(s)\right|\right)^{2/3}}{\gamma^2}\right)+\frac{k(s)\pi}{\gamma^2}\left(\int_0^{(k(s)|\rho(s)|)^{2/3}/\gamma^2}\mathrm{Ai}(\varsigma)d\varsigma-\frac{1}{3}\right)$$

$$\mathrm{Im}[Z_{CSR}^{s.s.NUR}(k(s);s)]\simeq\frac{2\pi k(s)^{1/3}}{\left|\rho(s)\right|^{2/3}}\left\{\frac{1}{3}\mathrm{Bi}'(x)+\int_0^x\left[\mathrm{Ai}'(x)\mathrm{Bi}(t)-\mathrm{Ai}(t)\mathrm{Bi}'(x)\right]dt\right\},\ x=\frac{\left(k(s)\left|\rho(s)\right|\right)^{2/3}}{\gamma^2}$$

- **Entrance transient CSR impedance**: [D. Zhou, IPAC'12 (MOOBB03)]

$$Z_{CSR}^{ent}\left(k(s);s\right)=\frac{-4}{s^*}e^{-4i\mu(s)}+\frac{4}{3s^*}\left(i\mu(s)\right)^{1/3}\Gamma\left(\frac{-1}{3},i\mu(s)\right)\qquad \begin{aligned}\mu(s)&=k(s)z_L(s)\\ z_L&=\left(s^*\right)^3/24\rho^2\end{aligned}$$

s^* is the longitudinal coordinate measured from dipole entrance

- **Exit transient CSR impedance**:

$$Z_{CSR}^{exit}\left(k(s);s\right)=\frac{-4}{L_b+2s^*}e^{\frac{-ik(s)L_b^2}{6|\rho(s)|^2}\left(L_b+3s^*\right)}$$

s^* is the longitudinal coordinate measured from dipole exit

$$Z_{CSR}^{drif}(k(s);s)\approx\begin{cases}\frac{2}{s^*},\ \text{if}\ \rho^{2/3}\lambda^{1/3}\le s^*\le\lambda\gamma^2/2\pi\\ \frac{2k(s)}{\gamma^2},\ \text{if}\ s^*\ge\lambda\gamma^2/2\pi\\ 0,\ \text{if}\ s^*<\rho^{2/3}\lambda^{1/3}\end{cases}$$

R. Bosch et al., PRST-AB **10**, 050701 (2007)

Impedance models: LSC

- M. Venturini, PRST-AB **11**, 034401 (2008)
- **On-axis LSC model**:

$$Z_{LSC}^{on-axis}(k(s);s)=\frac{4i}{\gamma r_b(s)}\frac{1-\xi K_1(\xi)}{\xi},\ \xi=\frac{k(s)r_b(s)}{\gamma}$$

- **Average LSC model**:

$$Z_{LSC}^{ave}(k(s);s)=\frac{4i}{\gamma r_b(s)}\frac{1-2I_1(\xi)K_1(\xi)}{\xi},\ \xi=\frac{k(s)r_b(s)}{\gamma}$$

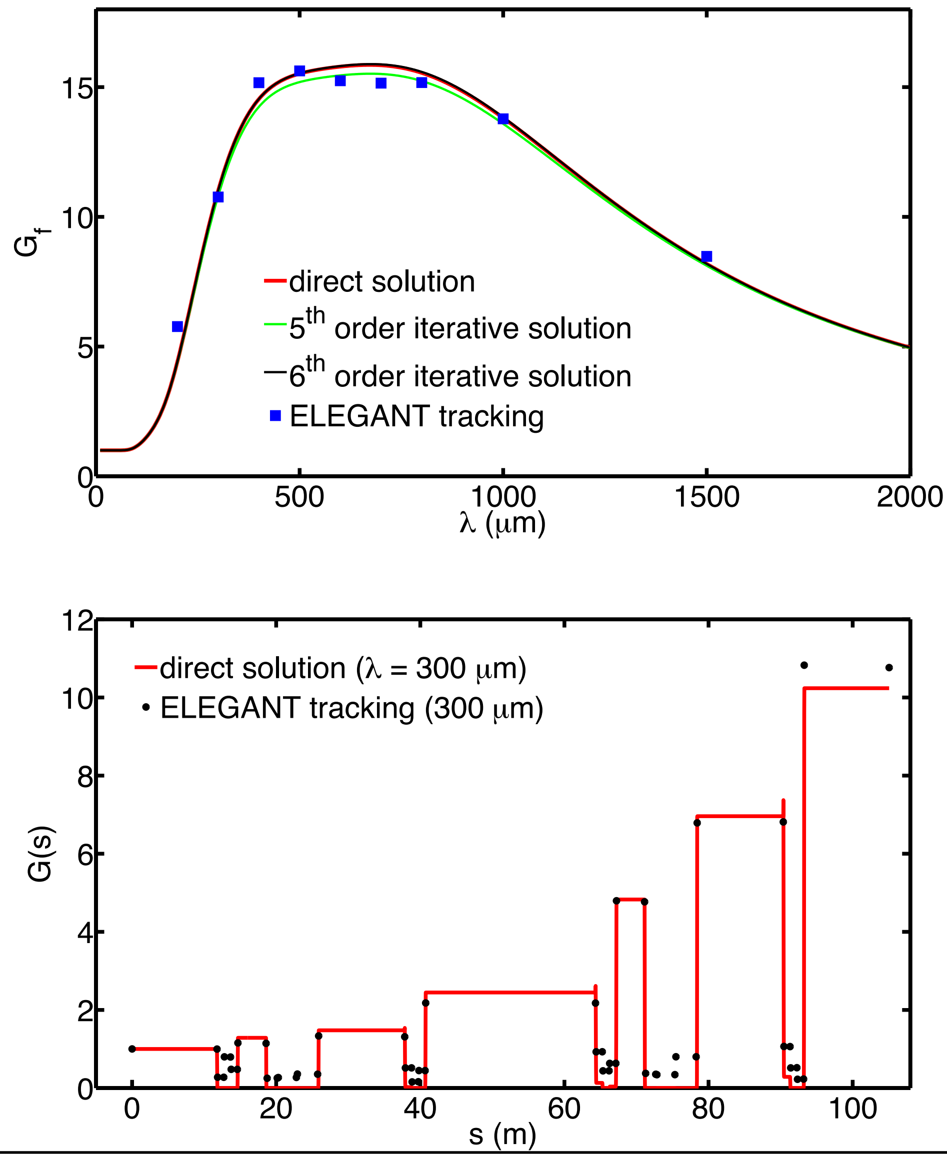
- **Transverse axisymmetric LSC model**:

$$Z_{LSC}^{ave.Gaussian}(k)=-i\frac{\xi_\sigma}{\sigma\gamma}e^{\xi_\sigma^2/2}\mathrm{Ei}\left(\frac{-\xi_\sigma^2}{2}\right),\xi_\sigma=\frac{k(s)\sigma}{\gamma}$$

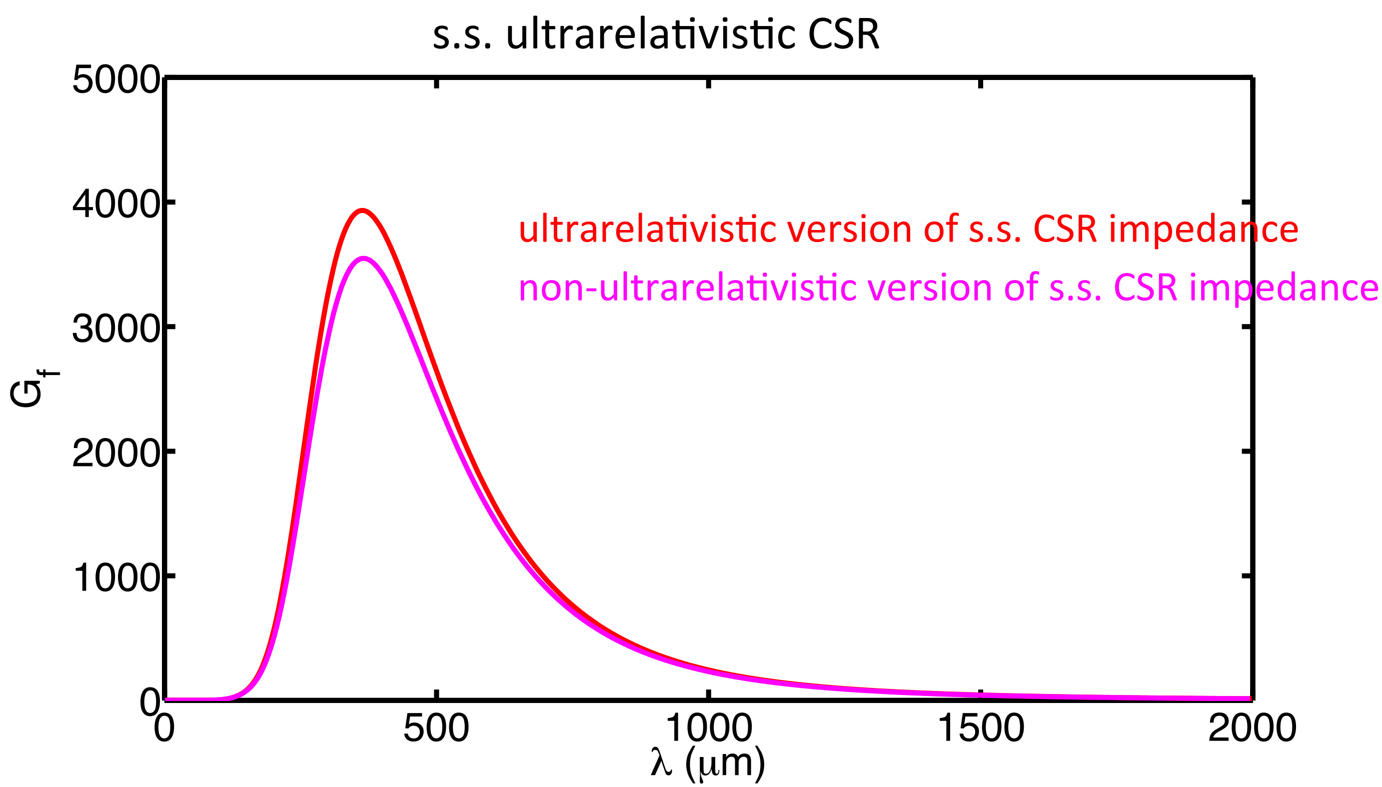
- These LSC models are implemented in our code by adopting transverse rms beam sizes σ_x and σ_y from ELEGANT and applying weighted average over them:

$$r_b(s)=\tfrac{1.747}{2}\left(\sigma_x(s)+\sigma_y(s)\right)$$

Microbunching gains for MEIC CCR with 10x emittance

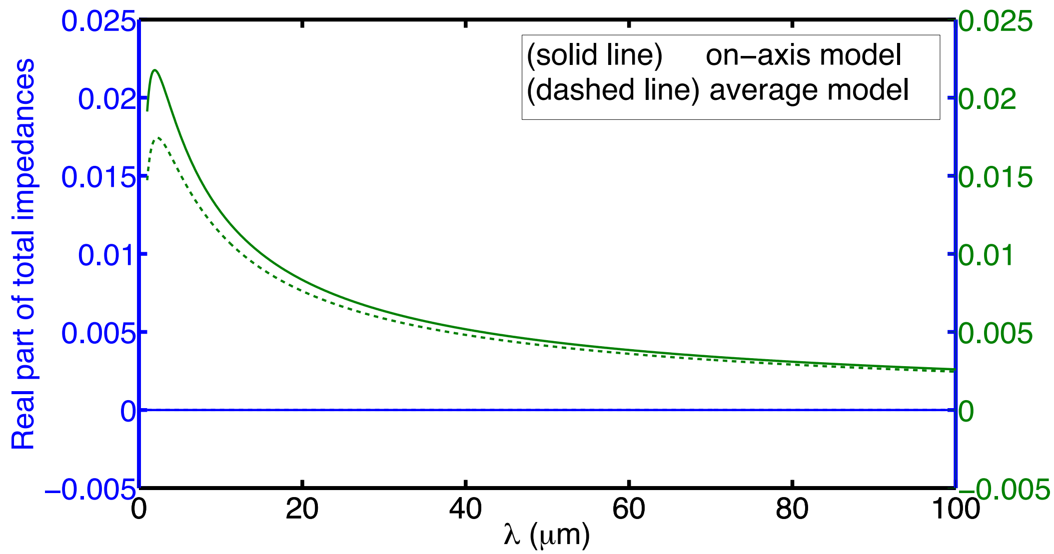


Application: MEIC Circulator Cooling Ring (CCR)



Impedance comparisons

LSC
(on-axis vs. ave.)



CSR
NUR vs. UR