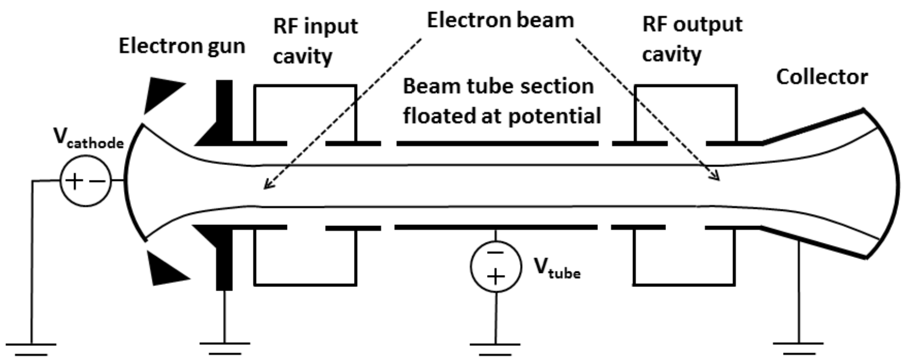
High-Efficiency Klystron with Post Acceleration Progress Report

Q4 FY19

In this quarter, we wrapped up the simulations performed by our University of Michigan student, Anna Cooleybeck. We completed the first systematic parametric study for the nonlinear space-charge bunching addressing Task 2 (“Analysis”) deliverables and uncovered some underlying critical phenomena that may limit this approach and will certainly change our analysis focus in FY20. The goals of this study are to:

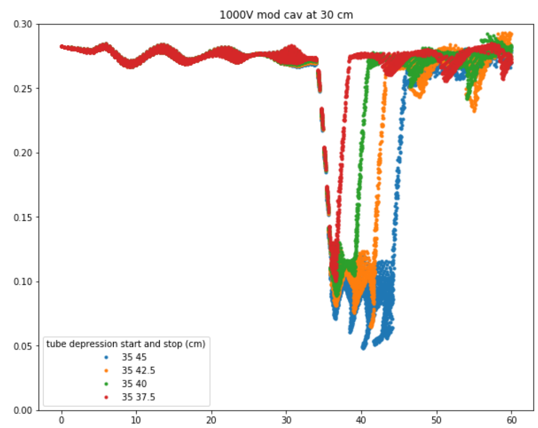
- Identify the threshold conditions for the nonlinear bunching shown in the proposal (using a single modulation cavity)
- Understand characteristics of the nonlinear bunching (using a single modulation cavity)
- Optimize the nonlinear bunching with multiple modulation cavities
- Quantify the beam’s energy spread after post acceleration

For the simulations described below, we are using the exact geometry shown in the proposal, reproduced below.

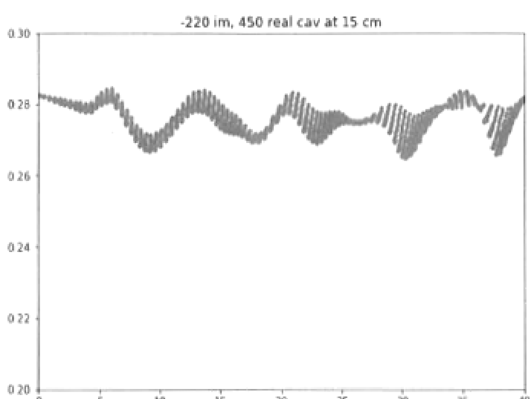


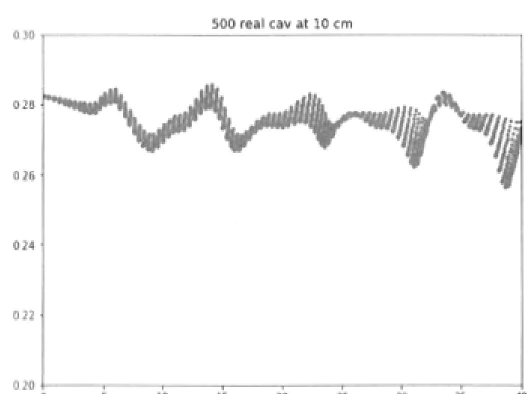
We are using the 2.5D FDTD PIC code TUBE to study the harmonic current as a function of axial position due to modulation in an initial cavity (called the RF input cavity in the figure above). We are also looking at plots of the electron’s relativistic axial momentum as a function of axial position to provide insights into the bunching phenomena. We are not including an RF output cavity yet (or, alternatively, we can consider one that is highly detuned and not disturbing the beam).

Importantly, for this study we used the nominal JLEIC klystron parameters (20 kV, 6 A, 956.2 MHz). Our focus in Q3 was observing the harmonic current evolution in this systematic study and found that the evolution did not correspond with our theoretical predictions. In Q4, we studied the nature of the bunching close to the space-charge limit (about 15 kV for our parameters) to understand why we’re not getting the expected enhanced harmonic current growth. The plot below shows the development of current spikes as a function of the length of the depression. As expected, the bunching at the start of the depressed section does depend on the space-charge in front of it. We have identified the curling over of the harmonic current in the energy-phase diagram (the right-most blue spike below) as the cause limiting the enhanced harmonic current.



As a first try of controlling the form of the energy depression and the energy-phase correlation, we added a second harmonic cavity close to the initial modulation cavity and before the depressed section of the klystron. While, ideally, a ramped energy-phase correlation can be established, which can help compress the bunch, our idea was to use the second harmonic cavity to precondition the beam to control the folding over the spike as it forms (the curvature arises because the particles with lower energy have lower velocity and can't keep up with the more energetic electrons in the spike; preconditioning the beam would imply advancing these electrons in axial distance before the bunch compression occurs). The longitudinal phase space plots below show two different "ramps" generated by the inclusion of the second harmonic cavity, to illustrate the type of control it provides over the beam. The ramp is centered at about 15 cm in the left plot, with later electrons having higher energies (the depressed section of the transport has been removed for clarity). The ramp is centered at about 12 cm in the right plot with the opposite energy-phase correlation.





While we have shown that we can use this knob to change the energy-phase correlation, a large energy spread at a given axial location remains which limits ability to induce the higher non-linear bunching. Interestingly the energy spread formed in the simulations we did for the proposal with a 10-kV, 1-A beam was not large enough to impede the nonlinear bunching as in this case. The change in microperveance, from 1.0 for the beam in the proposal to 2.1 for the EIC klystron beam is enough to generate an unacceptable amount of particle overtaking and energy spread.

This provides us a clear direction for Q1 FY20 work – we will back off the effect of the beam perveance (by one of multiple approaches) in order to reduce the offending energy spread. While not ideal, this is realistic as the conventional approach to higher efficiency klystrons is to reduce the perveance by using multi-beams and then to use some technique like the core oscillation method (COM), bunching alignment collecting (BAC), or core stabilization method (CSM) to increase the efficiency. Our new approach will mimic that, but we will continue to have the extra degree of freedom provided by the depressing the tube voltage which should lead to improved efficiency. Our metric will be to exceed the accepted formula for fractional klystron efficiency which is 0.82-0.2*μPerv given by Carter. Specifically, in Q1 FY20 we will match our klystron parameters to a proposed multi-beam klystron for the EIC by Yale University and Omega-P R&D, where each of six beamlets has 14 kV at 0.9 A (μPerv of 0.54) and the overall klystron has a simulated efficiency of about 72% (in good agreement with Carter's formula above).