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Test of a BAC Klystron

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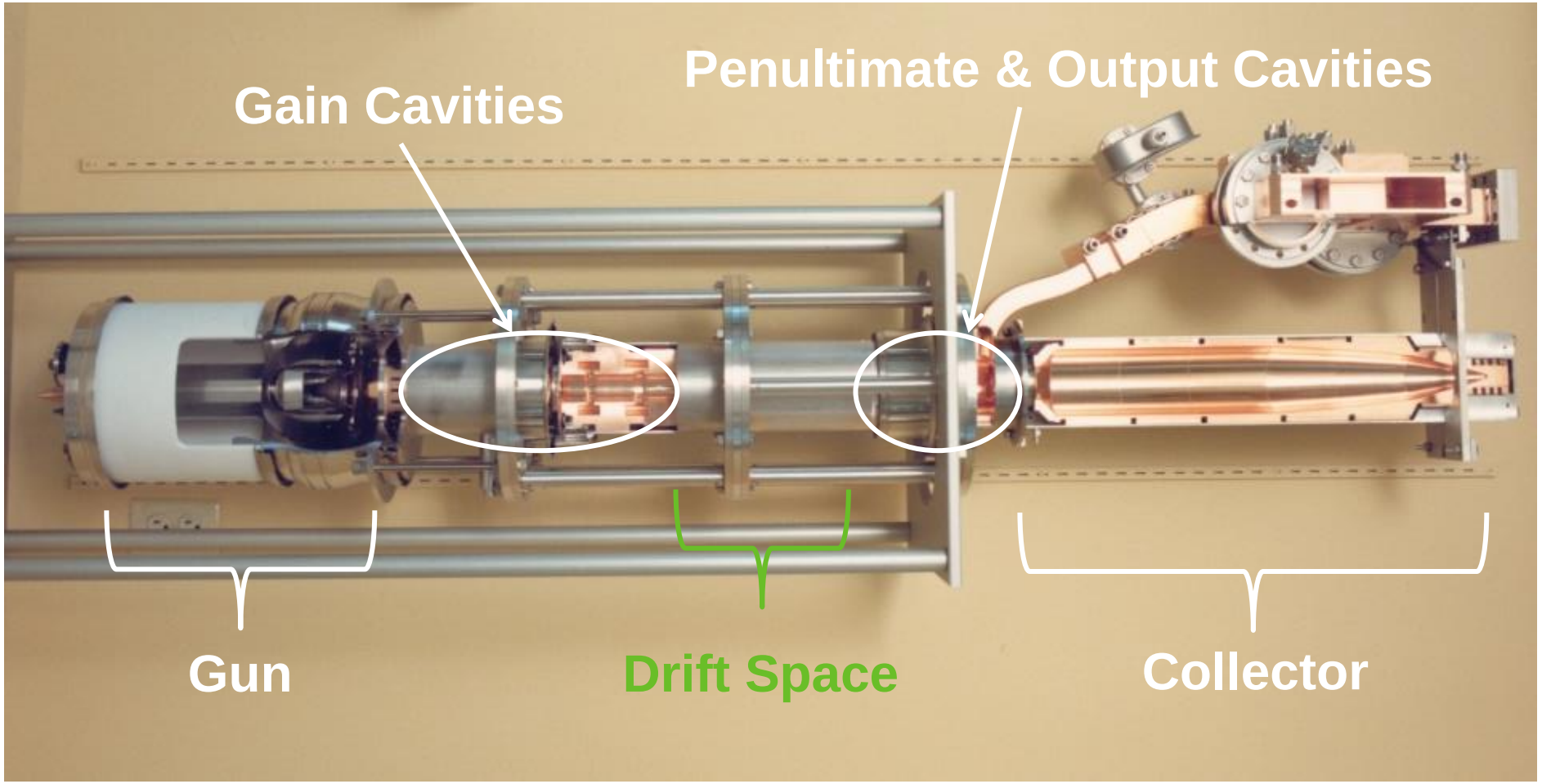
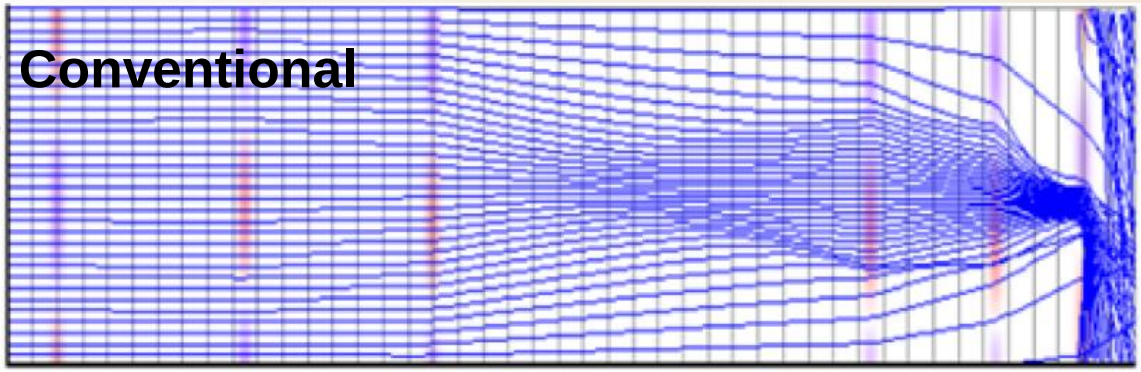
Background – SLAC 5045

- **The 5045 klystron is used in the SLAC linac**
  - ~250 in the accelerator
  - Frequency: 2.856 GHz
  - RF Power: 65 MW peak, 45 kW avg.
  - Nominal efficiency: 45%
  - Beam tunnel radius: 1.59 cm
    - γa= 0.70
  - Over 800 klystrons produced since 1983
  - More than 30 million operating hours
- **Ongoing effort at SLAC to increase energy efficiency of RF sources and accelerators**
  - Reduced cost per kWh
  - Sustainability

Existing 5045 Klystron (65MW peak power)

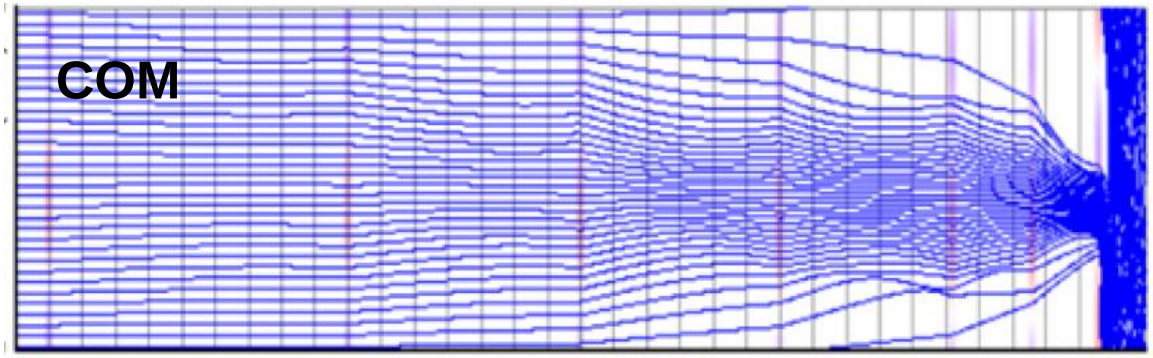


High Efficiency Klystron Design



Preliminary cavities are tuned conventionally for gain

One or more “penultimate” cavities are tuned high to squeeze the bunch

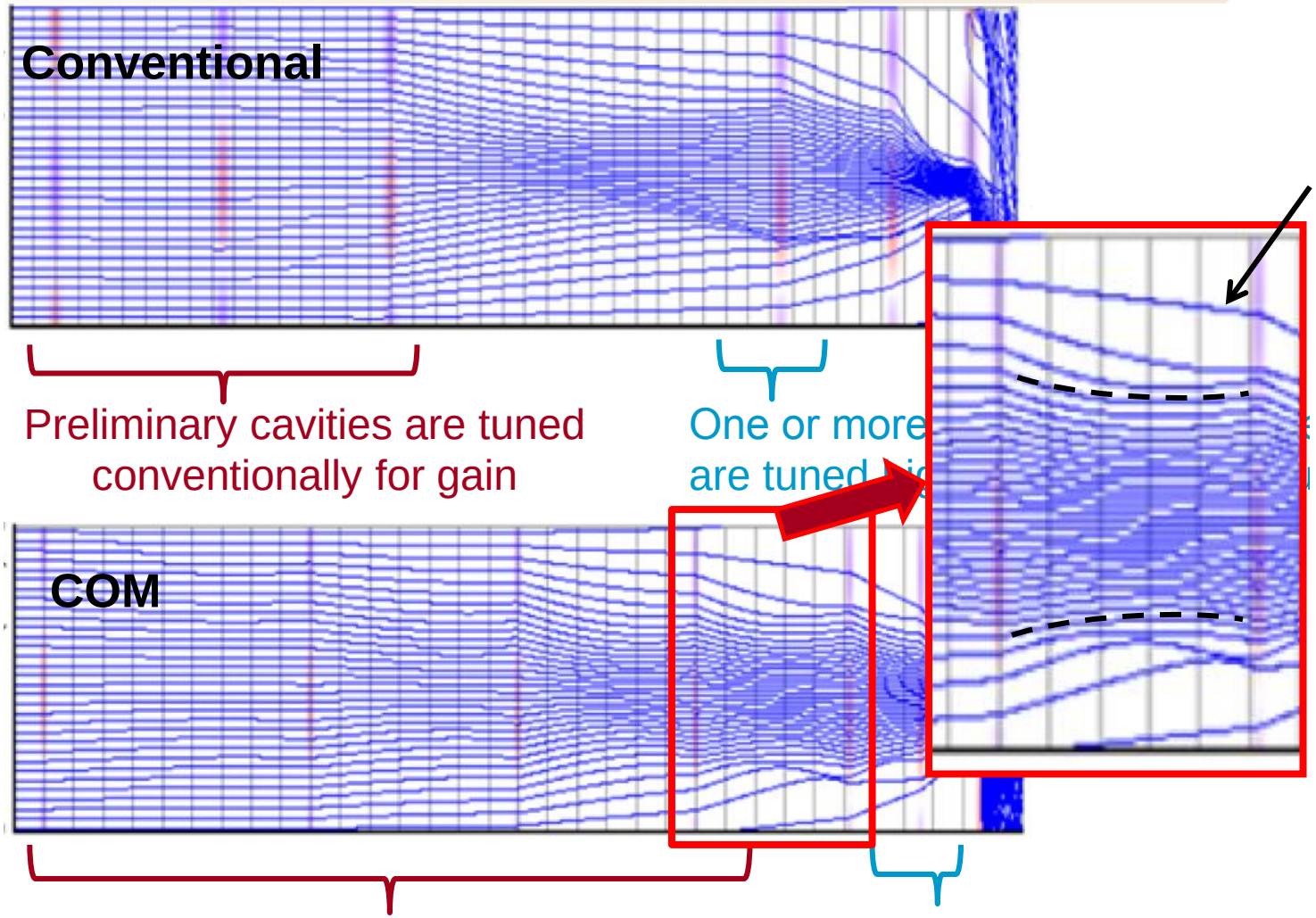


Most of the circuit sweeps electrons at the wrong phase into the right phase

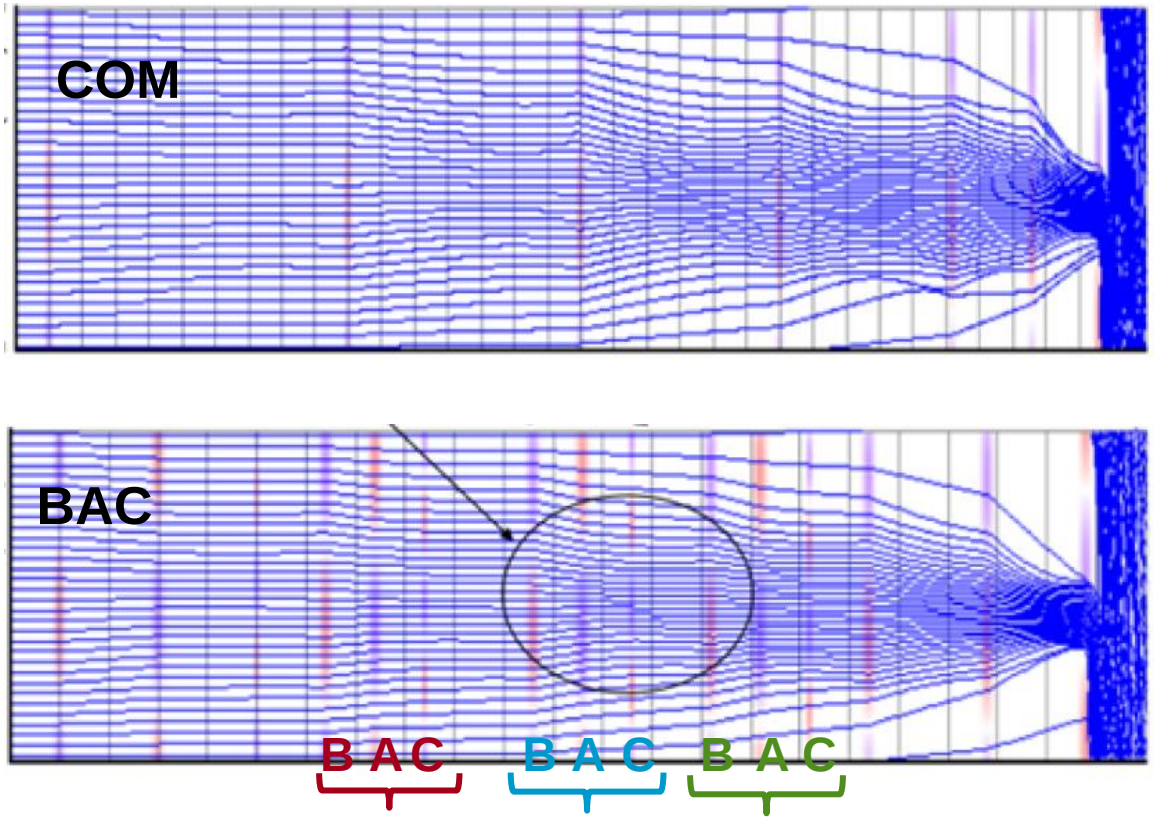
Only once most of the electrons are at the right phase is the bunch compressed

I. Syratchev
I. Guzilov
A. Baikov

High Efficiency Klystron Philosophy

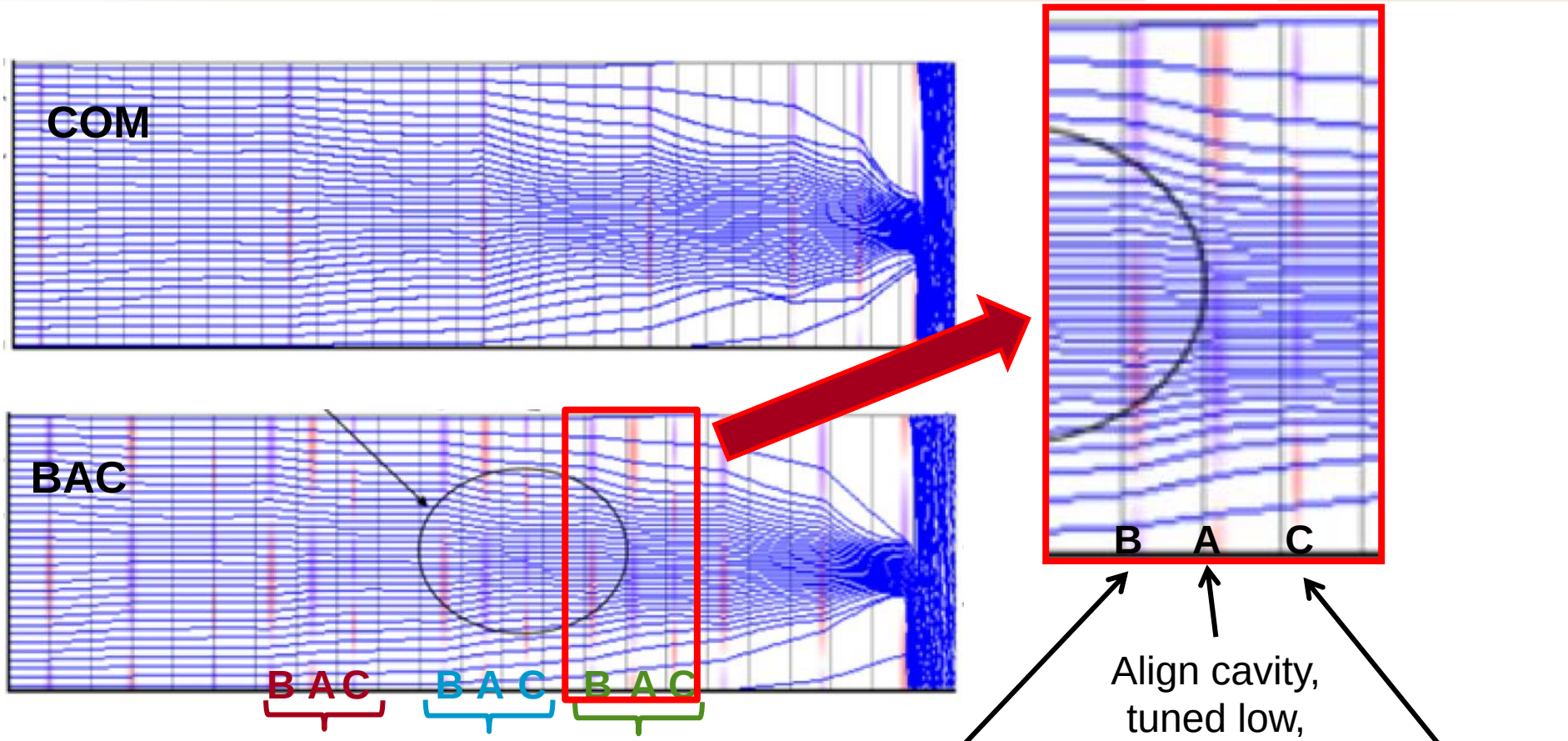


The Bunch Align Collect Method



In the BAC (bunch-align-collect), the same effect is achieved by BAC triplets

The Bunch Align Collect Method



In the BAC (bunch-align-collect), the same effect is achieved by BAC triplets

Bunch cavity kicks all electrons toward center

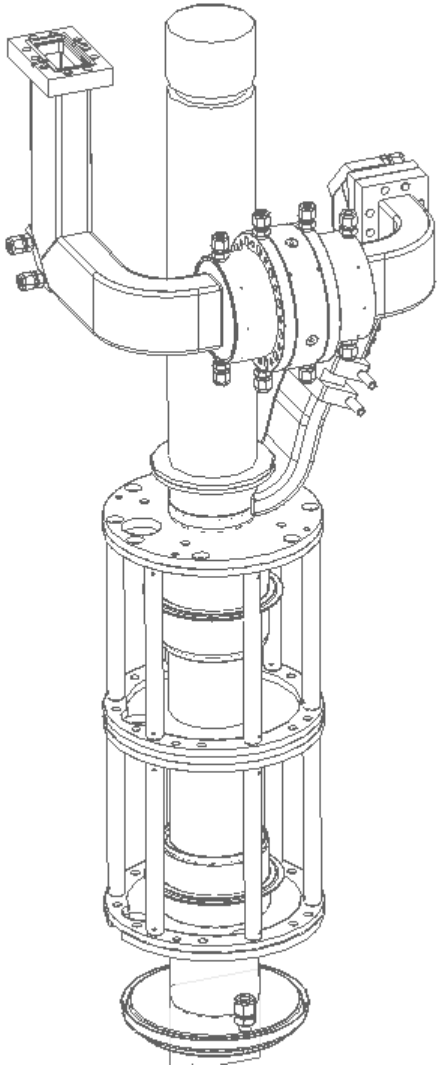
Align cavity, tuned low, defocuses center

Collect cavity, at second harmonic, primarily affects the peripherals

Overall Goals

- A form, fit, function replacement for the 5045 with higher efficiency
- Fit into existing solenoid

Standard 5045



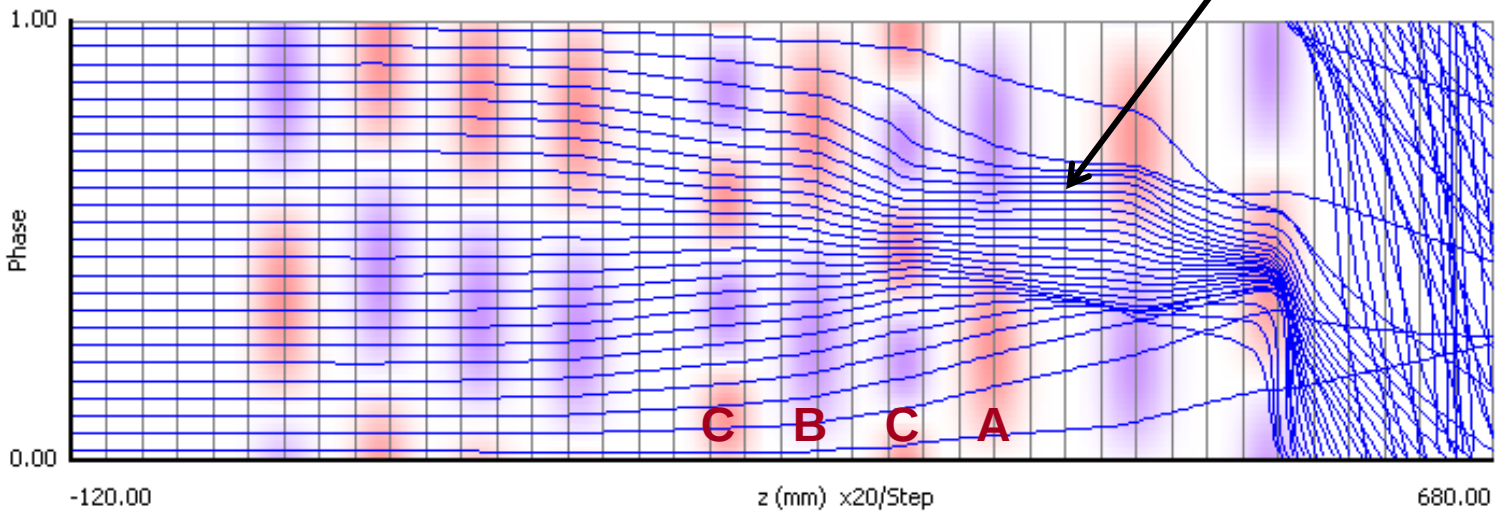
BAC 5045

5045 BAC Approach

- Targets: 80 MW peak output power; 55% efficiency
- New design utilizes BAC (Bunch Align Collect) method

Input and three gain cavities remain nearly unchanged, to simplify retrofit

Core remains fixed size, periphery electrons drawn in

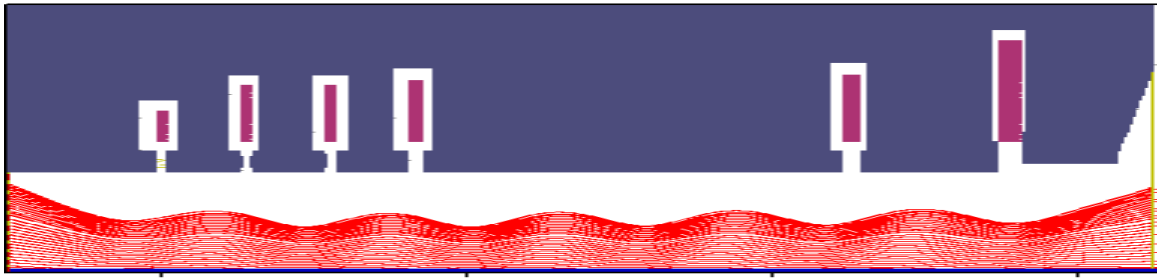


Modified form of the BAC method used to bunch beam

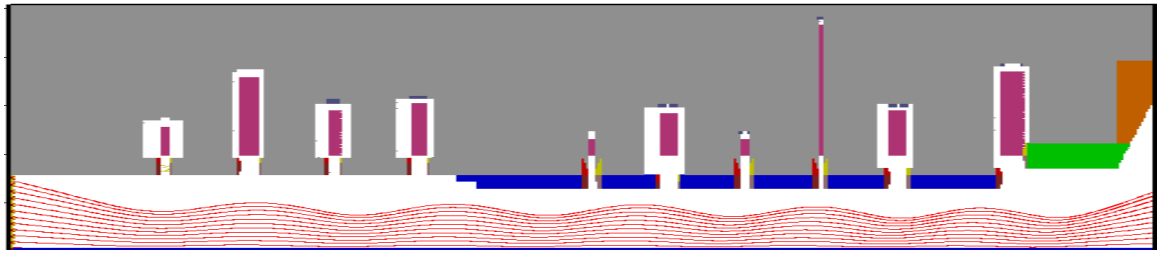
Two Dimensional Simulations

- MAGIC2D used for large signal simulations

Standard 5045

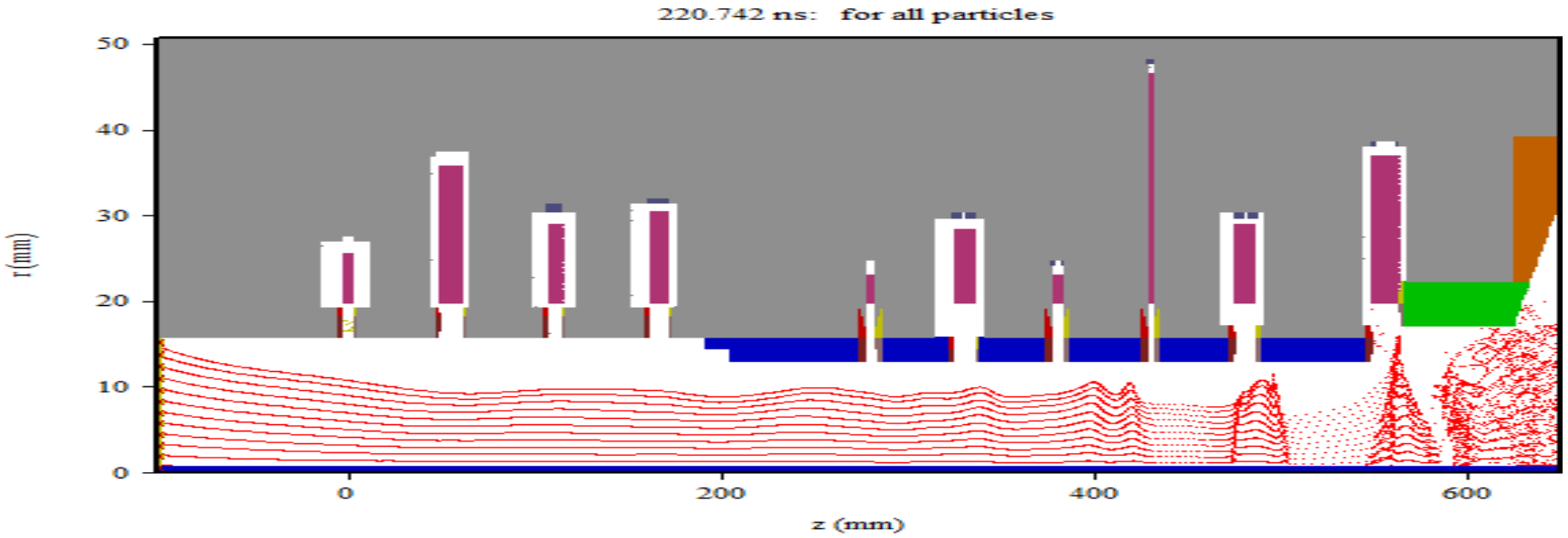


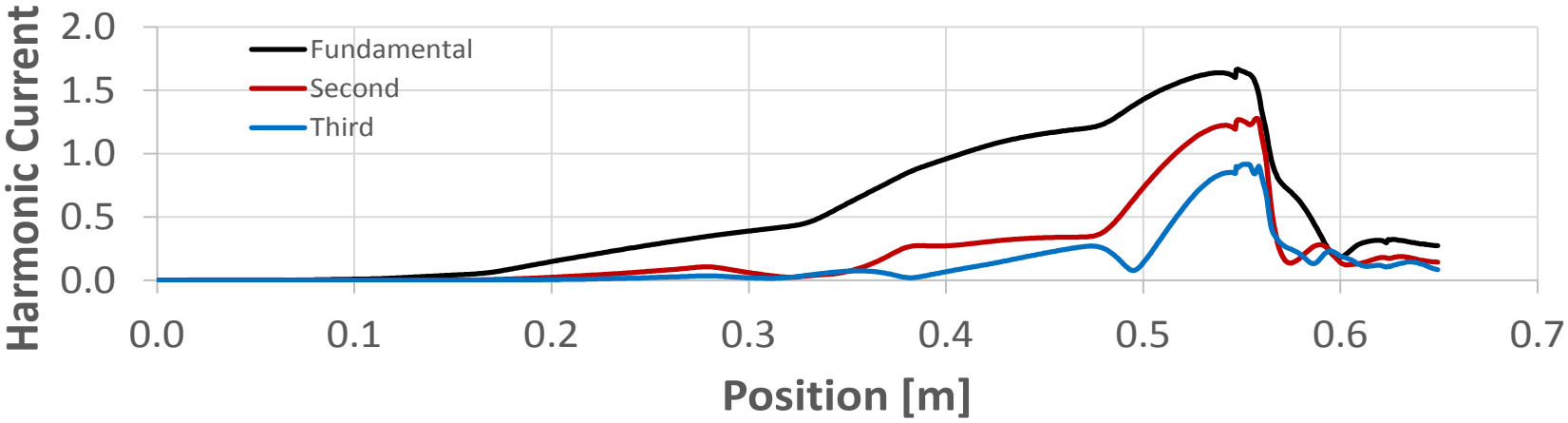
BAC 5045



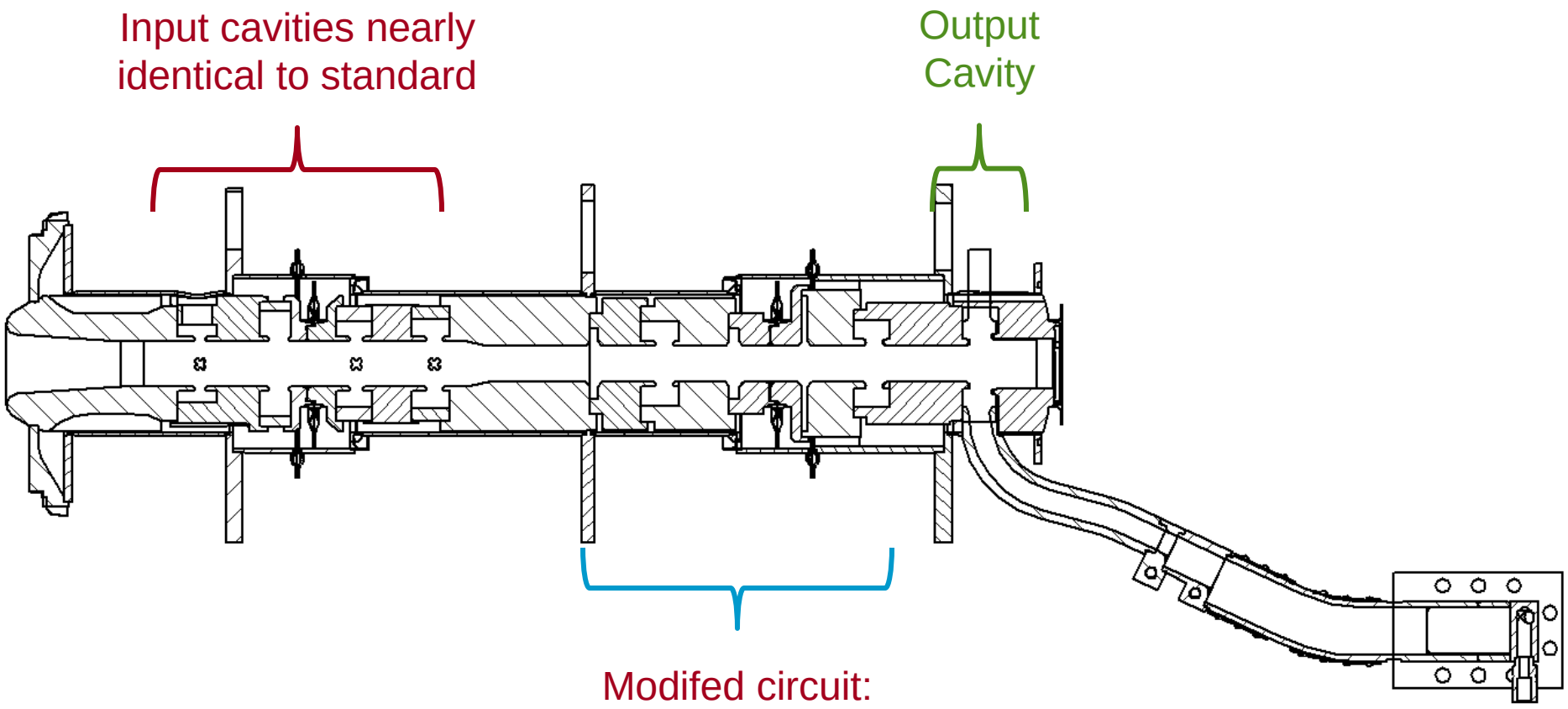
- Drift tube diameter reduced in output section so that drift tube is cut off to second harmonic
  - Reduced beam tunnel radius = 1.31 cm ($\gamma a = 0.57$)

BAC Simulations



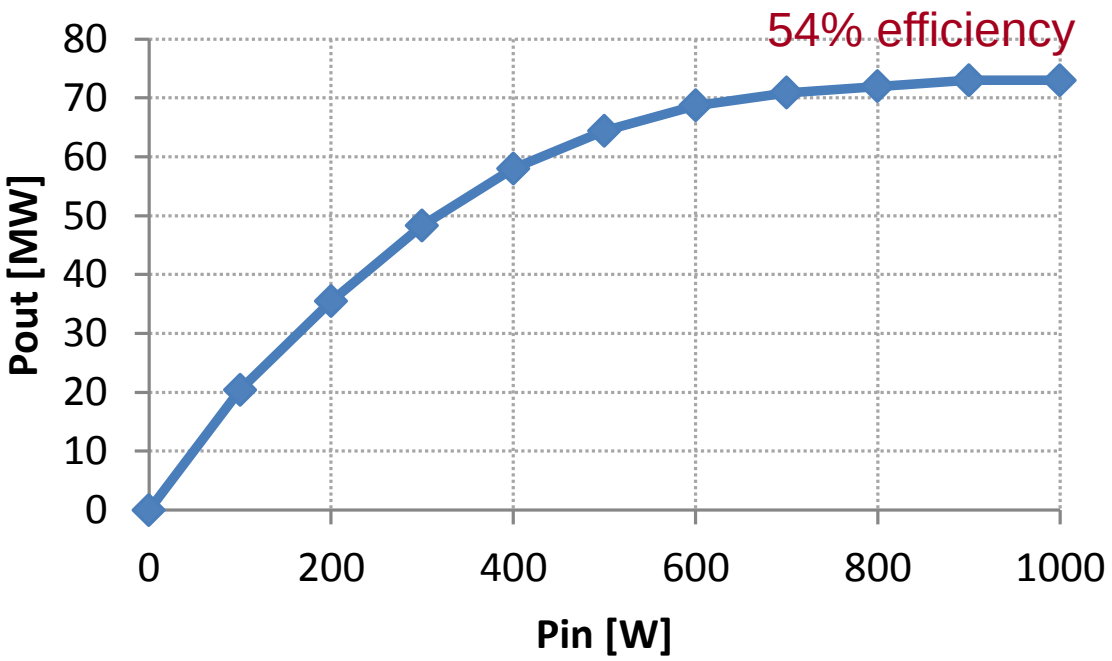


Circuit Assembly



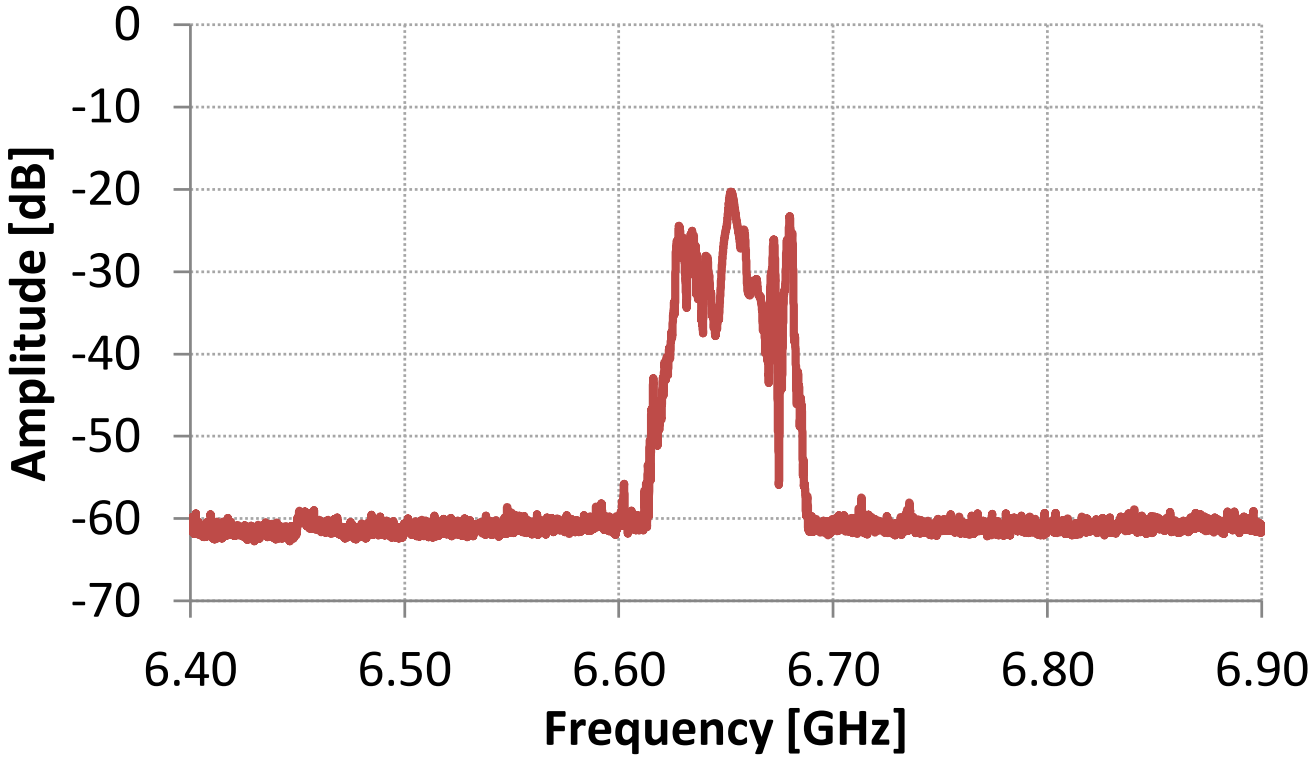
Test Data

- Pulse length limited to 100 ns to prevent oscillation
- Peak output power of 72 MW, for efficiency of 54%
  - Solenoid settings were optimized for stability, not efficiency (standard 5045 is 45% efficient)



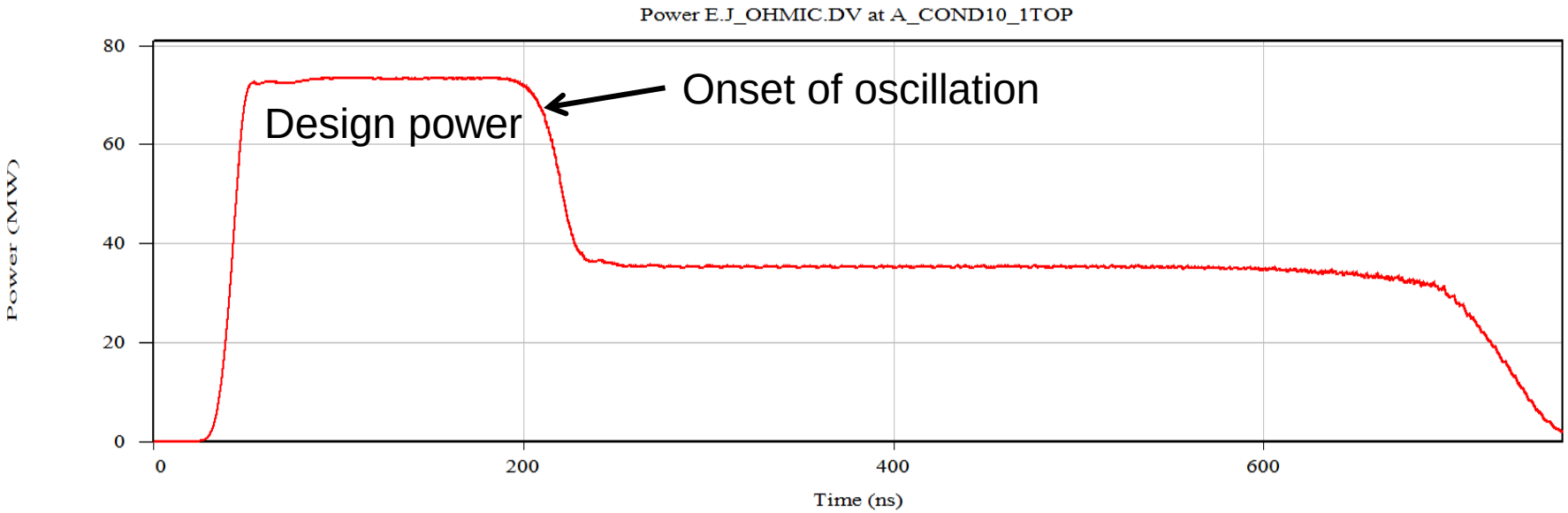
Oscillations

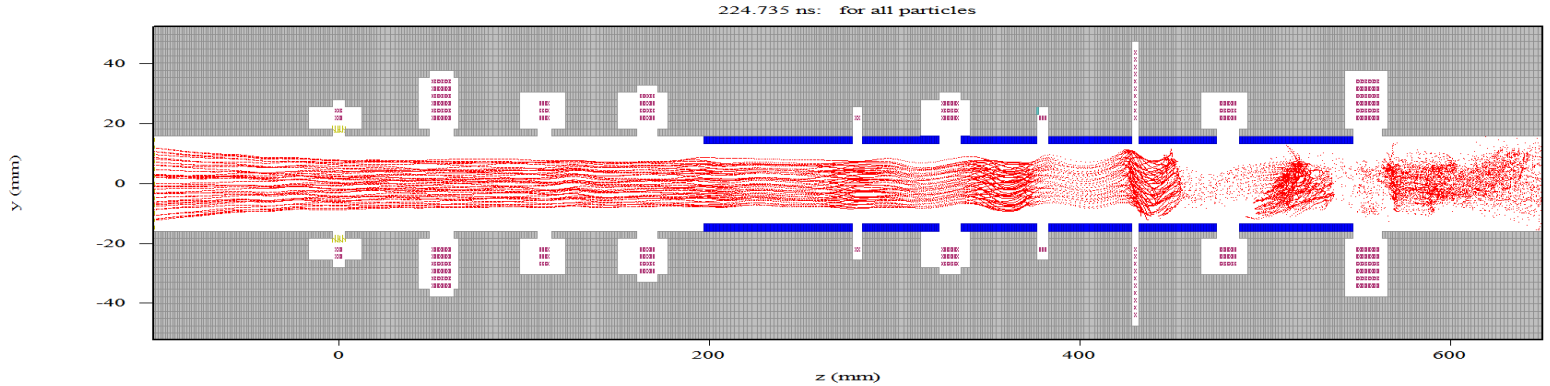
- Oscillation measured in output waveguide at 6.65 GHz



Oscillations

- MAGIC simulations run to longer time show oscillations

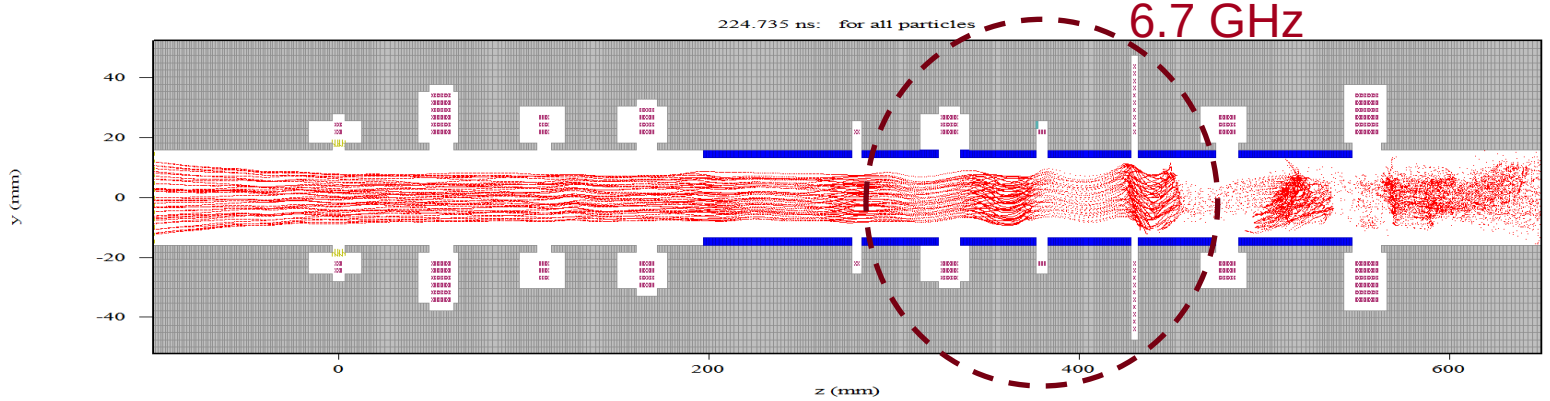




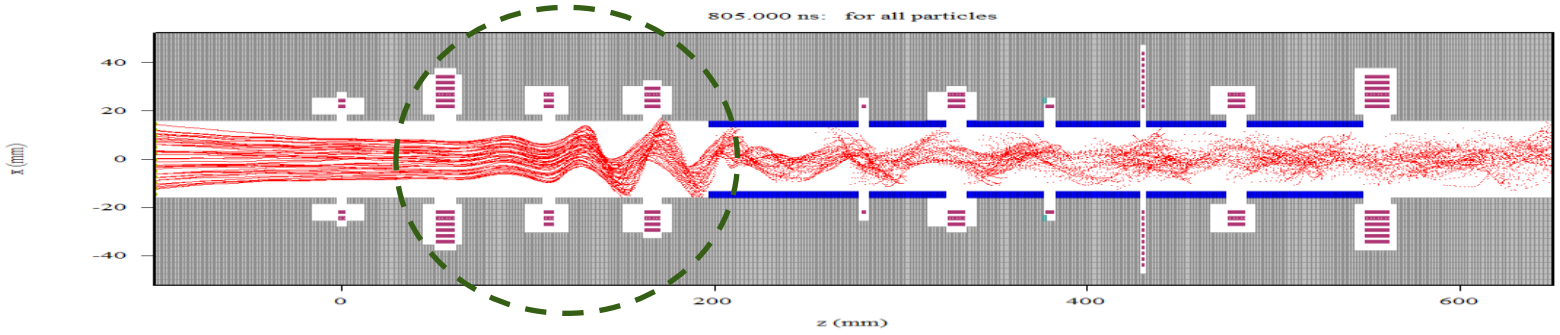
Oscillations

- MAGIC simulations showed that there are two potential oscillations:

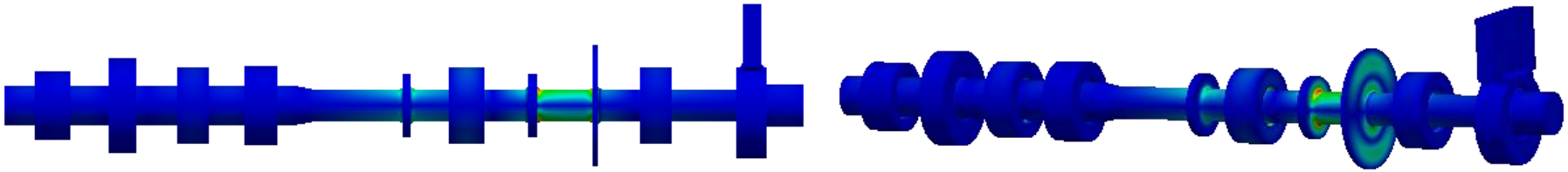
  - Cavities 6, 7, 8 oscillate at 6.7 GHz



  - Cavities 2, 3, 4 oscillate at 4.2 GHz



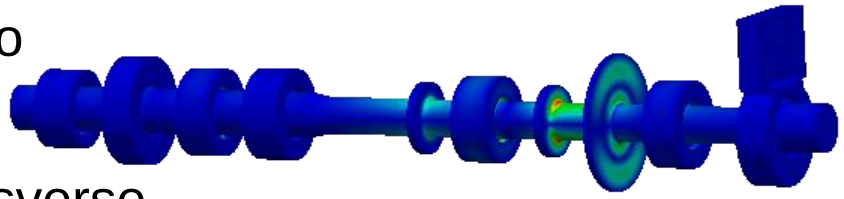
Oscillation Prediction

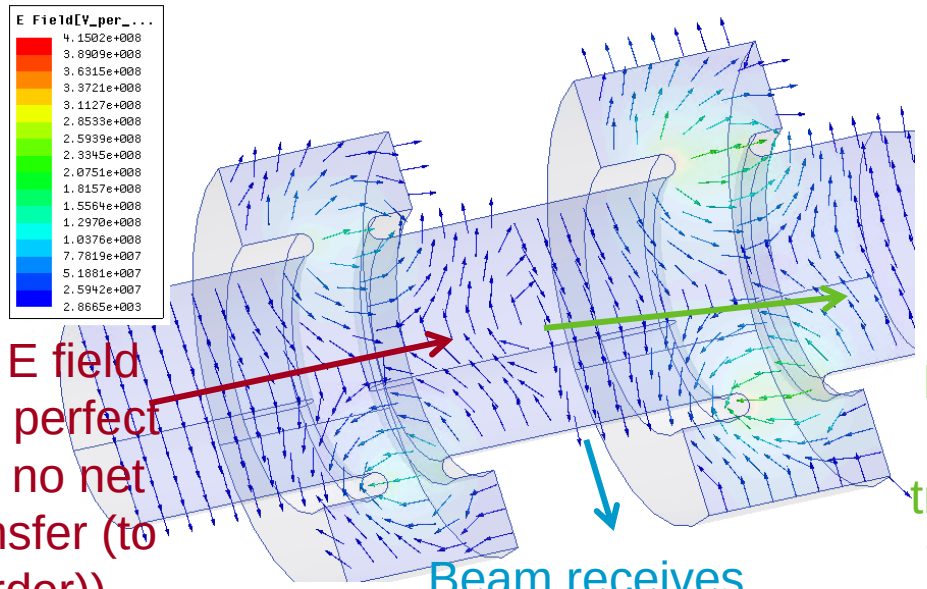


- Would like a standard method to find oscillation before building klystrons
- Initial plan:
  - Use ACE3P, the SLAC parallel electromagnetic code suite
  - Solve all cold modes in the circuit structure
  - Push particles through each mode, observe energy balance to determine if mode is stable

6.7 GHz Oscillation

- Drift tube is not cut off at this frequency, so individual cavities couple together
- Mode trapped between cavities, with transverse field in tunnel, axial field on gaps





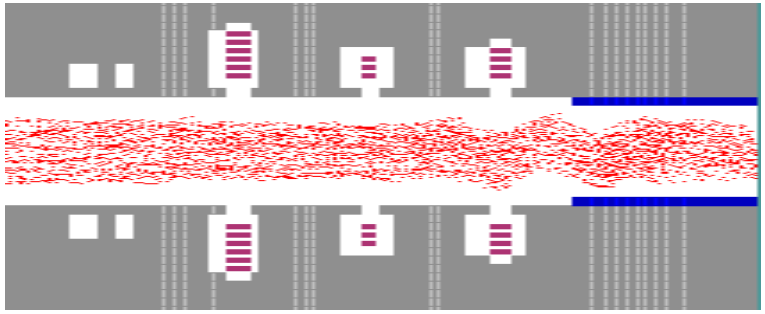
Zero axial E field on axis (for perfect alignment, no net energy transfer (to zeroth order))

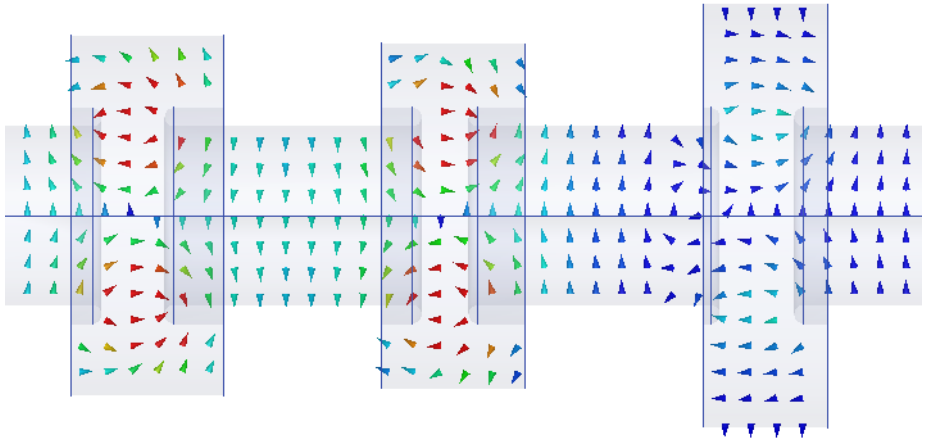
Beam receives transverse kick

If phasing is right, off axis beam transfers energy to the mode, driving the oscillation

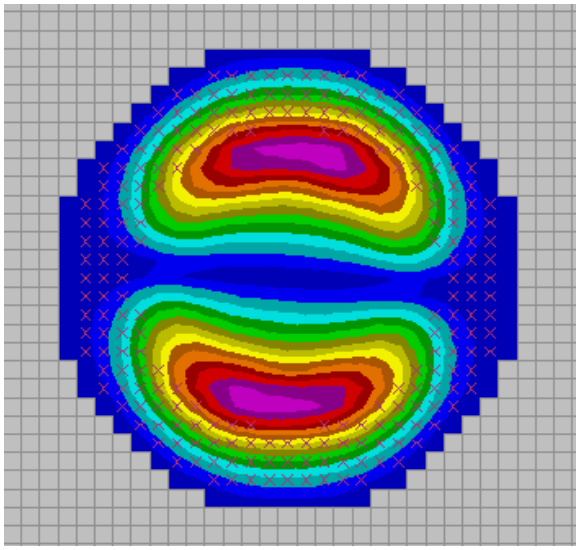
This is similar to a conventional monotron oscillation, and can readily be found by analyzing for net energy gain or loss

4.2 GHz Oscillation: Introduction



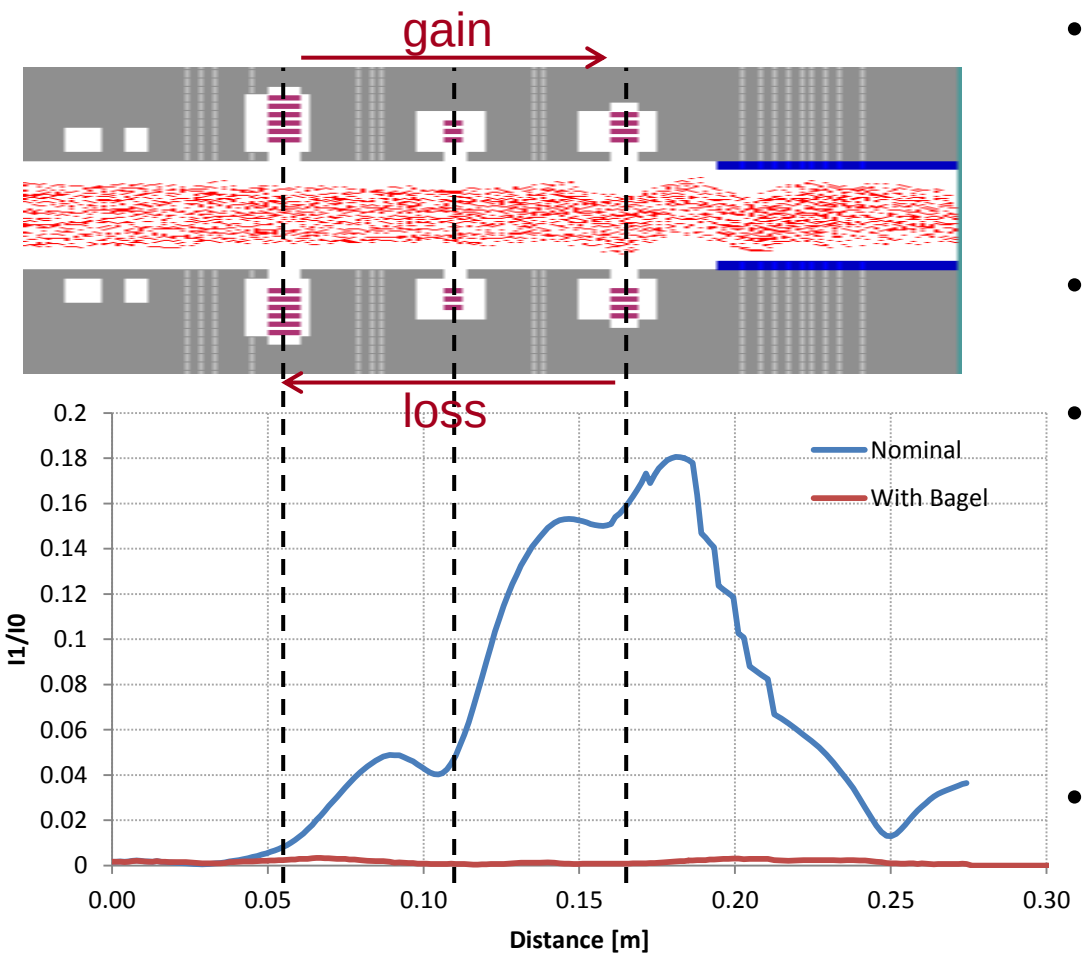


- Driven by TM11 modes in cavities
- Unlike previous example, drift tube is cut off, although barely
  - Cutoff frequency is 4.4 GHz
- Cavities still couple through cut-off drift tube, forming a 3-cavity mode
- BUT, mode is stable to the ACE3P analysis



4.2 GHz Oscillation: Explanation

- Measure of harmonic current (measured spatially) shows gain due to the self-excitation of the 4.2 GHz mode



- Drift tube is cut off, but barely, so provides feedback path, with loss due to exponential decay
- If loop gain exceeds 1, system will be unstable
- This type of oscillation relies on forward gain, thus the assumption of a single "mode" with constant amplitude, as in a monotron type oscillation, is not valid
- Large signal klystron analysis required to predict

4.2 GHz Oscillation: Explanation

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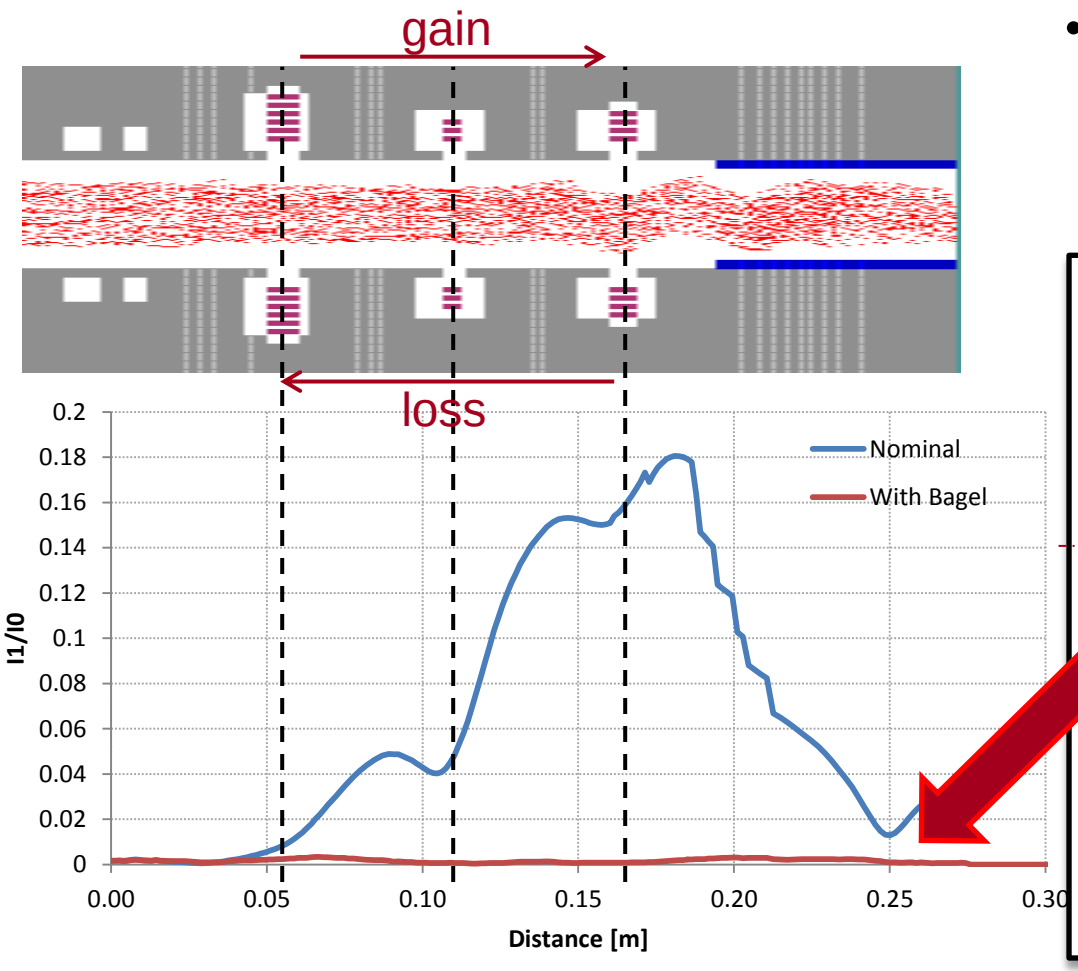

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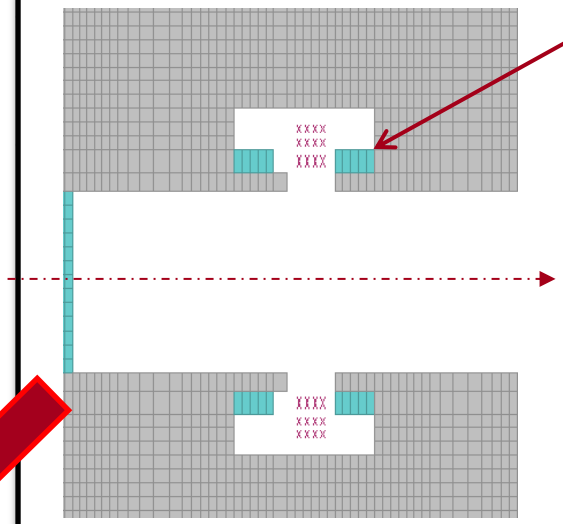
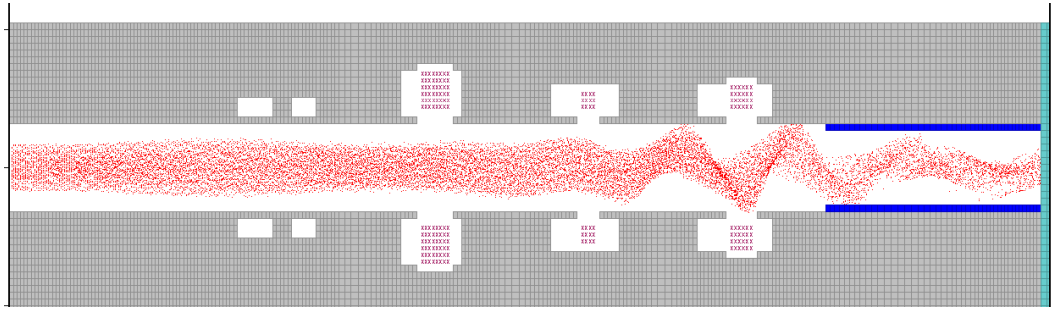
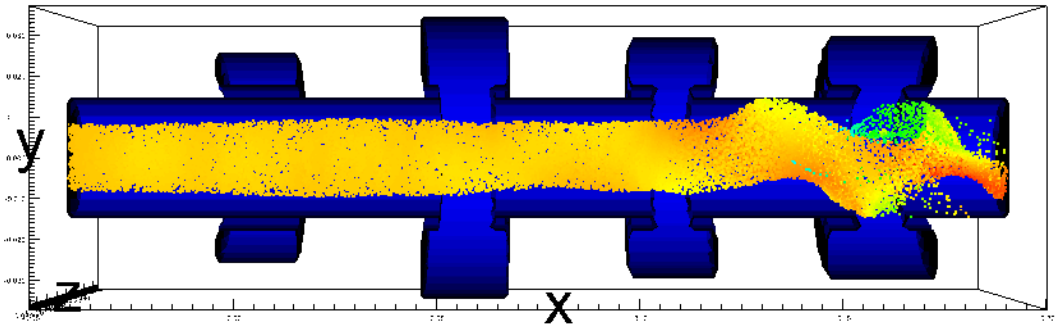


Ring added to tune the TM11, not the TM01, kills gain and oscillation

Oscillation Prediction

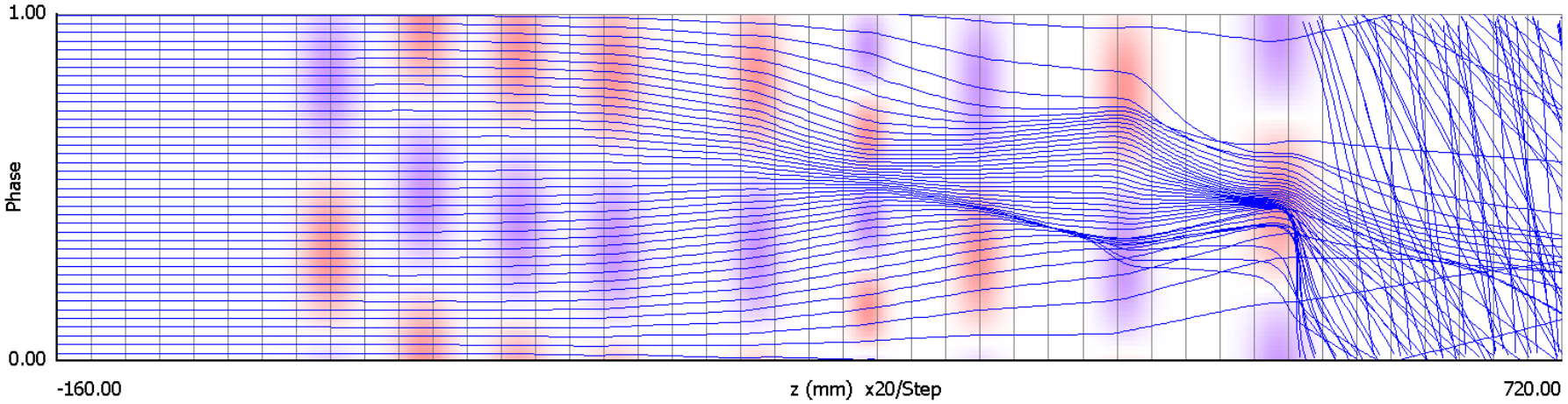
- Need to perform 3D PIC simulation to be sure of stability
- Compared Vsim and MAGIC in a model of the first four cavities
- Both predict the 4.2 GHz oscillation
- On a single core, both run at similar speed
- Vsim designed to be parallel
- A Vsim test with up to 128 cores will be performed soon, to assess scaling





Next Design

- **A next iteration of the BAC 5045 is being designed**
- **Number of cavities have been reduced to 9 from 10**
  - Increased spacing between cavities reduces likelihood of multicavity oscillation
  - Further cavity adjustments with bagels if oscillations seen in MAGIC
- **Circuit topology:**
  - Cavities 1-4 and 9 (output) same as previous version
  - Cavities 5-8: Bunch, Collect, Align, Bunch
- **Similar performance as first design seen in 1D: 81 MW, 56%**



Future Steps

- Finish translation of new 1D design to 2D MAGIC and tweak design for maximum efficiency
  - Address effects of radial beam distribution on efficiency, if possible
- Screen for oscillations using particle push method and MAGIC3D
- Finalize mechanical design of new cavities
- Retrofit previously built tube with new BAC cavities
- Begin testing of second iteration

Conclusions

- BAC method used to improve efficiency of SLAC 5045 klystron
  - Test results confirm that efficiency increases by ten percentage points
  - Oscillation prevented running at design pulse length
- Approach developed to predict oscillation before fabrication
- Second prototype underway to achieve the same efficiency and eliminate oscillations