High Efficiency Klystrons Using the COM Bunching Technique

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On behalf of HEIKA (High Efficiency International Klystron Activity)

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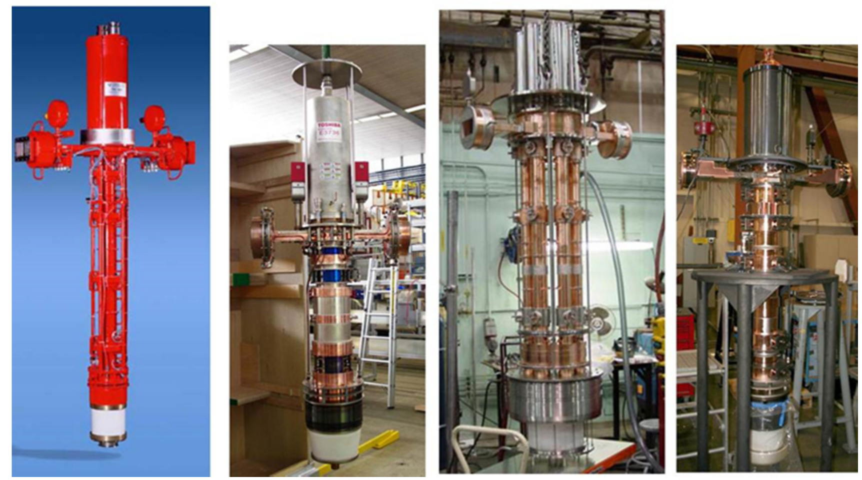
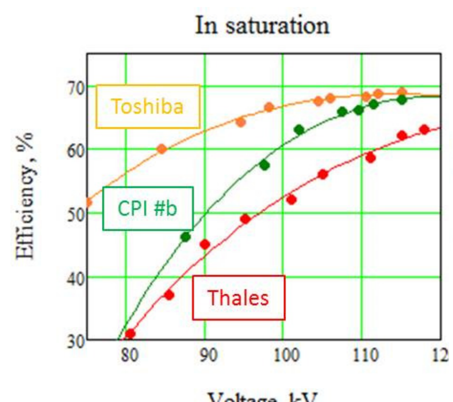
Why investigate high efficiency klystrons?

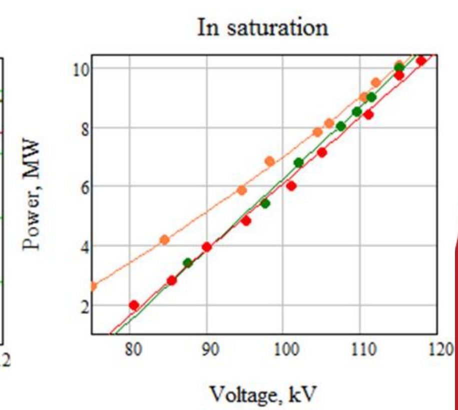
Lancaster University
The Cockcroft Institute of Accelerator Science and Technology

- RF demands of proposed large scale particle accelerators:
  - ~100 MW level power output.
  - High efficiency desirable.
  - Reliable, robust vacuum tubes.
  - Operation ~0.4-12 GHz.
- State of the art klystrons:
  - Few devices deliver efficiencies over 65%.
  - Multiple-beam klystrons (MBK's) - theoretical efficiency of 80%.
  - LHC uses 300 kW, 400 MHz, 65% efficiency klystrons.
- High Efficiency International Klystron Activity:
  - Focus on high efficiency, rather than high power.
  - Utilise modern computational methods.
  - Strong understanding of underlying physics.
  - New ideas and thinking.

Thales Toshiba CPI #a CPI #b







Example Target: Proposed FCC-ee HEKCW Tube

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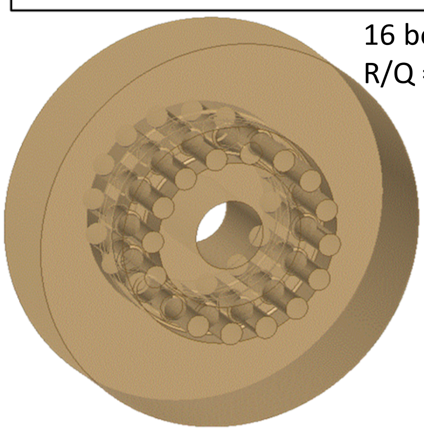


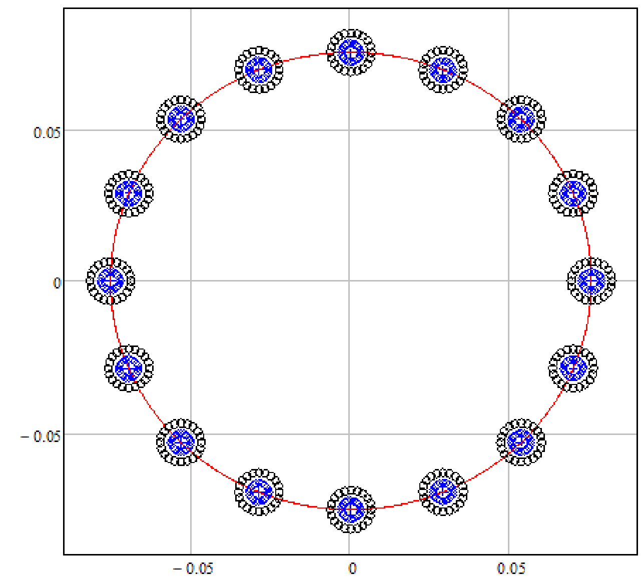
16 beams MBK cavity
R/Q = 22 Ohm/beam

Tube parameters:

- 1.5MW
- Voltage: 40 kV
- Total current: 42A
- **Target efficiency: 90%**
- N beams: 16
- µK/beamx10^6 : 0.23
- N cavities: 8
- Frequency: 800 MHz

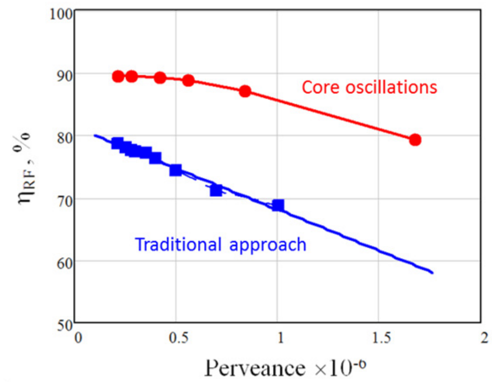
- Cathode loading: 2 A/cm^2
- Beam radius: 3 mm
  - Filling factor 8 mm
- Length: 2.3 m
- Beam circle radius: 75 mm
- Solenoid field (2x): 600 G
- Solenoid radius: 150 mm
- Collector: common
  - Nominal load: 170 kW

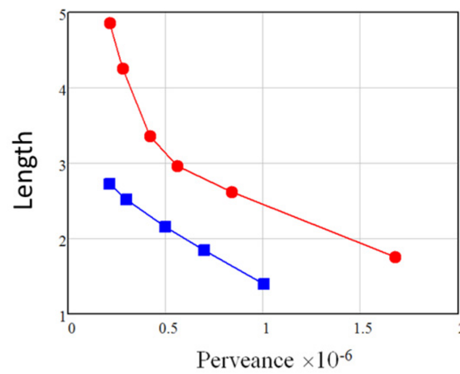
Pitch circle, cathode and beams

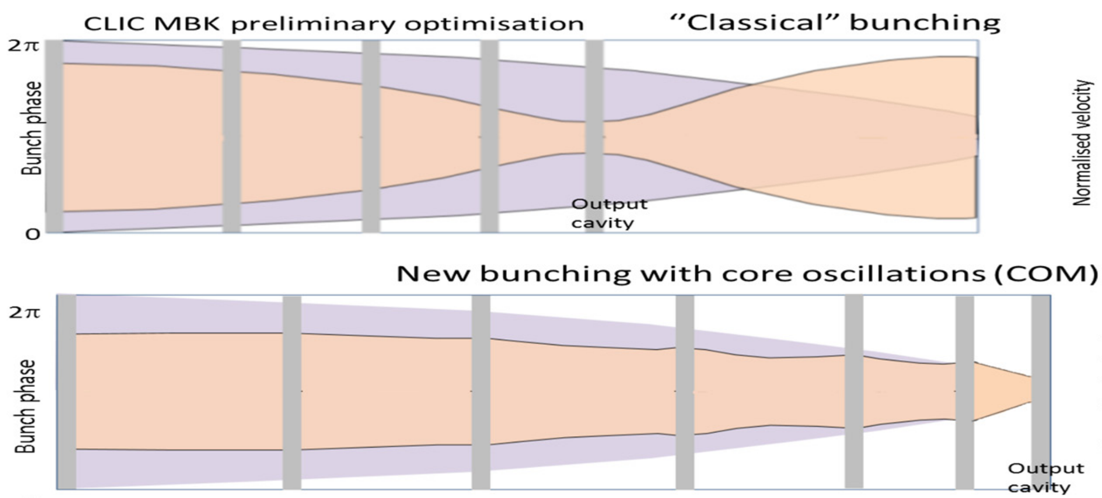


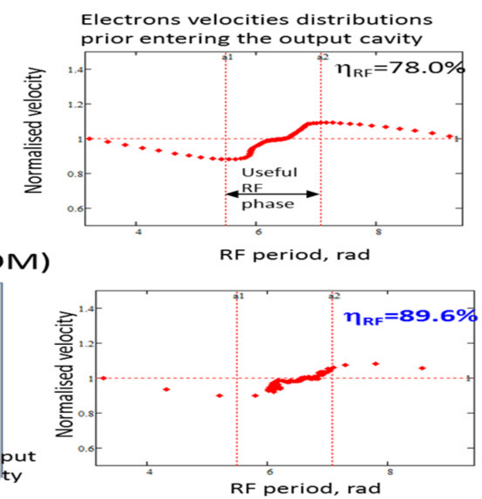
Core Oscillation Method (COM)

- Centre of bunch allowed to bunch and de-bunch between cavities.
- Core experiences larger space charge force.
- Outsiders brought monotonically to bunch.
- Outsiders experience larger phase shift due to smaller space charge forces.
- Results in tubes of longer length.
- More electrons contained within bunch at output gap.
- Therefore, higher maximum efficiency.









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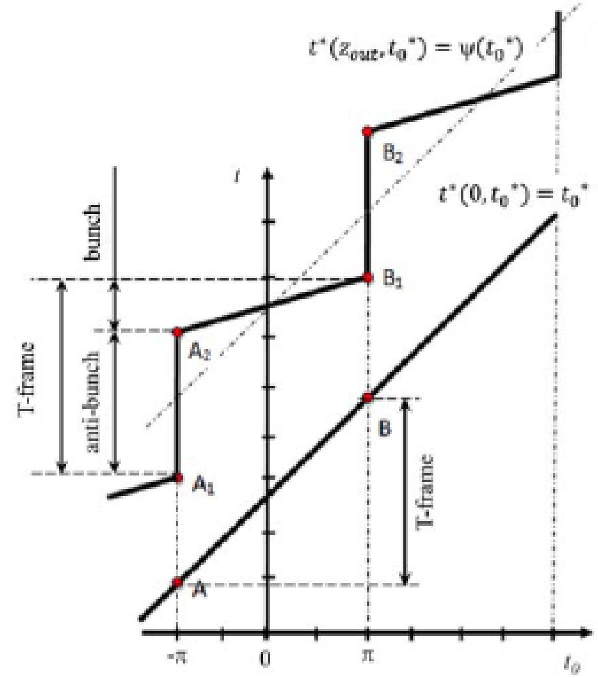
Ideal Electron Arrival Functions

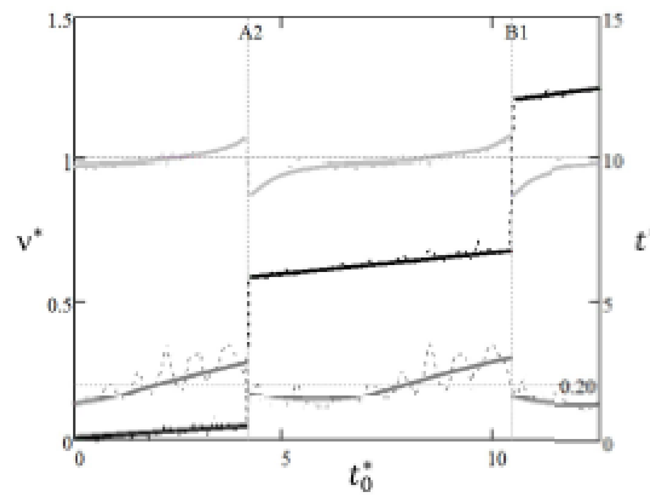
1-D Consideration

- To ensure maximum efficiency, we require:
  - At output, all electrons in bunch, none in anti-bunch.
  - Known as a Fully Saturated Bunch (FSB).
- At the output gap, the bunch is elongated:
  - Due to de-bunching forces experienced.
- Therefore, bunch must have a velocity profile:
  - Head of bunch must travel slower than tail.
  - All electrons have velocity component directed to bunch center.
  - Known as "congregated bunch".
- Post output gap:
  - Electrons should have identical (non-negative) velocities.
  - "Monochromatic" bunch.

Ideal arrival functions



7 Cavity Example



A. Yu. Baikov, C. Marrelli & I. Syratchev, "Toward High-Power Klystrons with RF Power Conversin Efficiency on the Order of 90%", *IEEE Transactions on Electron Devices*, **62**(10), pp. 3406-3412, Oct. 2015.

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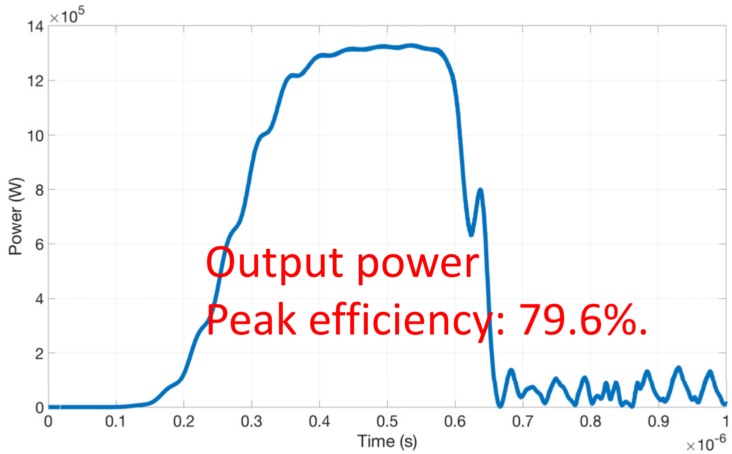
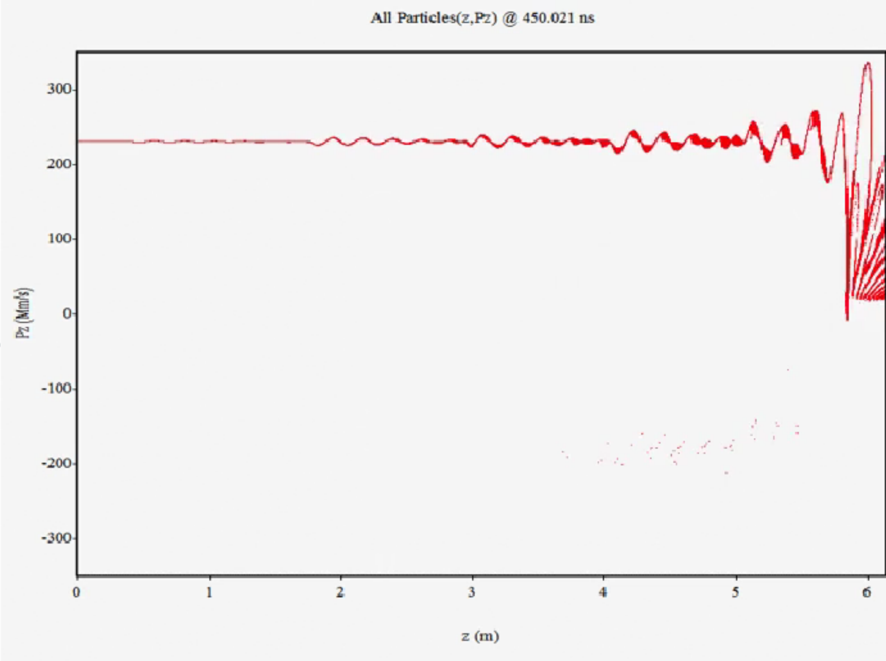
Reflected Electrons

A cautionary tale

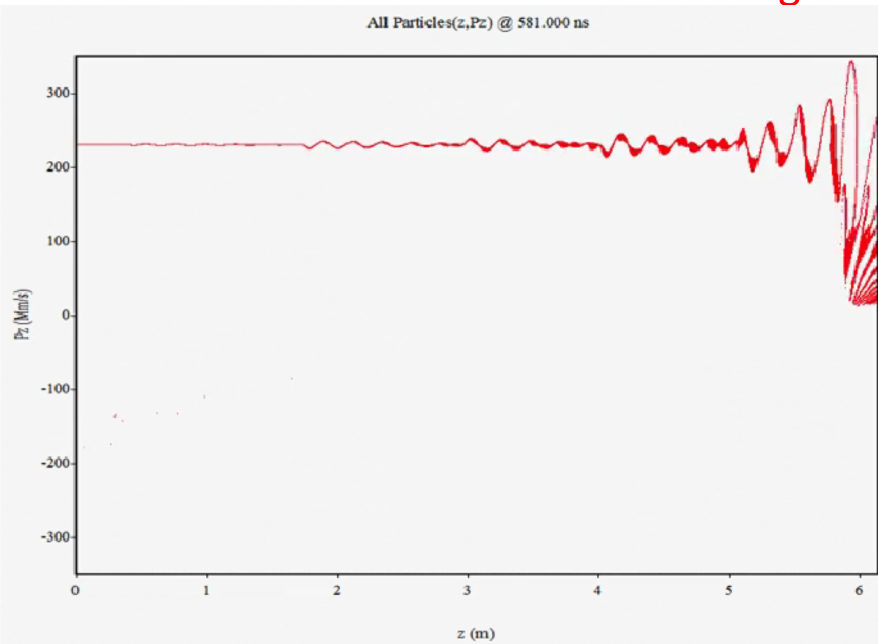
- Issue with high efficiency:
  - Too much energy extracted from electrons leads to reflected particles.
  - Destabilizes tube - destroys efficiency of tube.
  - Runaway effect – some reflected particles lead to several more.
  - Often not predicted in 1-D modelling. 2D required.
- Have to be avoided at all costs:
  - Profiling of electron bunch is crucial to this.





Around maximum output power

Unstable regime



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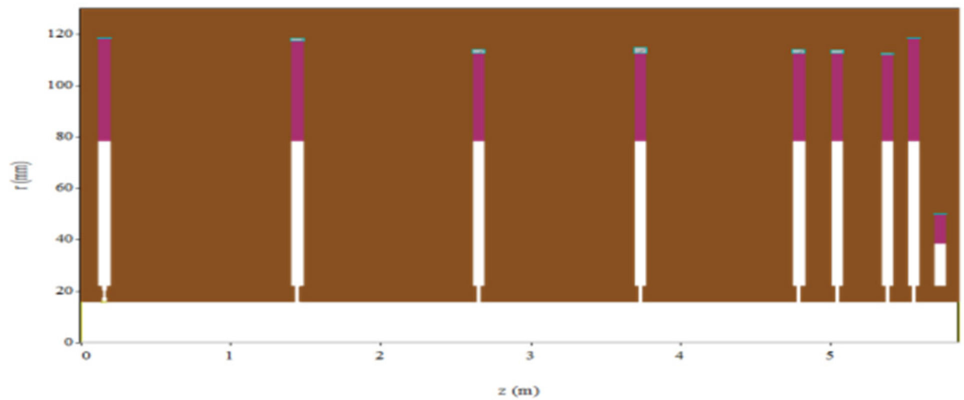
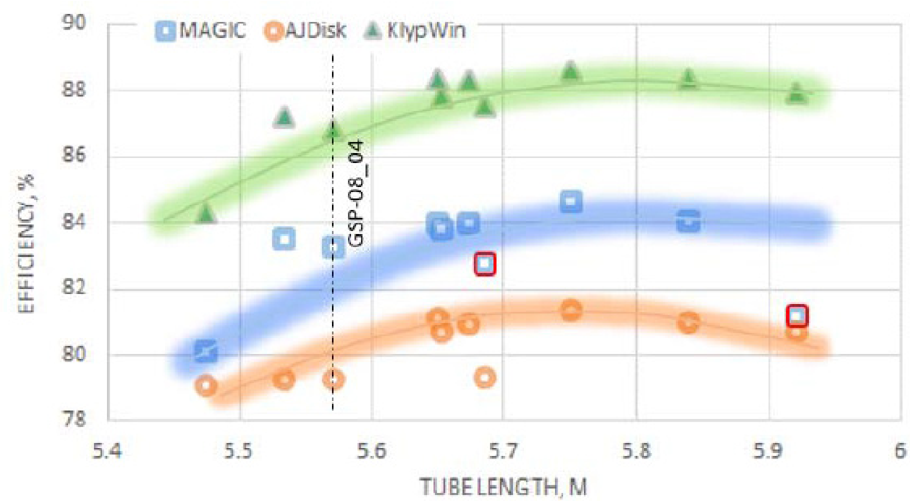
COM Optimization Process

Overview

- 8 cavity, single beam tube:
  - Proof of principle of COM.
  - 1-D & 2-D modelling: KlypWin, AJDISK, TESLA, MAGIC2-D.
  - Beam parameters, 133.85 kV, 12.551 A.
  - R/Q = 143 Ohms, fill factor = 0.54.
  - Tube length, ~6m; impractical at 800 MHz.



- Optimization to increase efficiency of tubes:
  - 1-D disk modeler KlypWin used.
  - Beam parameters (voltage and current), beam tube radii, cavity gaps and impedances kept constant.
  - Cavity drift lengths, frequencies, Q factors as free parameters.
  - >20,000 cases simulated.



- 10 tubes considered further:
  - Consistent trends across codes.
  - Some reflected electrons predicted by MAGIC.

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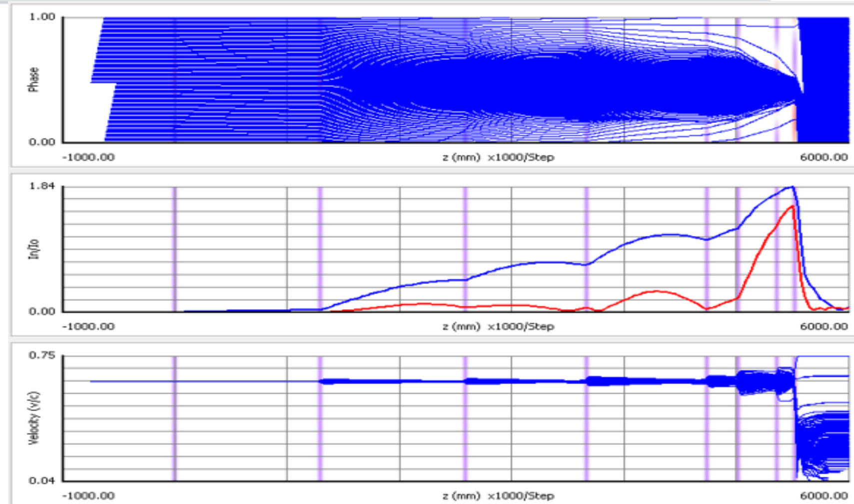
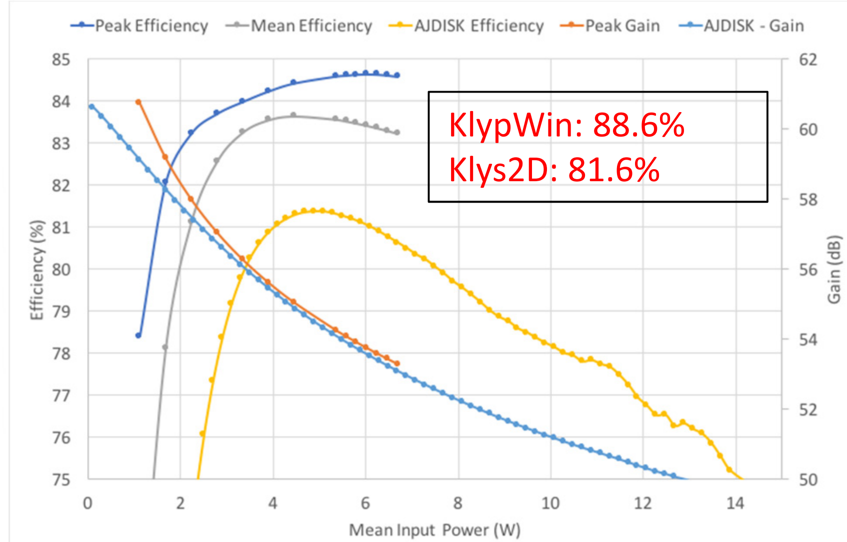
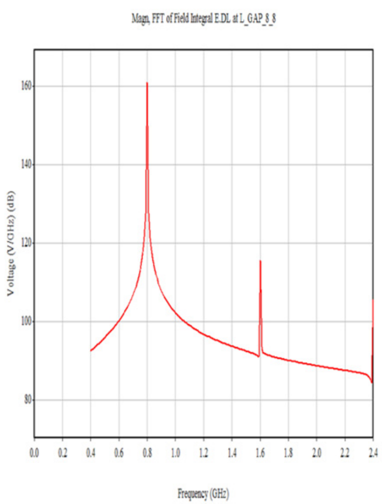
COM Tube

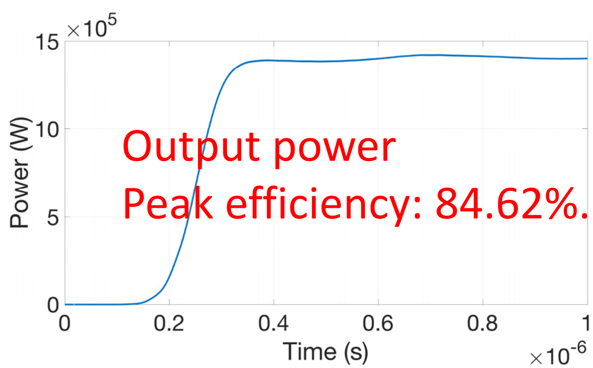
Tube Overview

- 8 cavity, single beam tube:
  - Peak efficiency – 84.62%, 1.42 MW.
  - Stable transfer curve – no reflected electrons.
  - Good agreement between codes.
  - Peak efficiencies > 81.5%.
  - AJDISK indicates not all disks contained in output bunch.









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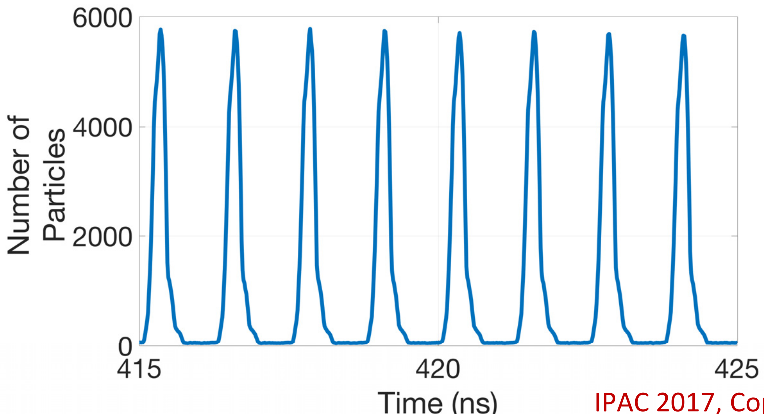
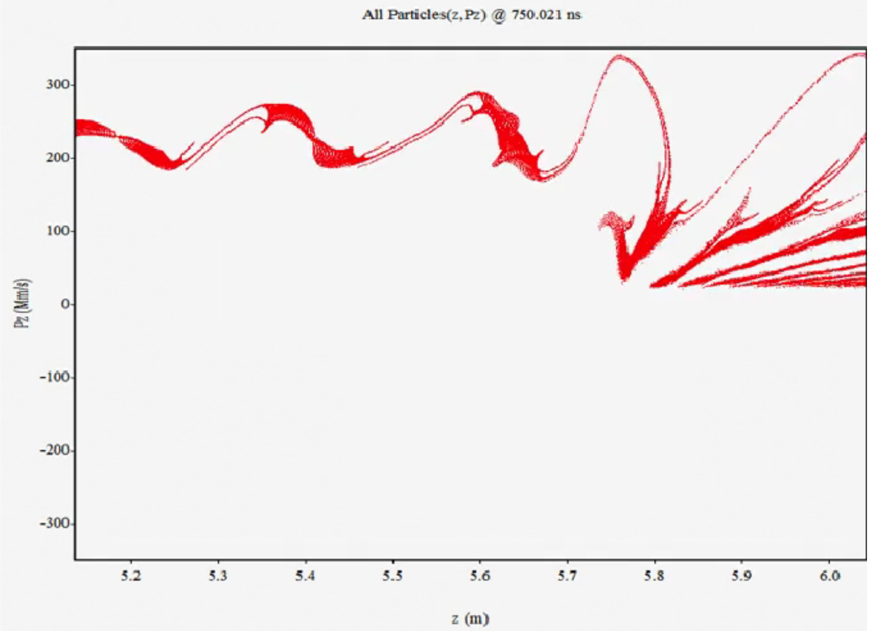
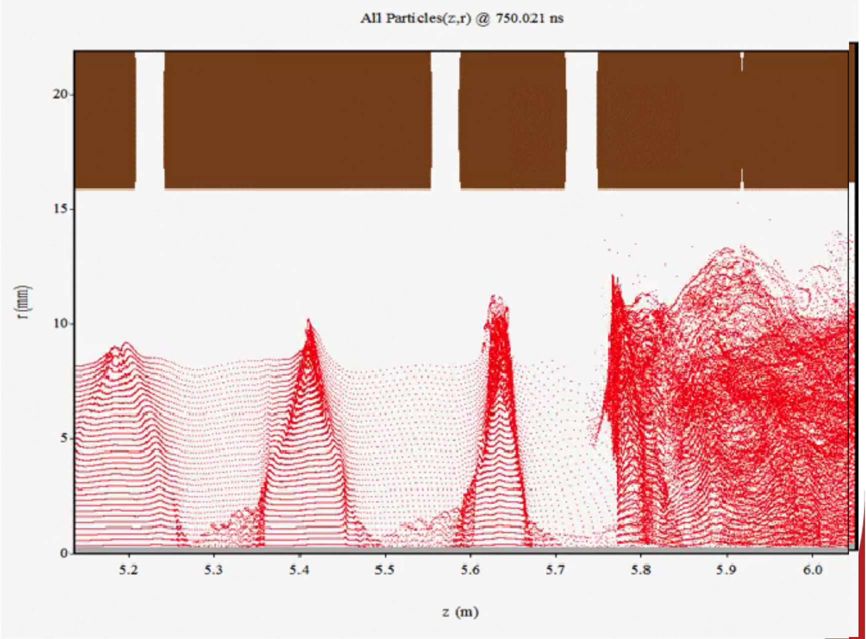
MAGIC2-D – Phasespace Diagrams

- Phasespace around final cavities:
  - Cavities 6 and 7 rotate bunch into alignment in Pz-Z space.
  - Some particles have all energy extracted before being accelerated by AC field.
  - On-axis pedestal which extends to following bunch - radial stratification.
- Bunch profile:
  - Integral performed prior to final cavity.
  - Consistent number of particles in bunch.
  - Not perfect FSB, <0.1% of particles in anti-bunch.
  - Step like profile on trailing edge of bunch.







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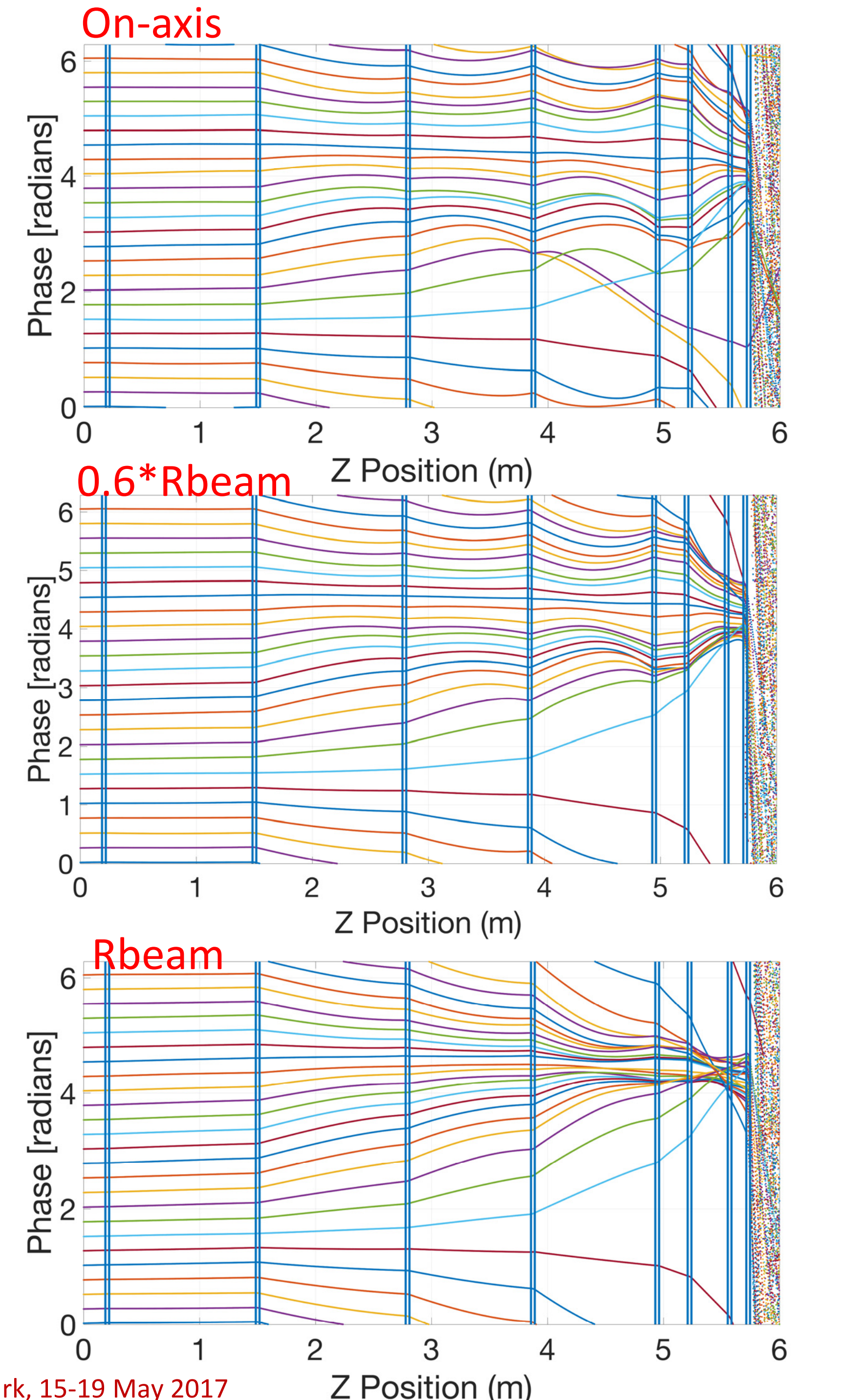
MAGIC2-D - Applegate Diagrams

- Applegate construction:
  - Particles emitted at 20 radial positions over 1 RF period.
  - Position and velocity recorded.
  - Core oscillation clearly observed.
- Bunching varies radially across bunch:
  - Not all test particles in bunch.
  - On-axis: under-bunched.
  - 0.6*Rbeam: well bunched, some crossovers prior to output cavity.
  - Beam edge: over-bunched – crossovers prior to cavity 7 – particles over/undertaking others in bunch.
- PIC Applegate diagrams confirm radial stratification on axis:
  - Phase width of bunch varies across beam.



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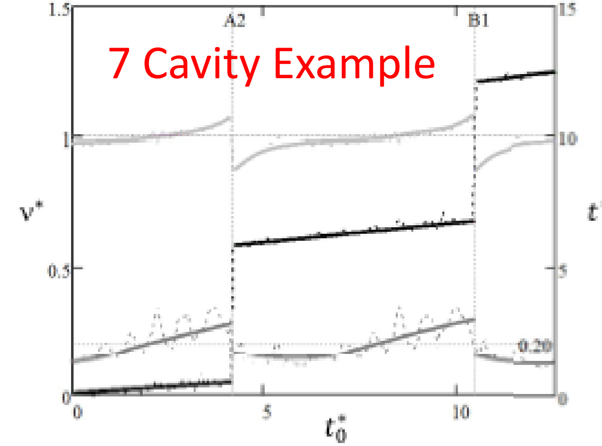
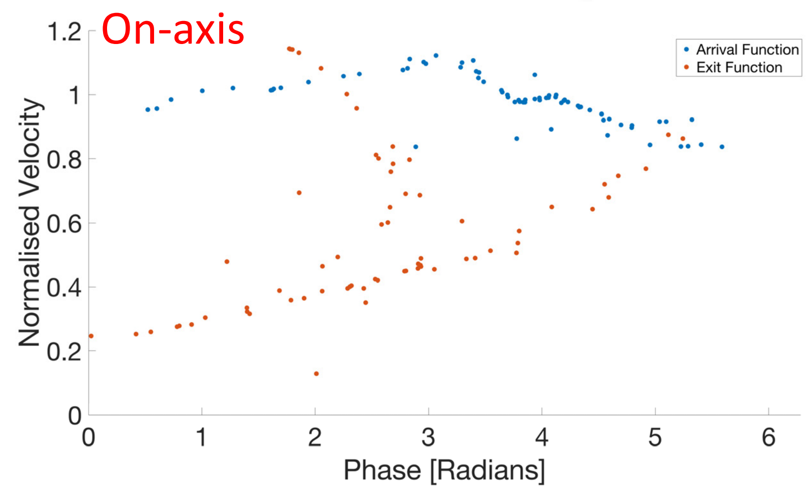
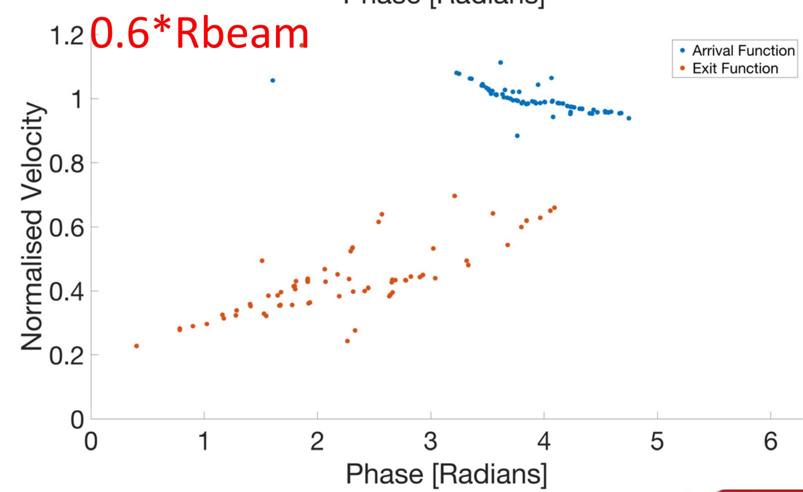
Electron Velocities

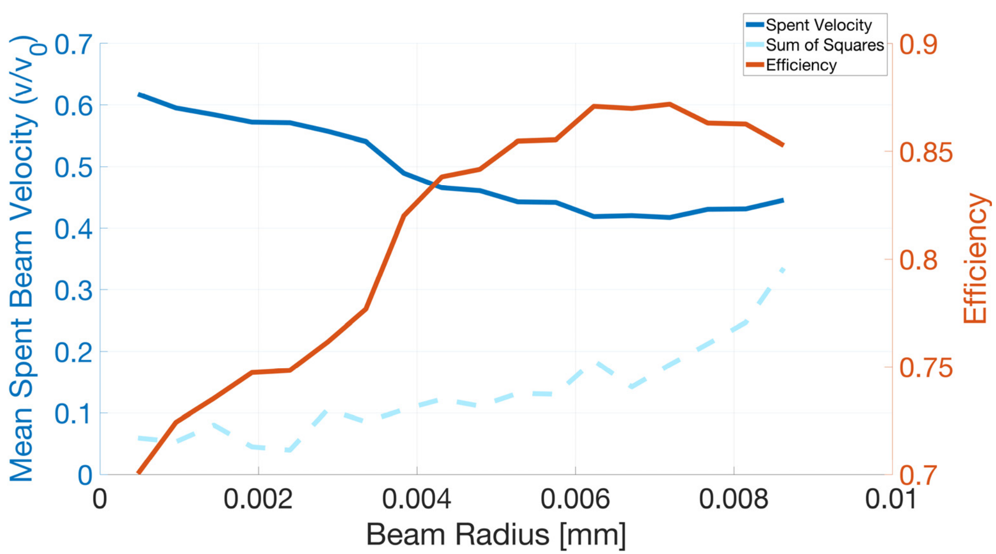
MAGIC2-D – Arrival & Exit Functions

- Compare COM tube velocity profiles with ideal 1-D case:
  - Measured +/- 48 mm from cavity.
  - Some particles contained in anti-bunch.
  - Arrival velocities varies across beam.
  - Almost flat on axis, gradient closer to ideal (yet mirrored) at 60% beam radius.
  - RF efficiency across the bunch > 70%.









Summary & Future Research

- Core Oscillation Method:
  - Maximum efficiency, 84.62 % achieved in PIC, but very long tubes.
  - Applegate analysis in PIC highlights bunching variation across beam.
  - Quantification of radial stratification at distinct radii.
  - >70% RF efficiency across output electron bunch.

- Future:
  - Use of Applegate/arrival functions to directly tune tubes.
  - Scaling of perveance to produce shorter COM tubes.
  - Extend PIC modelling to 3-D.

- Thanks to:
  - Members of HEIKA.
  - ATK's Alliance Partnership Program for the use of MAGIC2-D.