Advances and results towards super-efficient klystrons

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on behalf of **HEIKA** (High Efficiency International Klystron Activity)

Introduction

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The Cockcroft Institute of Accelerator Science and Technology

- Increase in RF generation efficiency is high priority for the future large accelerators (CLIC, ILC, FCC, ESS)

- "Recent" klystron developments targeted high power neglecting high efficiency
- Few high power klystrons offer **65%+** efficiency

- Deeper understanding of the klystron physics, new ideas and modern computational power will help us towards **90%** efficiency
- HEIKA collaboration of many experts working towards this

Future Machines…large numbers!

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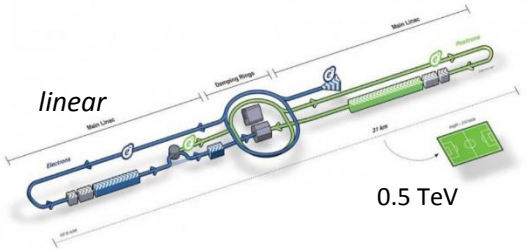
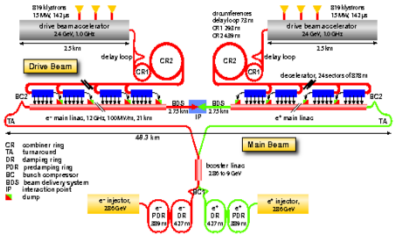
linear



0.5 TeV

ILC $^{e+e-}$: Pulsed, 1.3 GHz, P_{RF} total= 88 MW



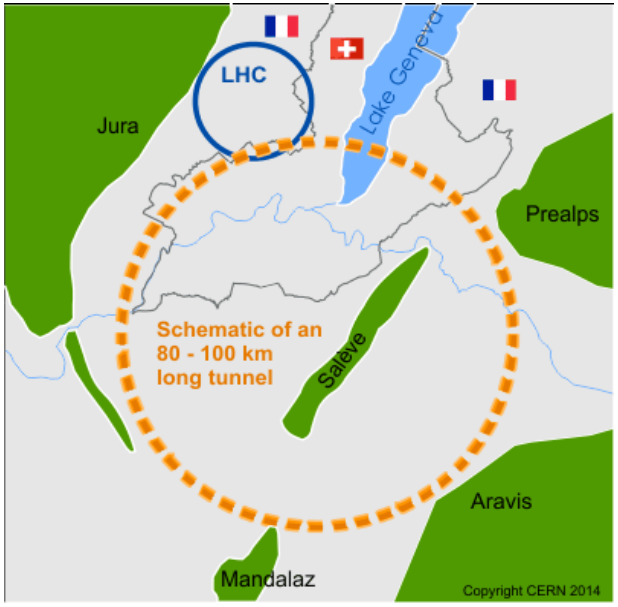
3.0 TeV

CLIC $^{e+e-}$: Pulsed, 1.0 GHz, P_{RF} total= 180 MW

- Achieved efficiency at 10 MW peak RF power level
- The existing MBK klystrons provide efficiency very close to 70%
- Each 1% saves 400k€/year

circular

FCC



FCC ^{ee}: CW, 0.8 GHz, P_{RF} total= 110 MW

Thales

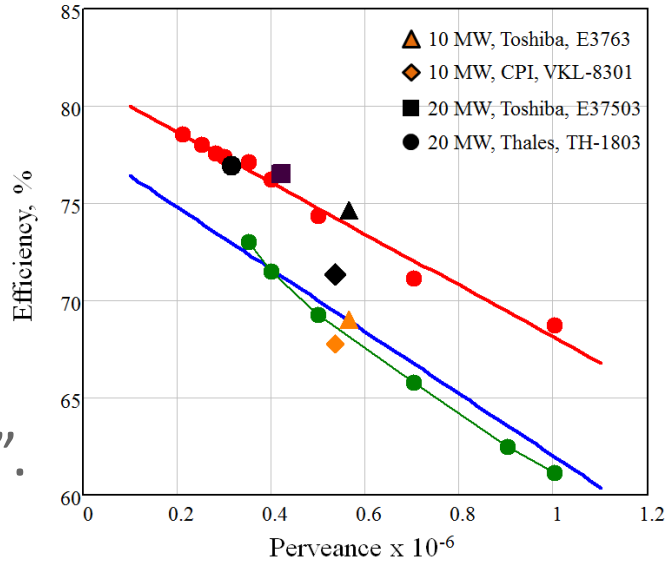
Toshiba

CPI #a

CPI #b

Traditional Approach

- For high efficiency traditionally we chase low perveance:
  - High voltages
    or
  - Low currents (many beams)
- For high power both become “unpleasant”.



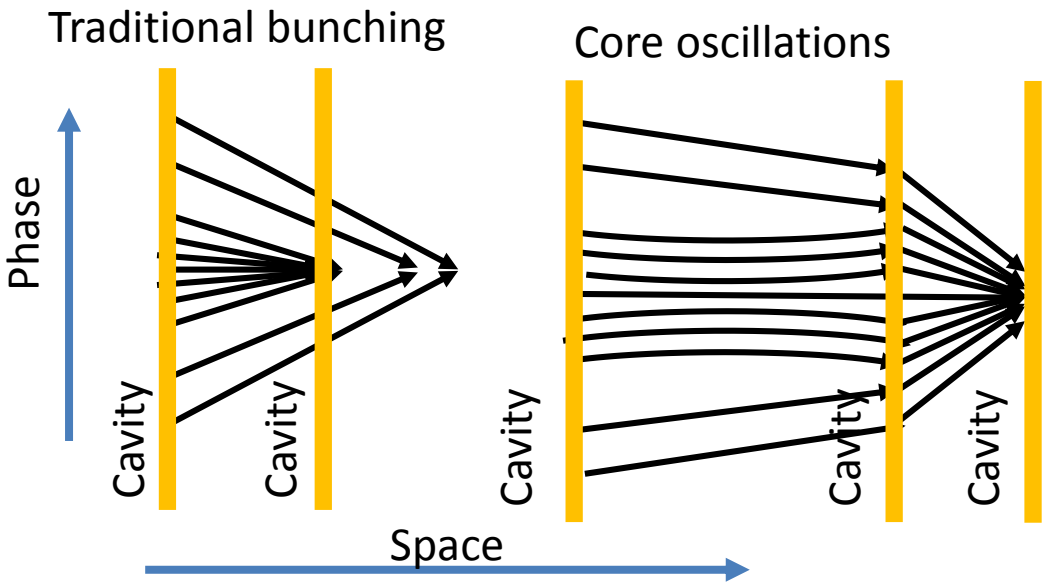
- Performance limited by the slowest electrons (***must*** avoid reflecting electrons)

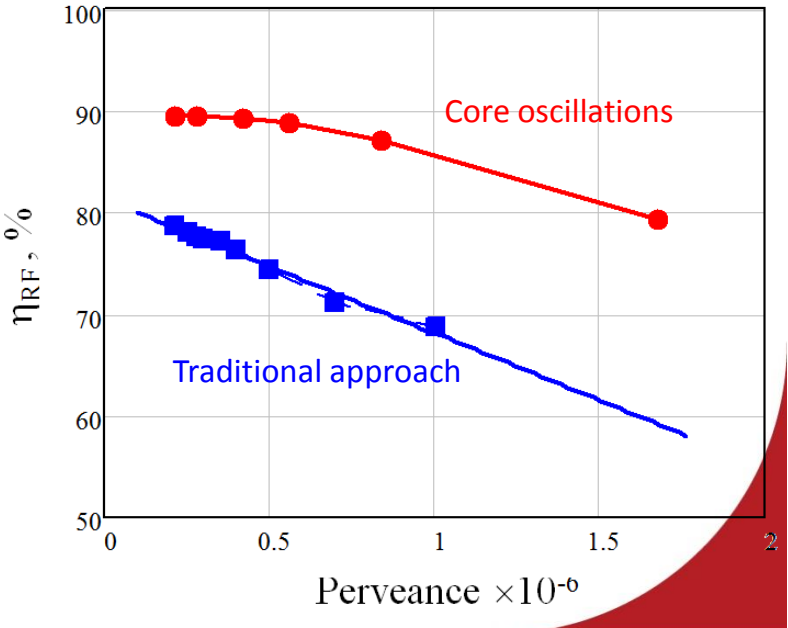
- Traditional theoretical efficiency limited to 80% @ 0.1-0.2ish microperv

Method to get high efficiency

Core Oscillation (space charge debunching)

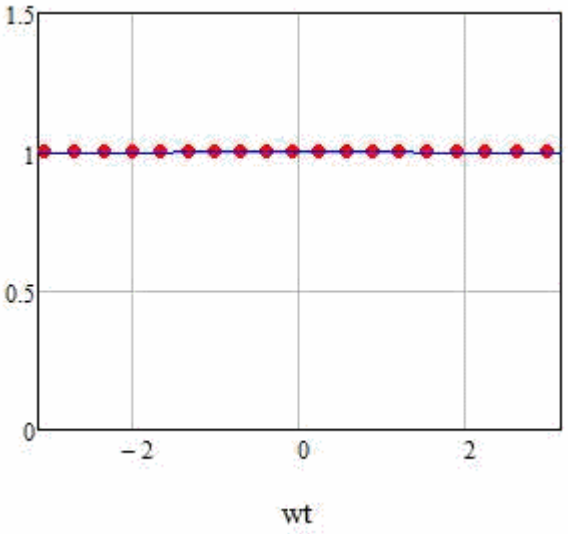
- Bunching split into two distinct regimes:
  - non-monotonic: core of the bunch periodically contract and expand (in time) around center of the bunch
  - outsiders monotonically go to the center of the bunch
- Core experiences higher space charge forces which naturally debunch
- Outsiders have larger phase shift as space charge forces are small
- **Very long, very efficient** tubes result.



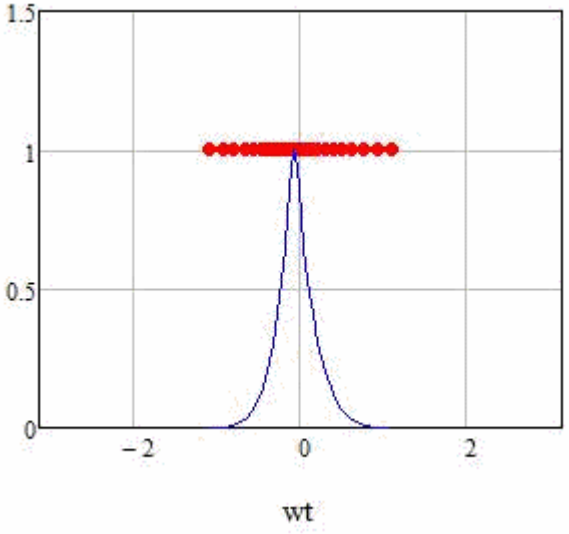


Bunch congregation

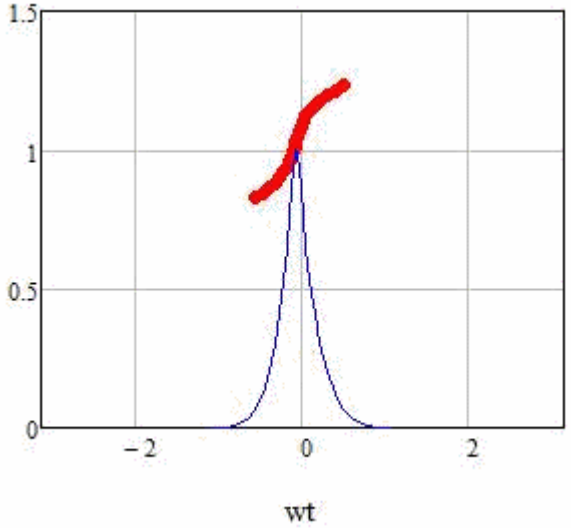
- To take out max power we also need to take care of the velocity spread.



The fully saturated (FS) bunch



Final compression and bunch rotation prepare congregating FS bunch.

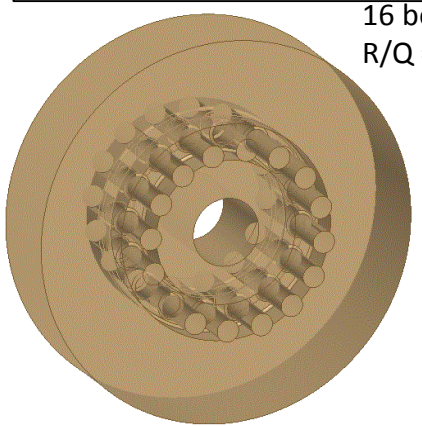


After deceleration all the electrons have identical velocities.

HEKCW Tube

HEIKA/HEKCW working team:
(early 2016)

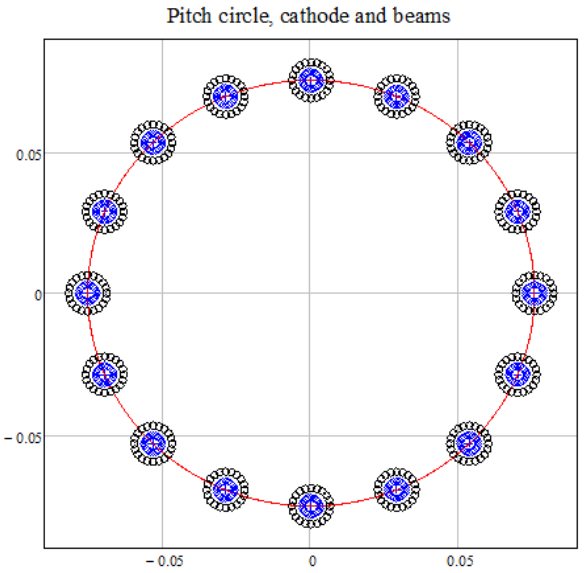
I. I. Syratchev (CERN)
II. C. Lingwood (Lancaster)
III. G. Burt (Lancaster)
IV. D. Constable (Lancaster)
V. V. Hill (Lancaster)
VI. R. Marchesin (Thales)
VII. Q. Vuillemin (Thales/CERN)
VIII. A. Baikov (MUFA)
IX. I. Guzilov (VDBT)
X. C. Marrelli (ESS)
XI. R. Kowalczyk (L-3com)



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

Tube parameters:

- 1.5MW
- Voltage: 40 kV
- Total current: 42A
- N beams: 16
- μK/beamx10^6 : 0.33
- N cavities: 8
- Bunching method #1: COM
- 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



PIC Simulation complexities

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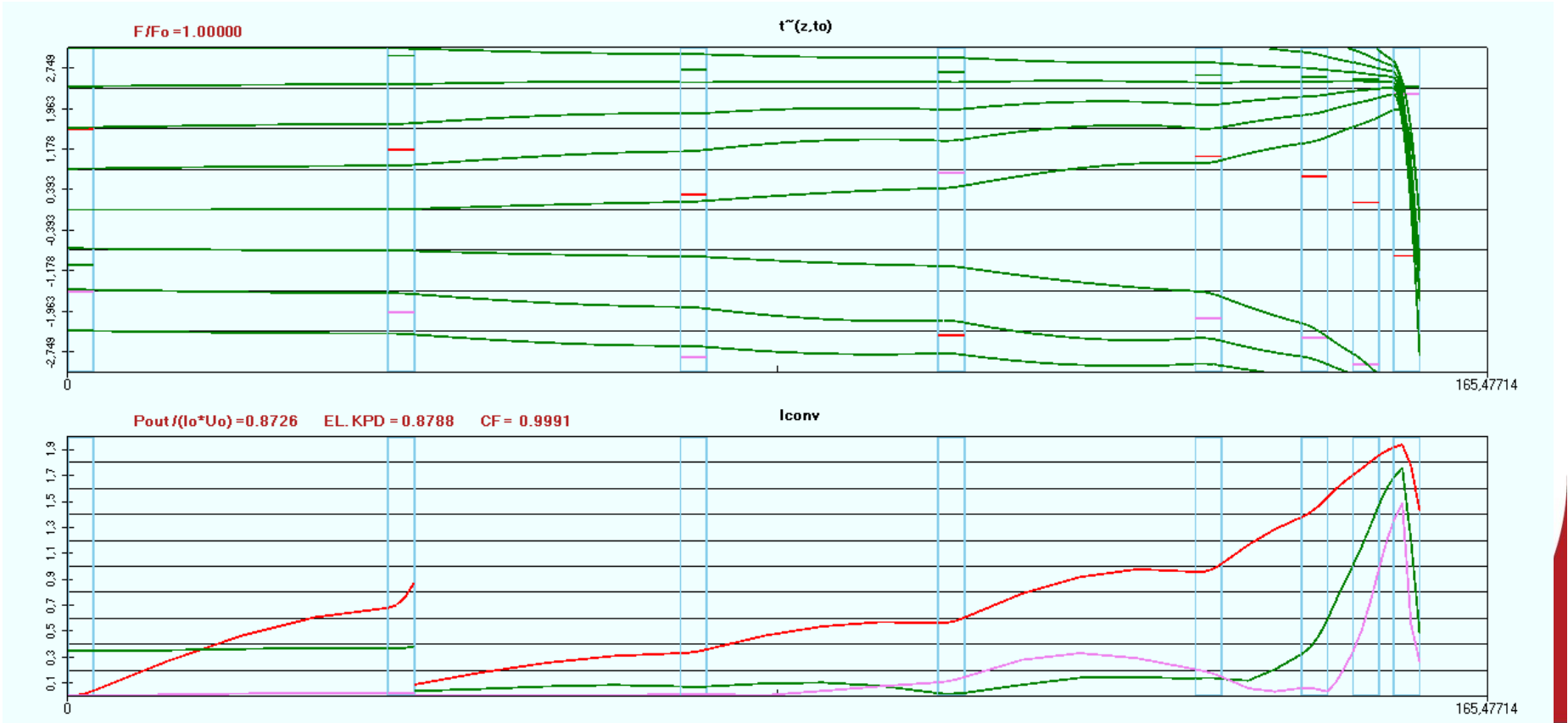
- Working in 2D for speed
- Coaxial cavity not possible in 2D
- It is not possible to get a re-entrant cavity to replace the coax cavity
- R/Q cannot be reached with beam pipe parameters (353 Ohm)

- Use GSP technique to translate tube through generic parameters while keeping bunching “equivalent”:
  - In this case move to higher voltage to lower R/Q
    - Required R/Q is now 182 Ohm (easy)
  - Results should be equally applicable

Candidate Structure #08-01

Andrey Baikov (MUFA)

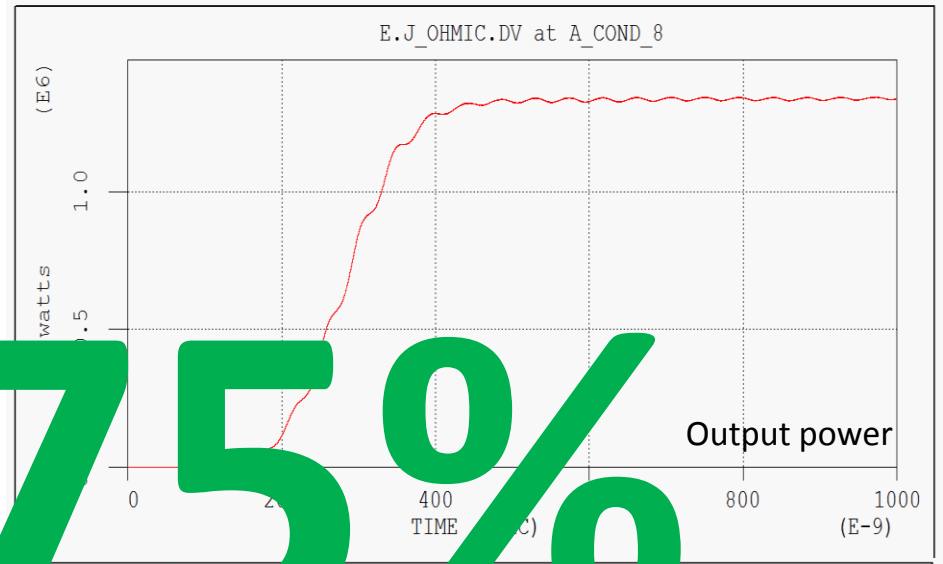
- Learnt lessons to produce the first ‘robust’ (2D) design 87% in Klypwin, 82% in Klys2D
- No overtaking - Larger cavity F separation – 8 cavities

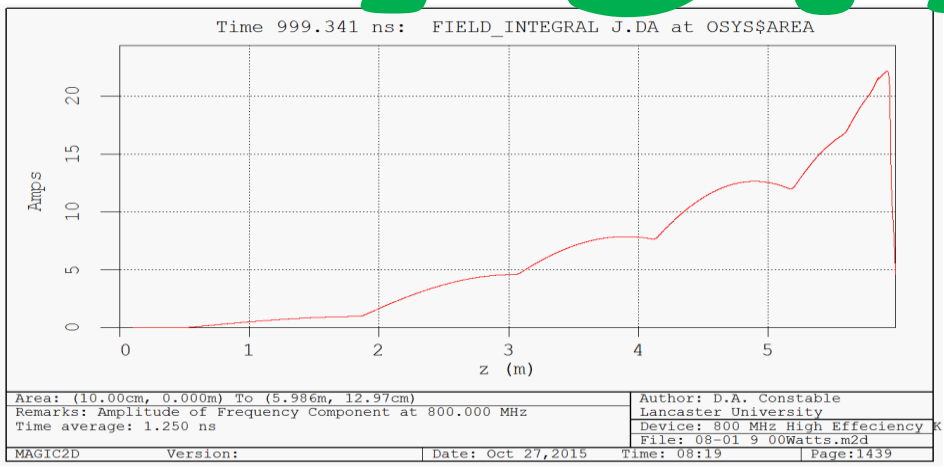


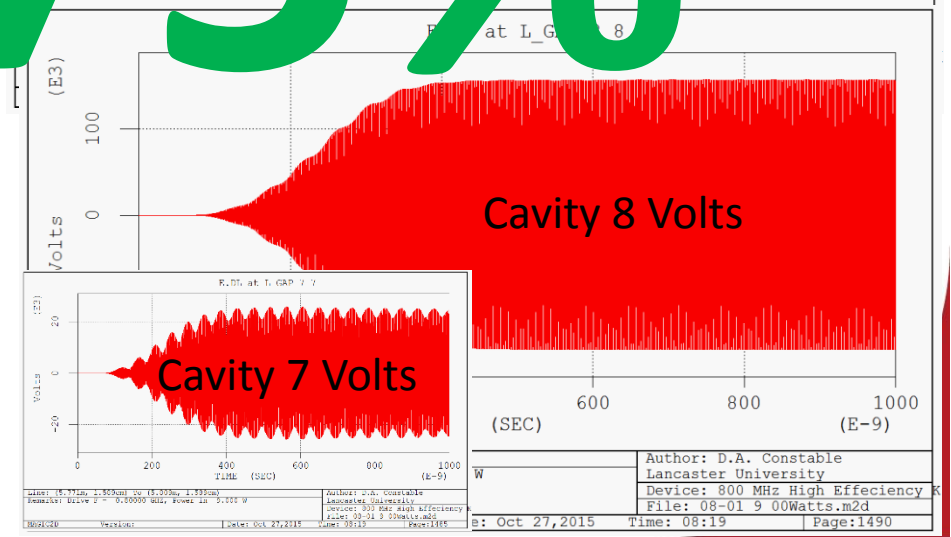
Magic2D PIC HEKCW #08-01
First Stable PIC Results!

- Cavity 1 voltage, 1.28 kV:
- Normal modulation for COM (good match)
- Fairly Stable output
  - Cavity 7 beats a bit
- Efficiency…….

79.75%

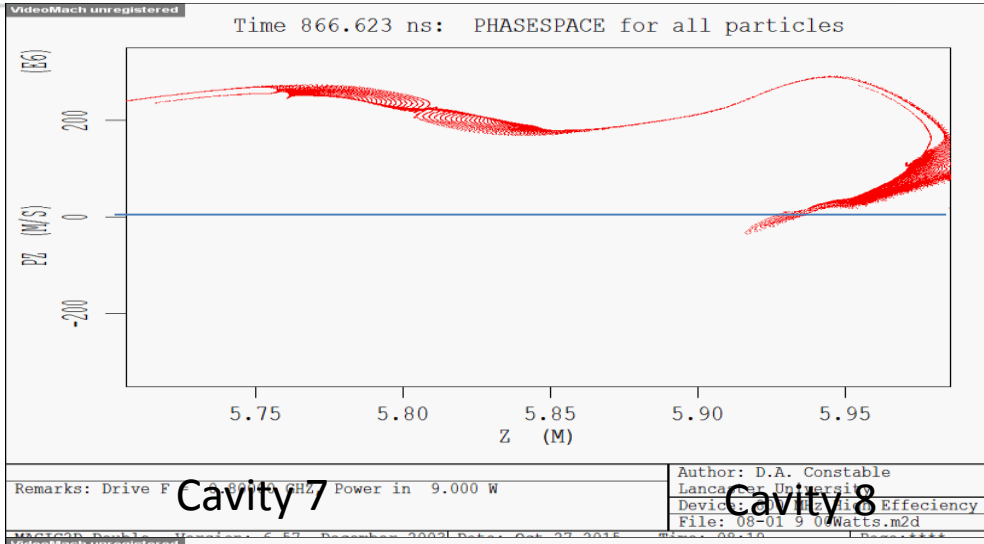






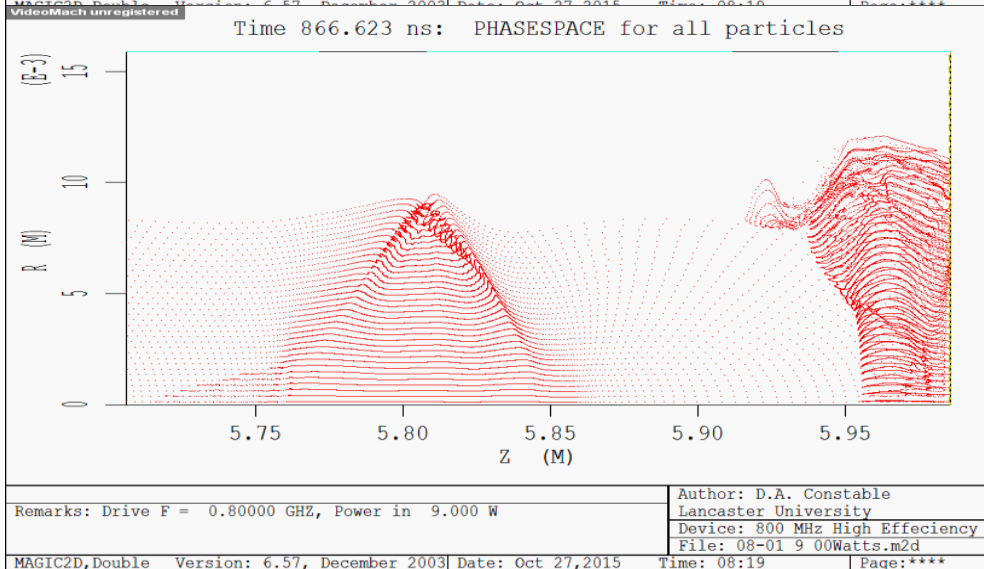
Magic 2D PIC #08-01

- Electrons “bounce” in output gap but are not reflected
- Phase space fairly clean



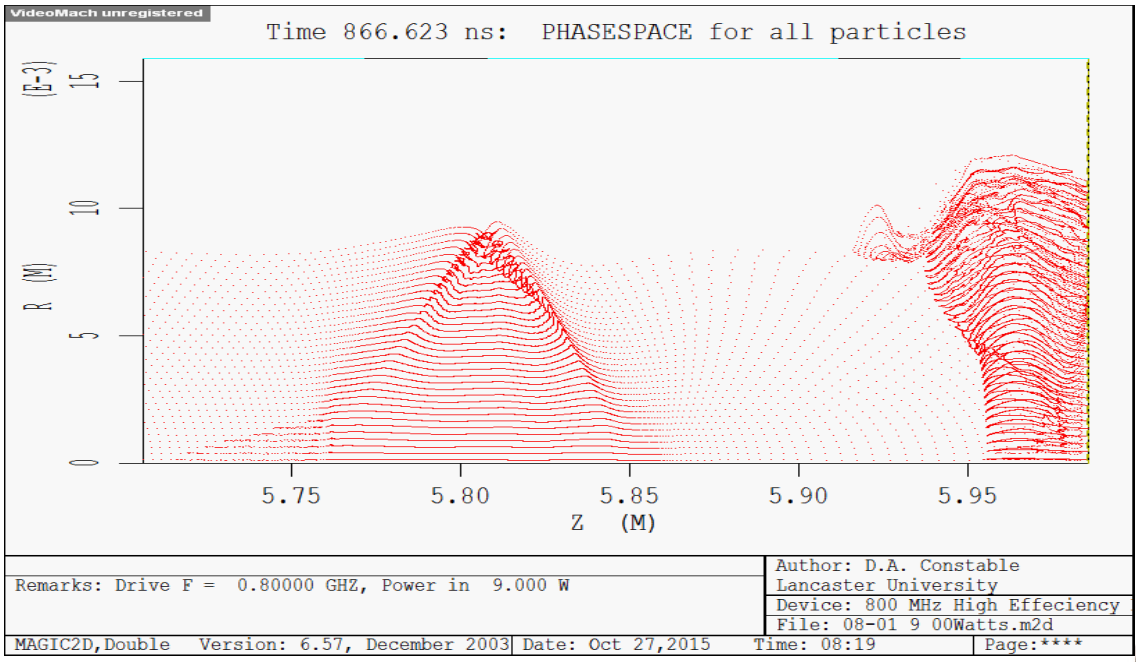
Cavity 7

Cavity 8



Radial Variation

- The centre of the beam does not behave in the same way as the outer
  - "Lens" shaped bunch
- At least one of these regimes is not optimal (maybe both)
  - Outside looks over decelerated for instance



#08_04

Rich Lowalczyk (L3)

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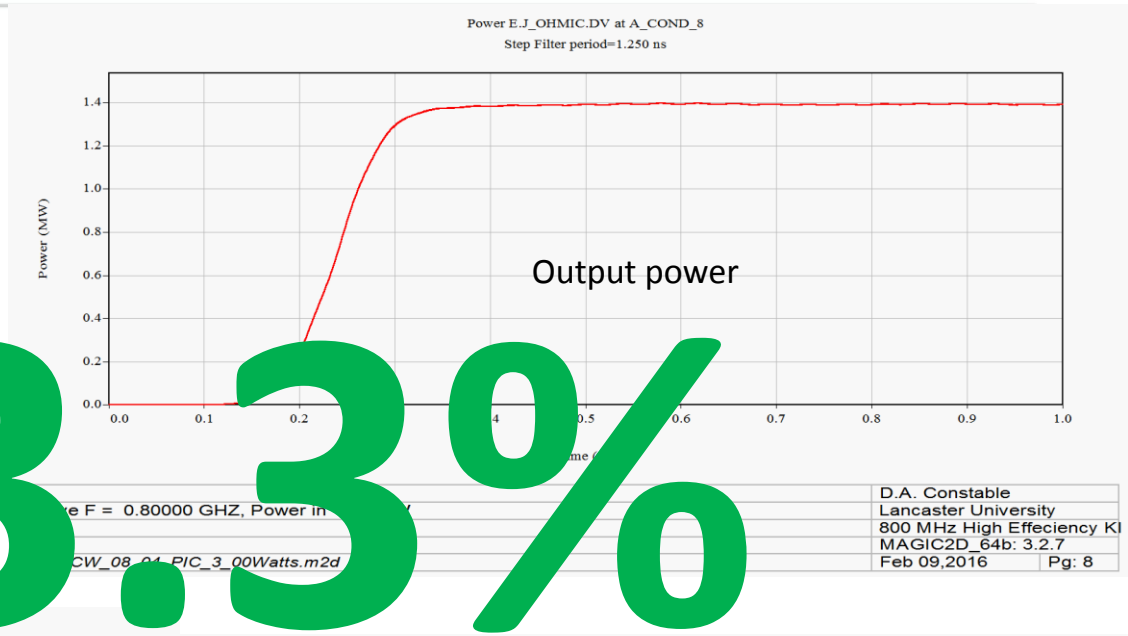
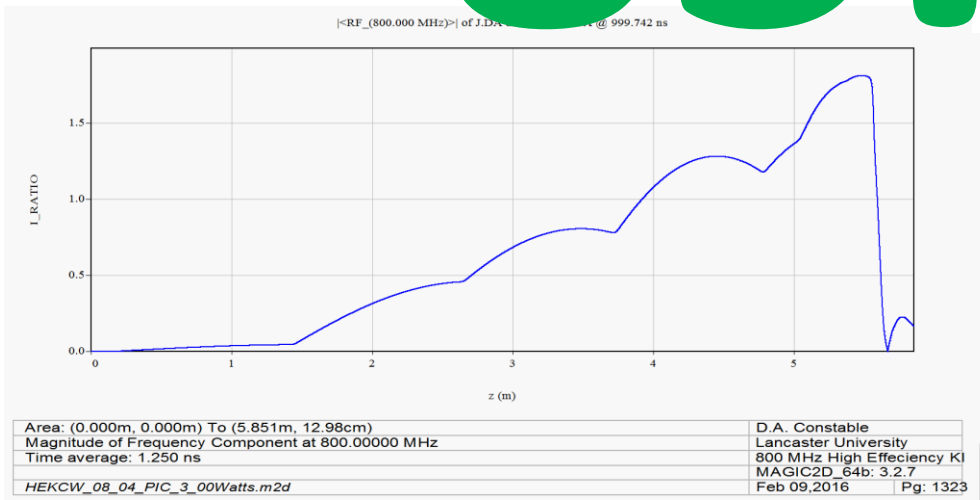
- Redesign of of previous tube targeting the slab like bunch.
- No reflections predicted along transfer curve (in Tesla)
- Tesla predicted efficiency, ~80% (1.34 MW).

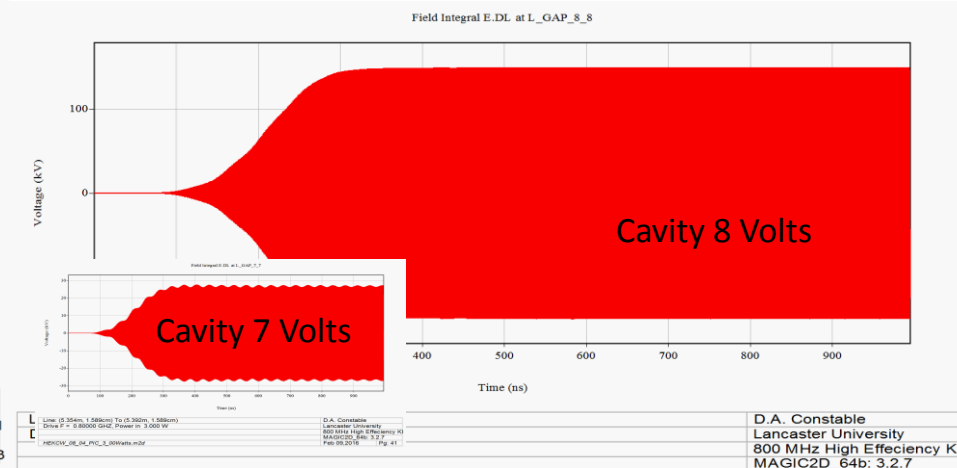
Magic HEKCW #08-04

- Cavity 1 voltage, 0.45 kV:
- Nice Stable output
- No reflected electrons
- Slightly odd modulation current
- Stable output
- Efficiency…..

83.3%

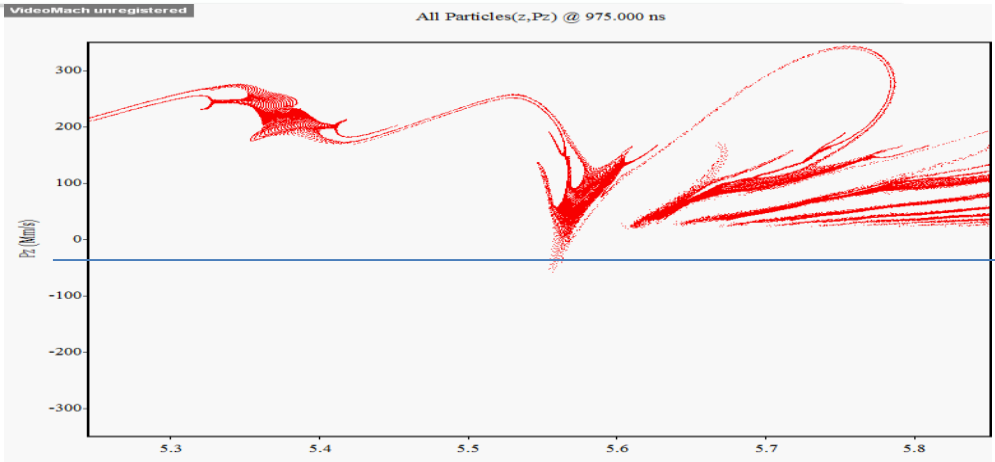




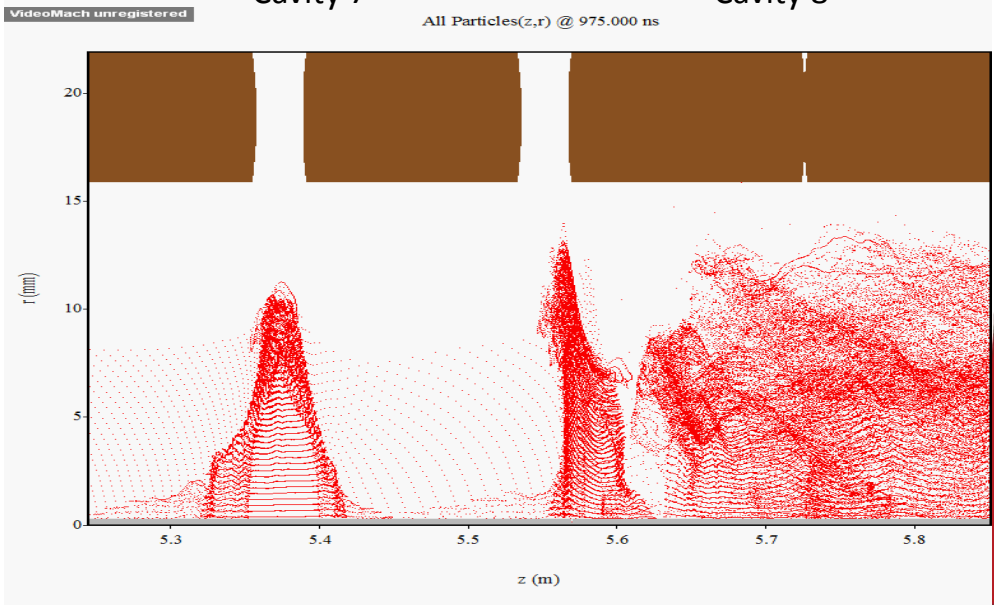


Magic HEKCW #08-04 Electron Animations

- Bunch ”bounces” (less?)
- Superficially nightmarish phase space
  - Good chunk decelerated well though
- Quite a good slab bunch
  - but not *great* in the center



Cavity 7 Cavity 8



#08_01 vs #08_04

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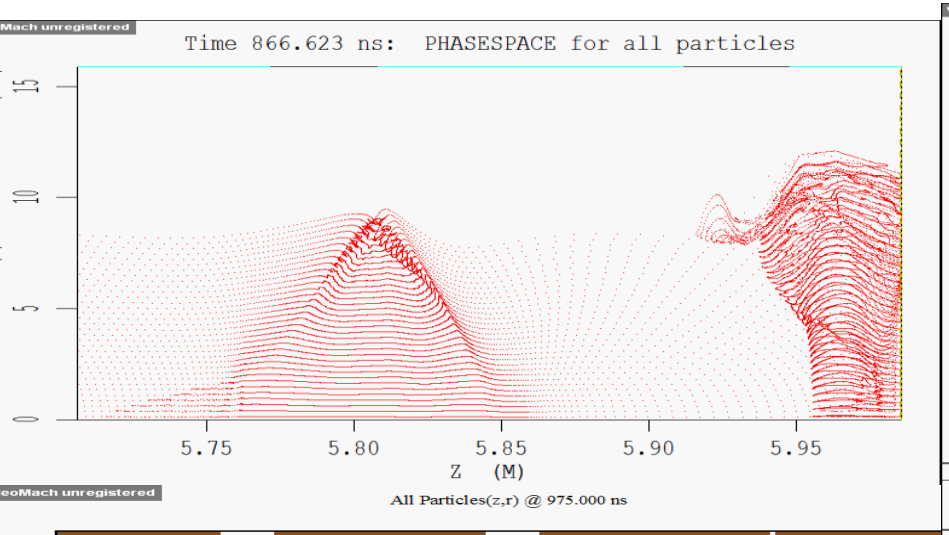
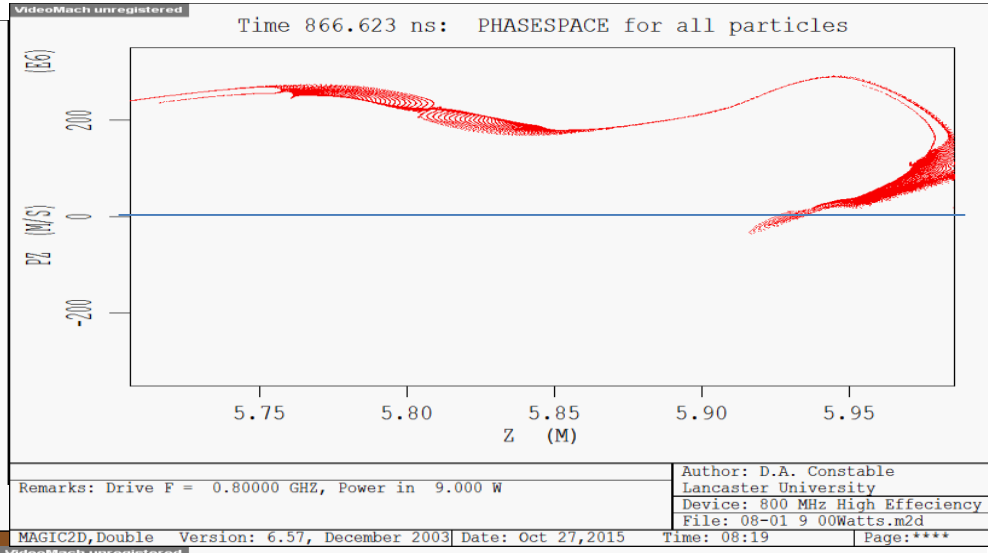
08_01





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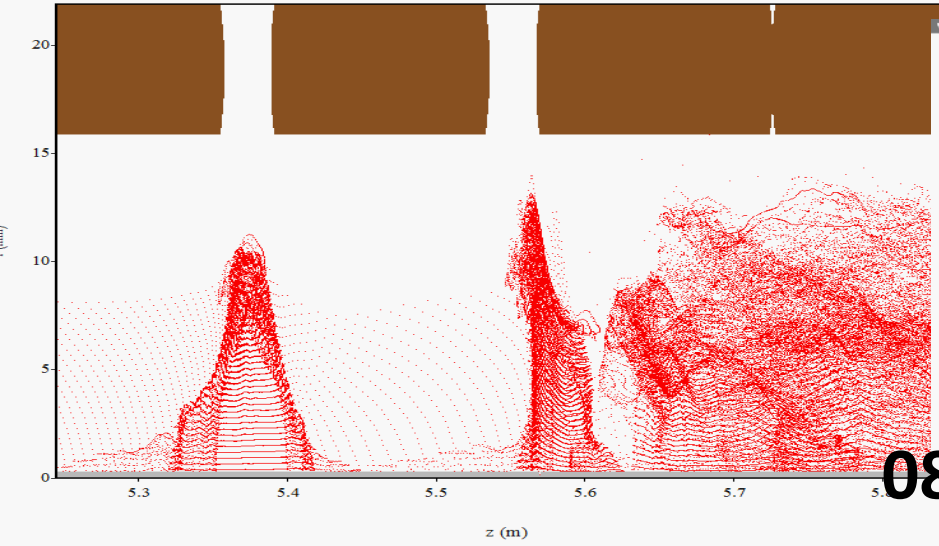
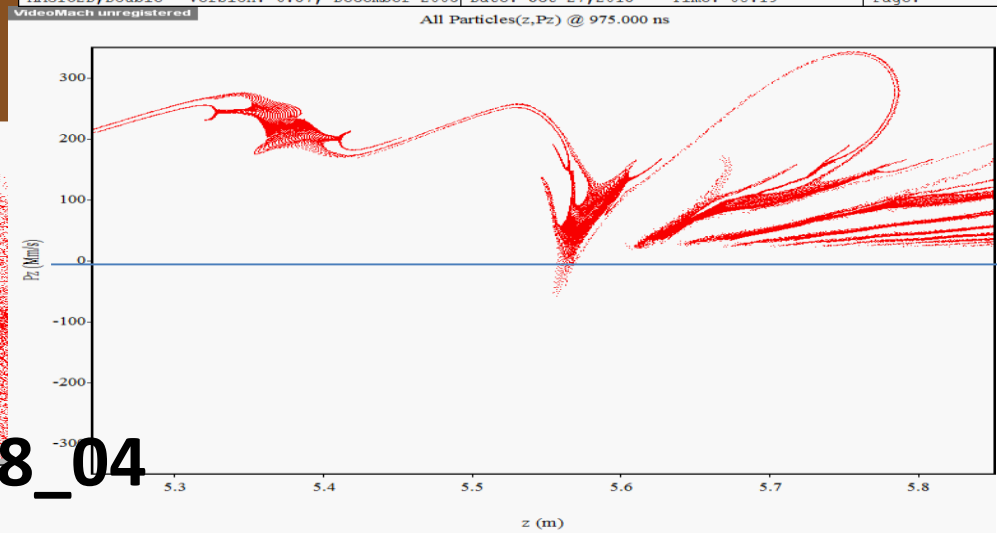
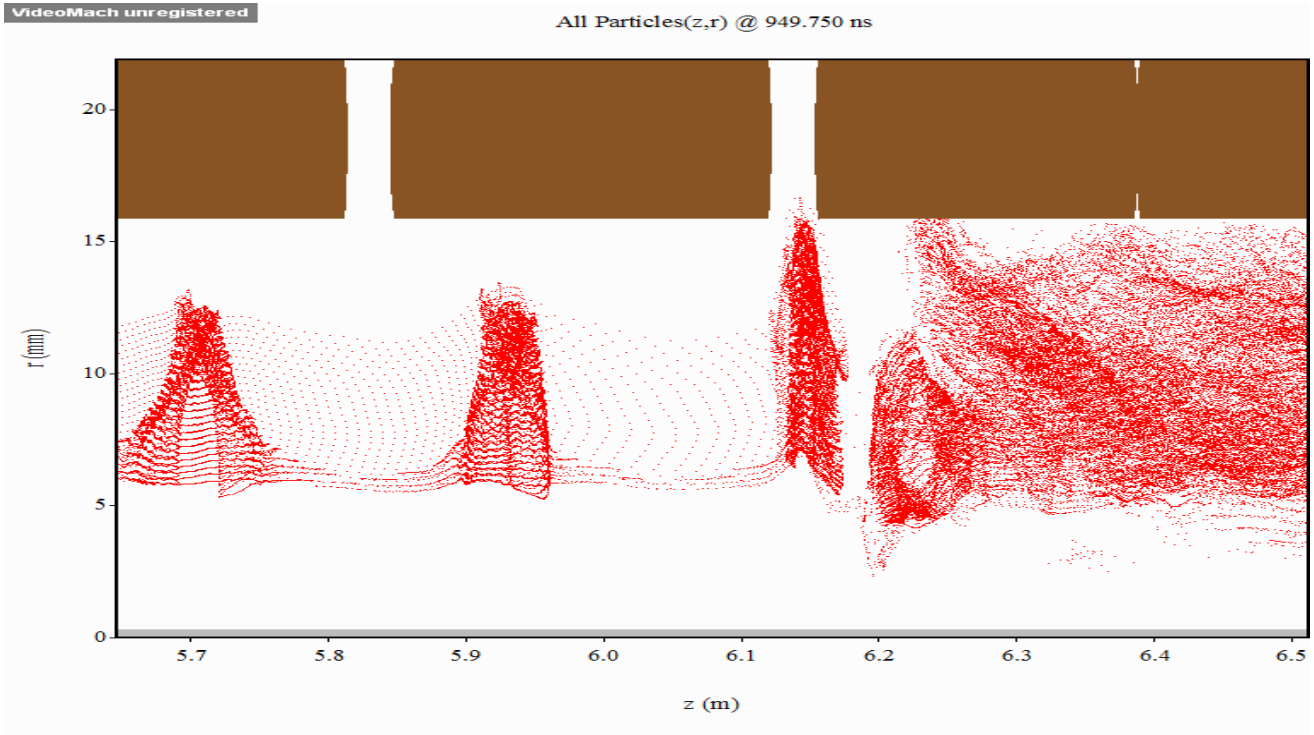




Hollow?

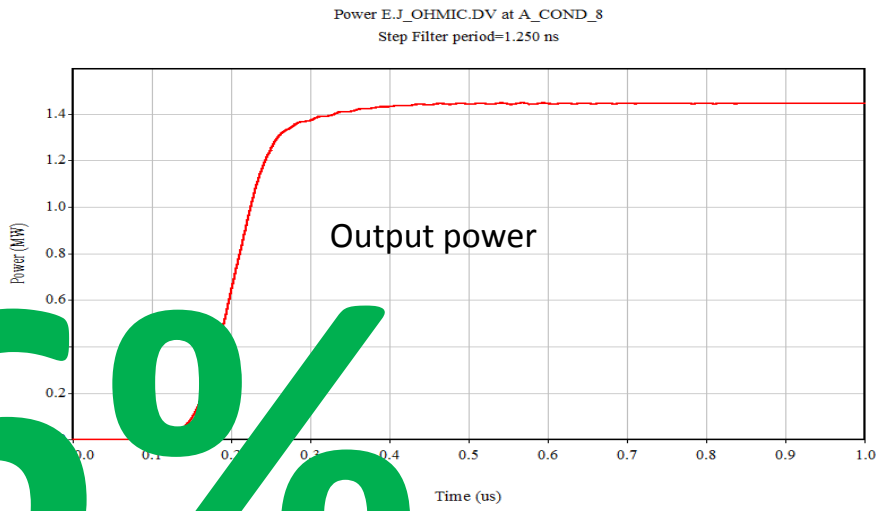
- Our bunch is *excellent* off axis…
- Less excellent on axis…
- What if we just don't bother emitting it on axis?

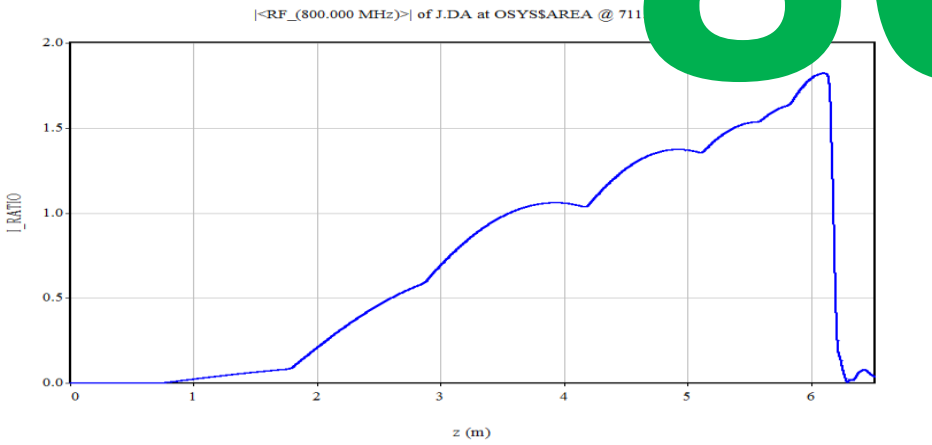


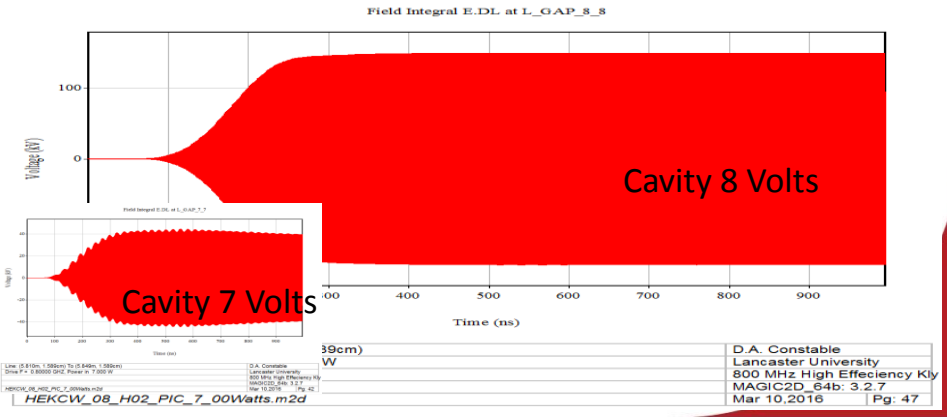
Magic HEKCW #08-H02

- Cavity 1 voltage, 1.35 kV:
- Nice stable output
- No reflected electrons
- Peak modulation current ratio 1.82
- Nice modulation current growth
- Efficiency…..

86%

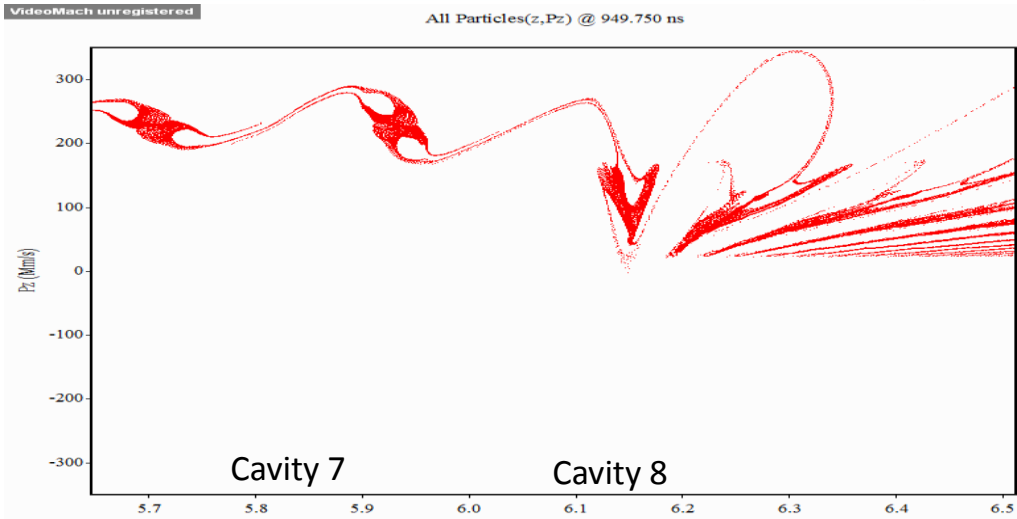


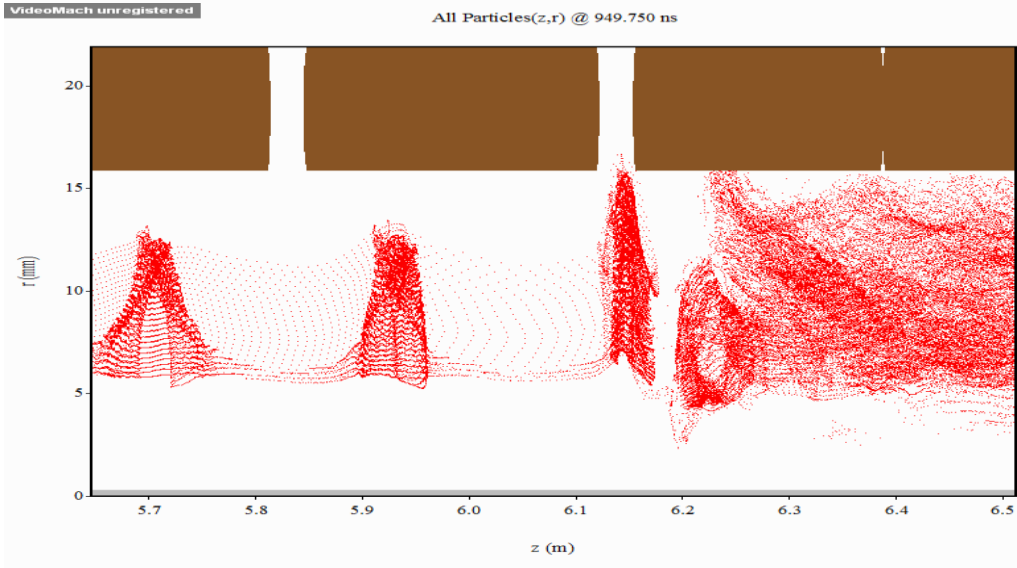




Magic HEKCW #08-H02 Electron Animations

- Some interception, spent beam too close to walls
- Less horrendous bunch but still a bit odd looking
- Deceleration of beam at final gap to less than 0 m s^{-1}





#08_04 vs #08_H02

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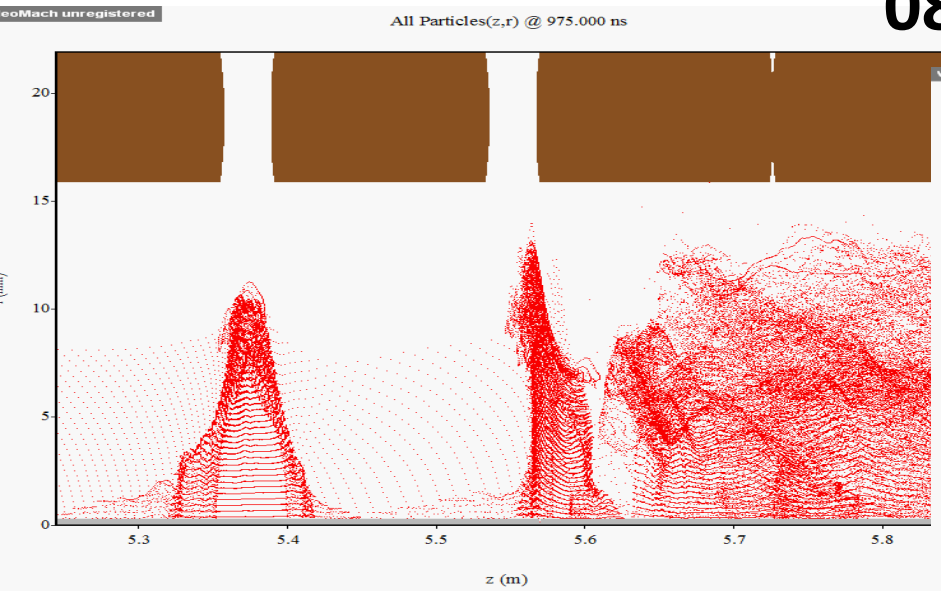
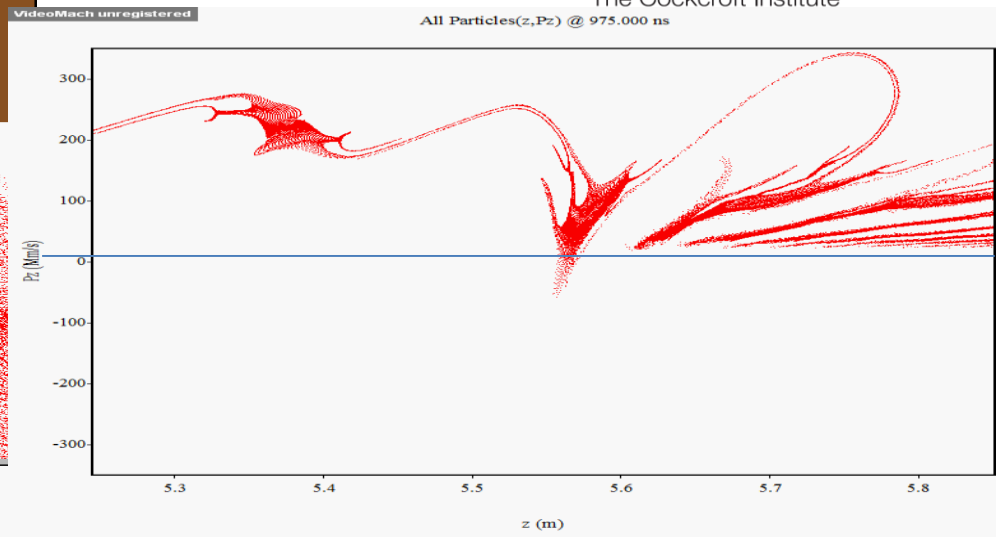
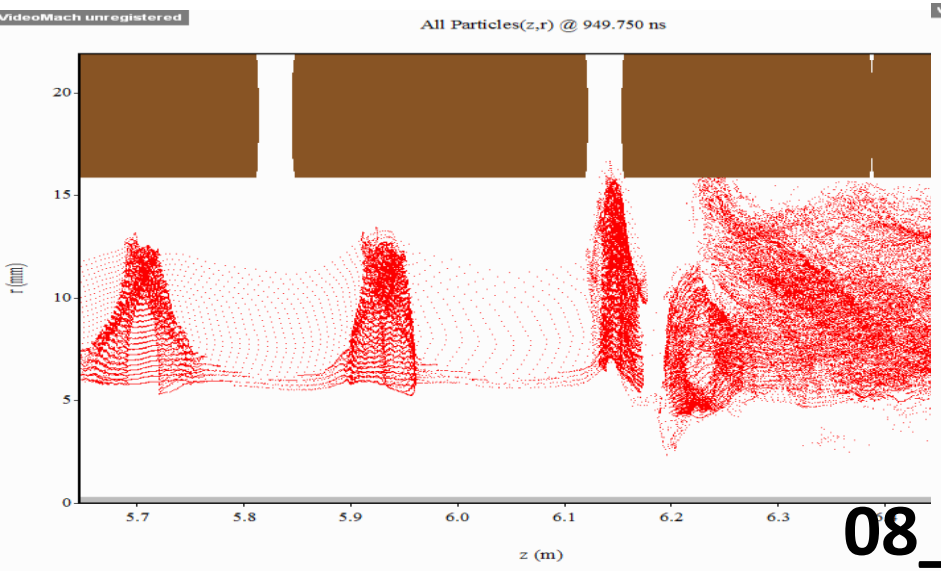
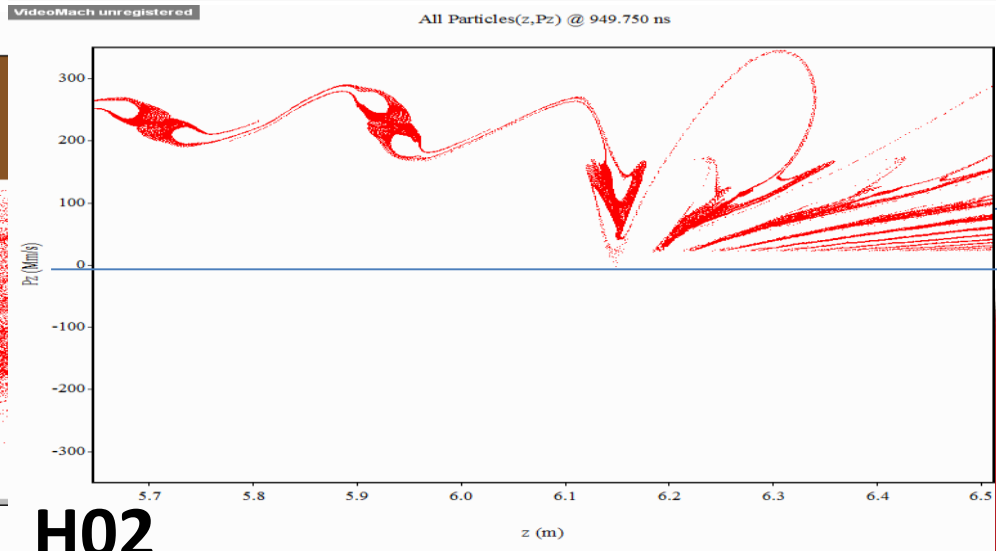
08_04









08_H02

Conclusion and Outlook

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- Using new bunching theory 80%+ looks possible for FCC/CLIC/ESS/ILC klystrons
  - No new materials or manufacturing techniques needed
  - Little additional complexity (extra cavities)
  - **Simply existing technology reconfigured**
  - Prototypes for proof of concept have happened
  - Lower voltages combined with high efficiency appears achievable
- 86% Achieved in PIC
- 90% not yet achieved but ever closer
- Prototypes and further validation required
- International collaboration at work
  - Next step BAC for shorted tubes