The Cockcroft Institute
of Accelerator Science and Technology

Lancaster University

Development of klystrons with ultimately high - 90% RF power production efficiency

A. Baikov (MUFA), I. Syratchev (CERN), C. Lingwood, D. Constable (Lancaster University)

Introduction

- FCC has high power requirements due to high SR in FCC-ee.
  - 100 MW CW
- Traditional Klystrons -> 70%
  - Theoretical efficiencies up to 80%
- MBIOT -> 80%
- Simple minded calculation of wall plug power
  - @ 70% = ~140 MW
  - @ 90% = ~**110 MW**

State of art: L-band 10 MW MBK klystrons for ILC.

Thales

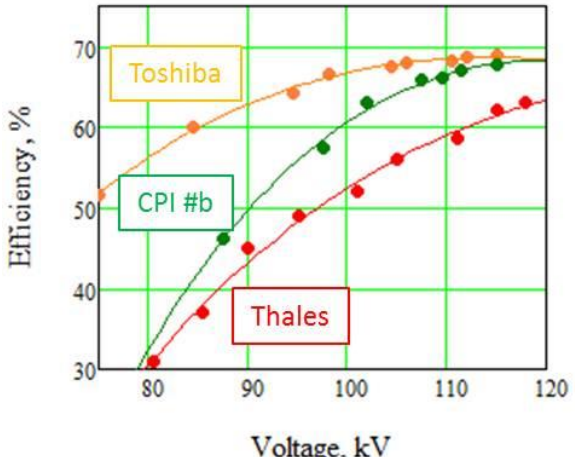
Toshiba

CPI #a

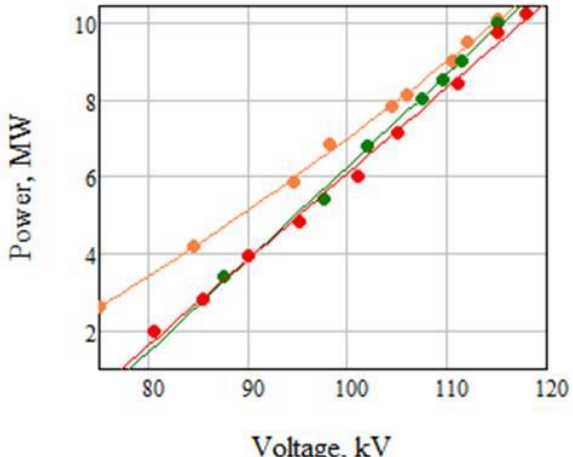
CPI #b

In terms of achieved efficiency at 10 MW peak RF power level, the existing MBK klystrons provides values very close to 70%.

In saturation

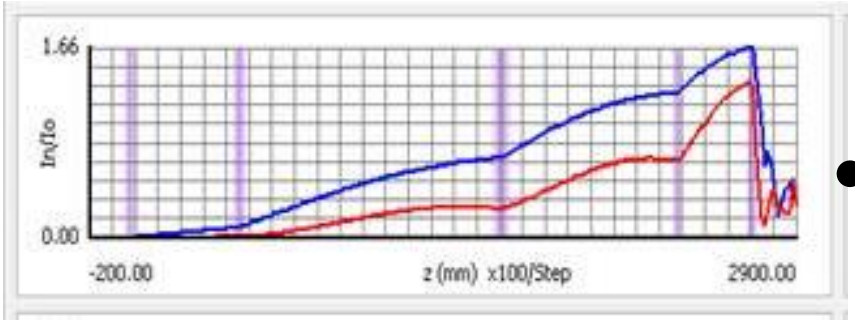


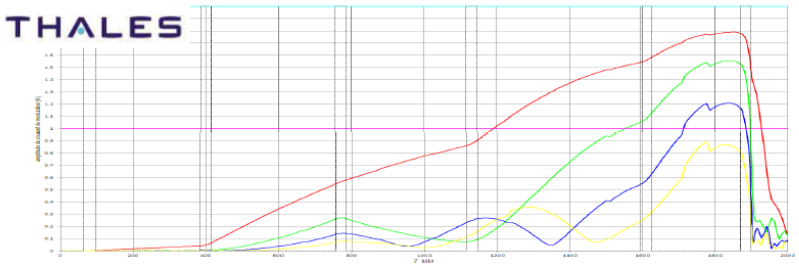
In saturation

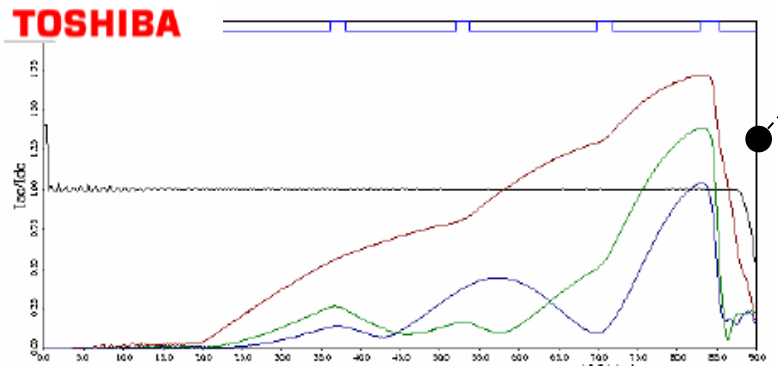


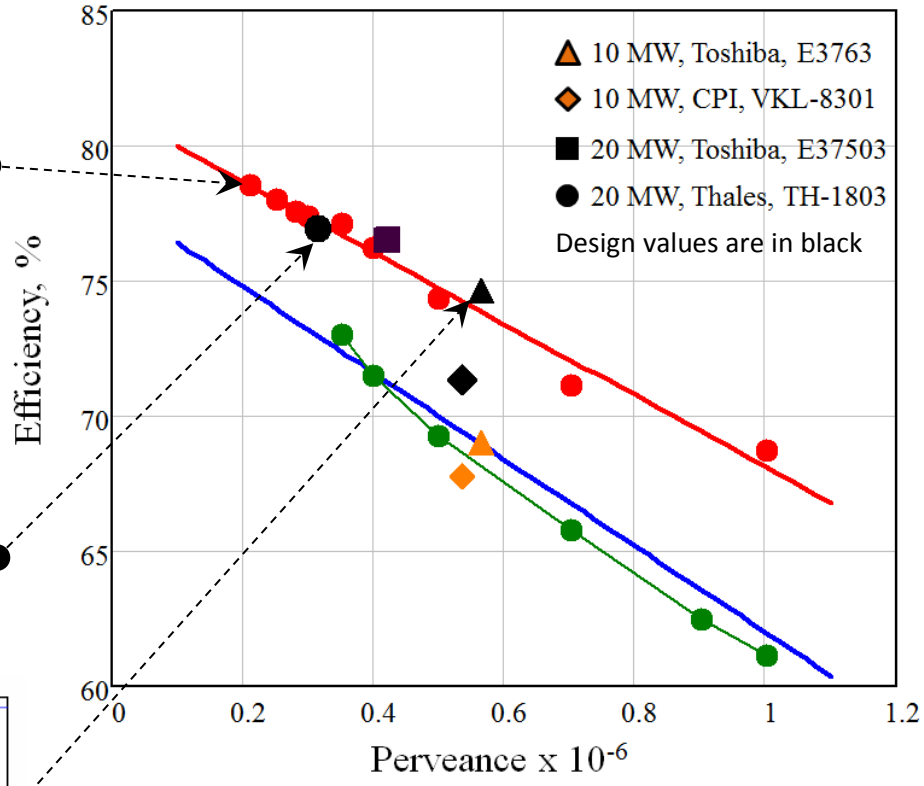
Scaling of the klystron parameters

thanks to (C Marelli)



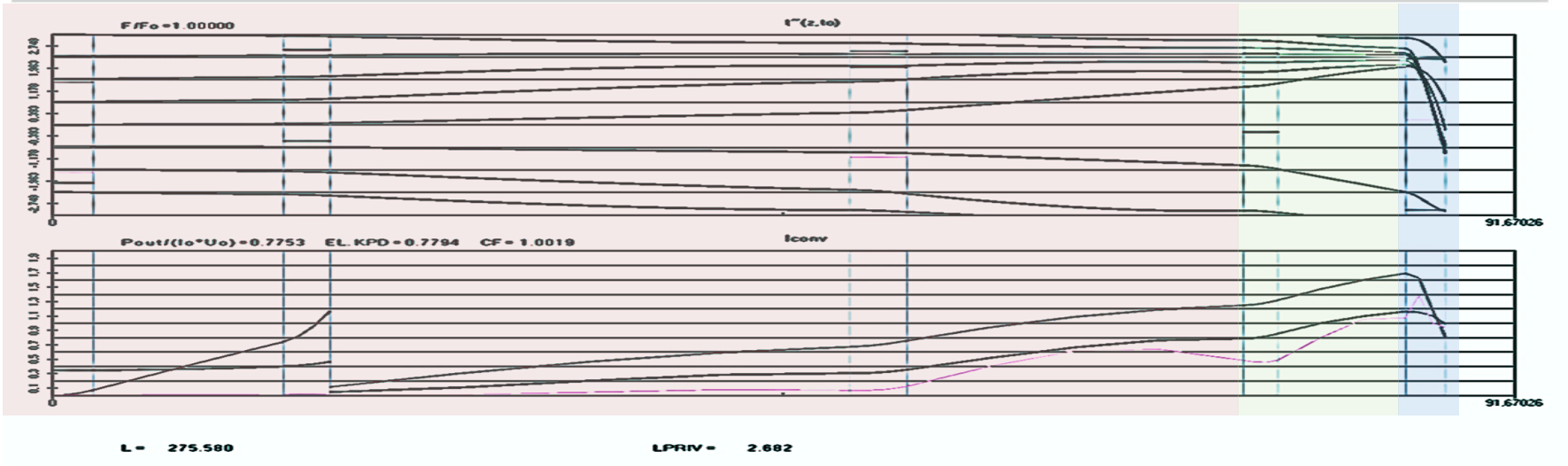




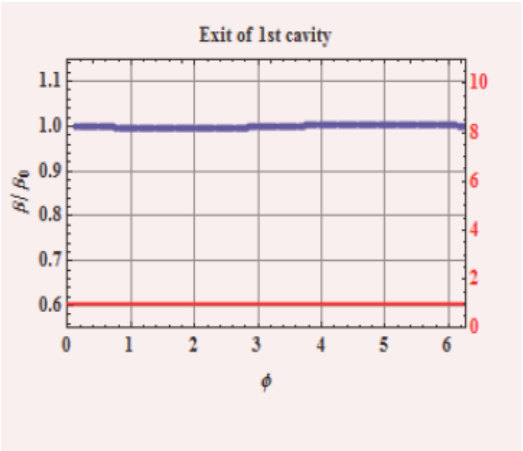


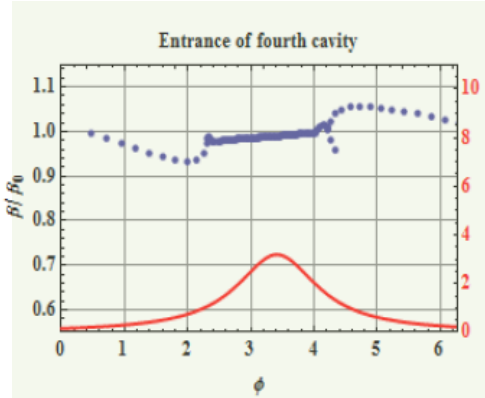
To go higher in efficiency, the intrinsic limits of the bunching processes and deceleration in the output cavity need to be understood

Process in the *traditional* Klystron

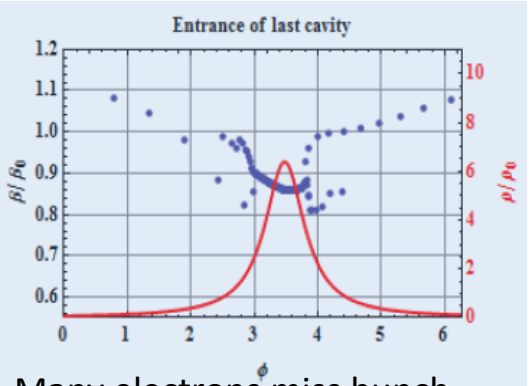


Bunching monotonic – electrons move to center of bunch



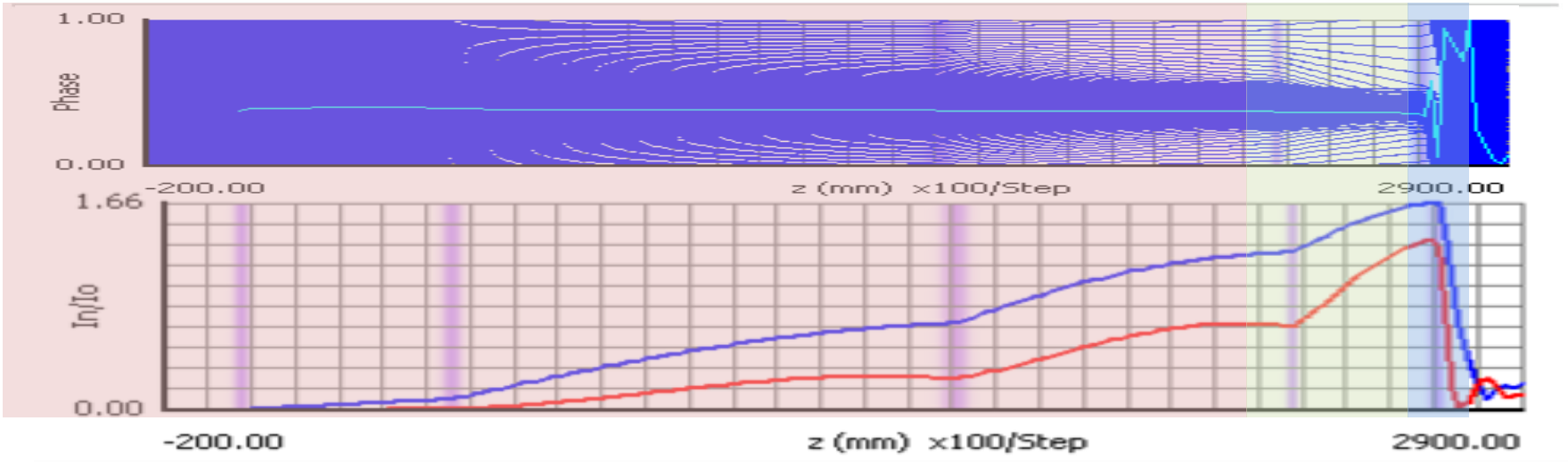


Significant charge outside bunch. Velocities aligned…

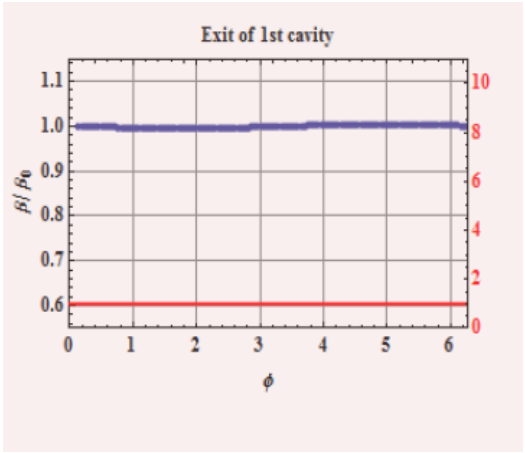


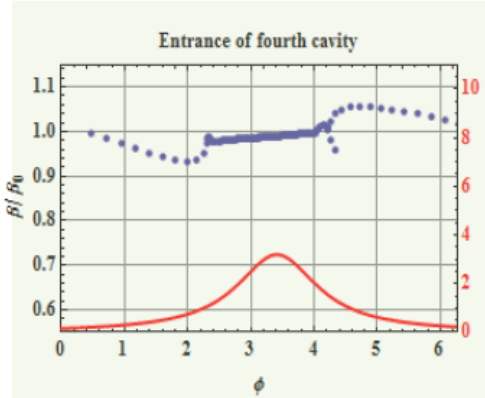
Many electrons miss bunch. **Significant energy left in bunch!**

Process in the *traditional* Klystron



Bunching monotonic – electrons move to center of bunch





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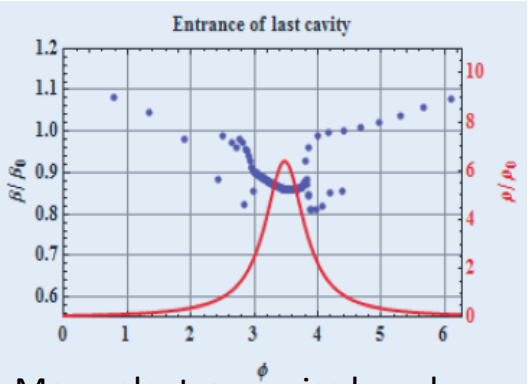


Many electrons miss bunch. **Significant energy left in bunch!**

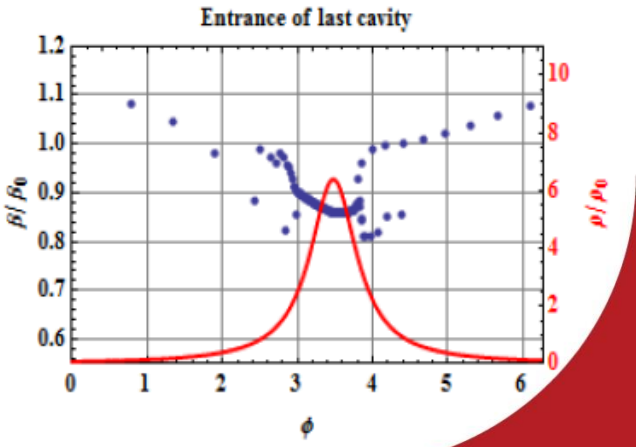
Limitations

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

- Limited by the slowest electrons (***must*** avoid trapping or reflecting electrons)

- Ultimate theoretical efficiency

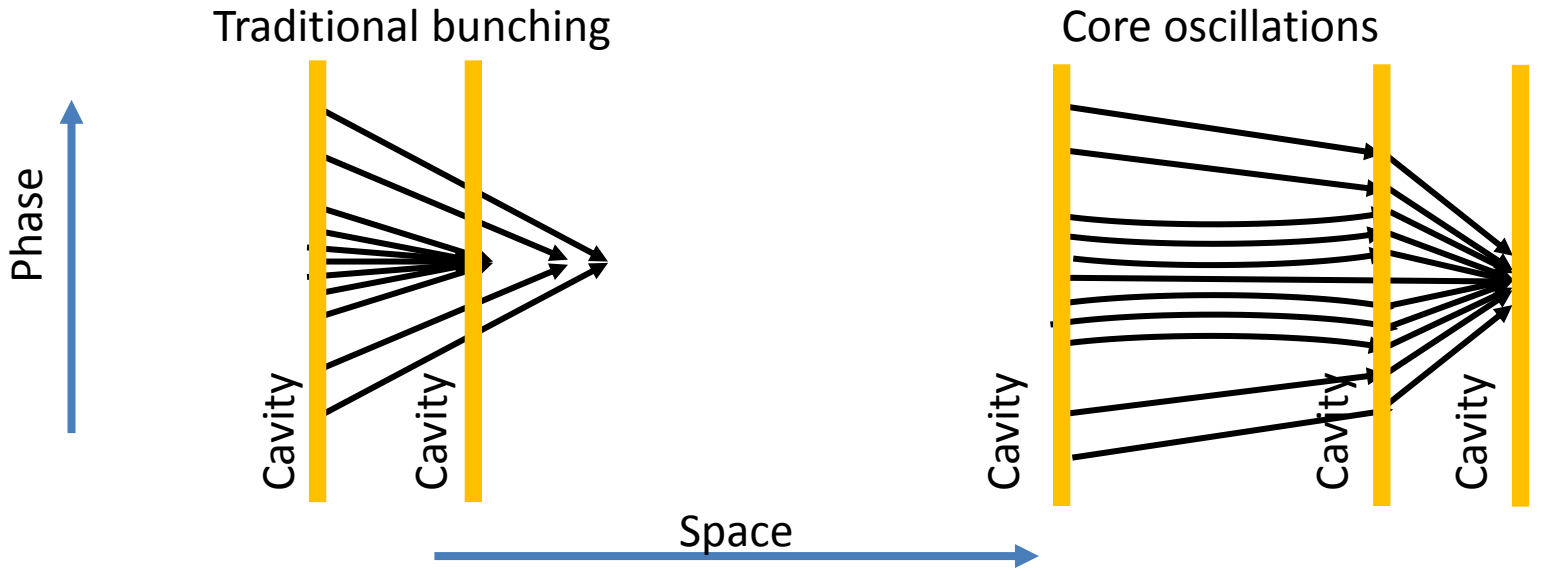
  limited to 80%



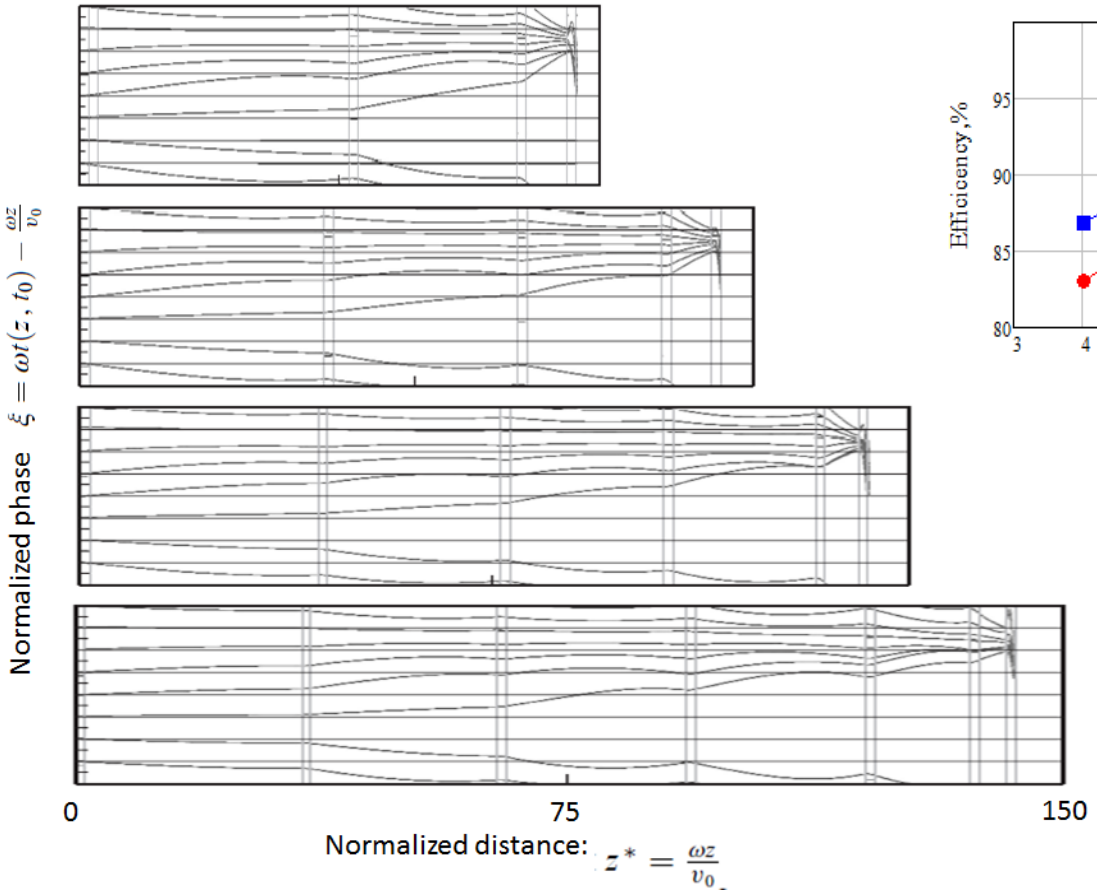
Methods to get high efficiency

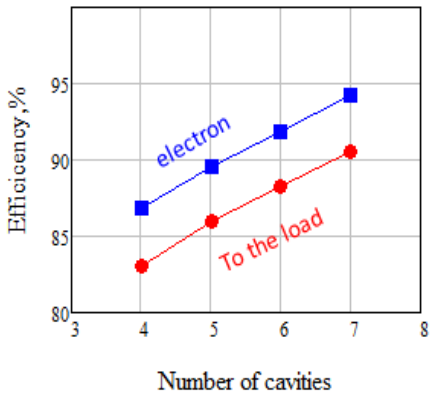
Space charge Debunching

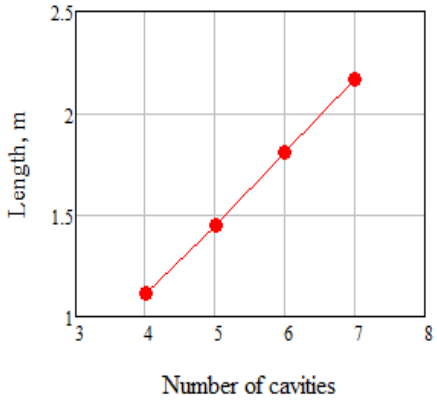
- Bunching split into two distinct regimes:
  - non-monotonic: core of the bunch periodically contract and expand (in time) around center of the bunch
  - outsiders monotonically go to the center of the bunch
- Core experiences higher space charge forces which naturally debunch
- Outsiders have larger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



90% Efficient Klystron







Simulation of Conditions for the Maximal Efficiency of Decimeter-Wave Klystrons

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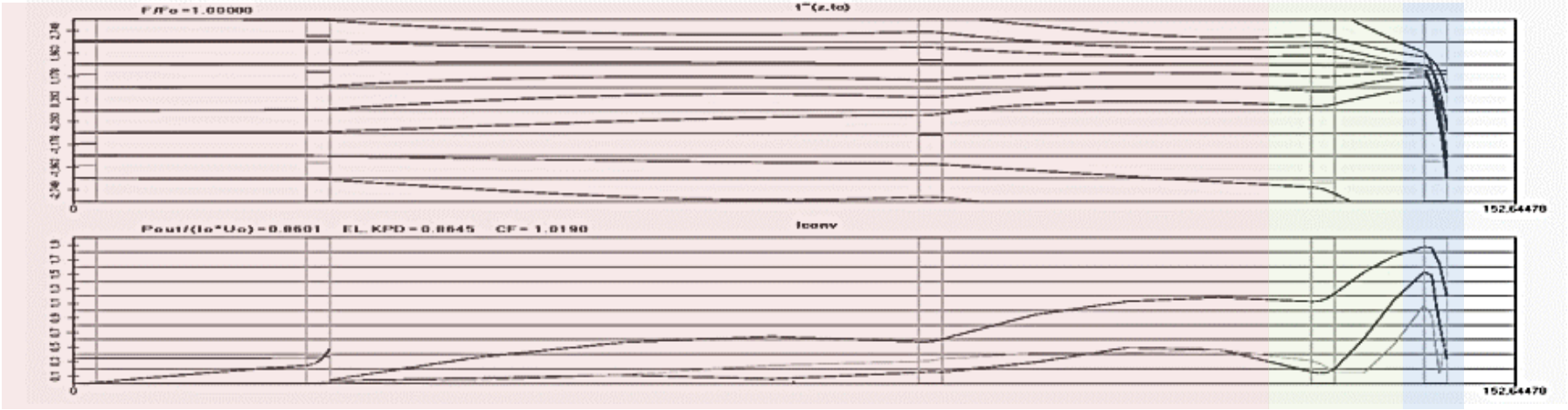
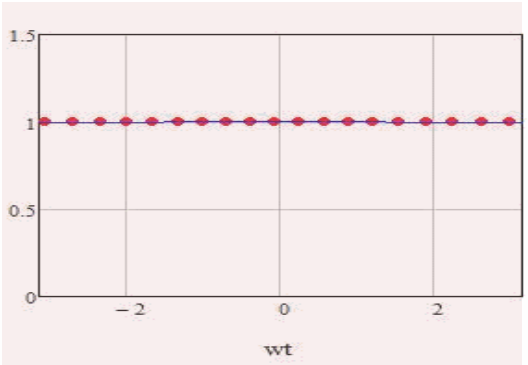
- Efficiency increases with number of core oscillations and reaches 88-90% for 4-5 oscillations

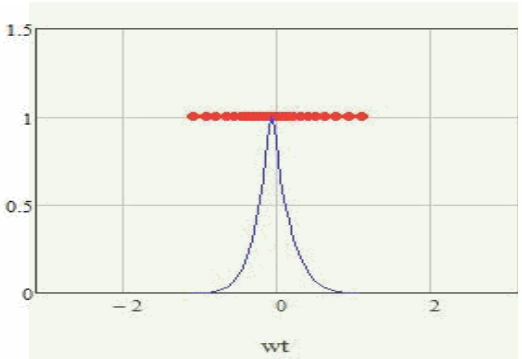
Process in the high efficiency klystron



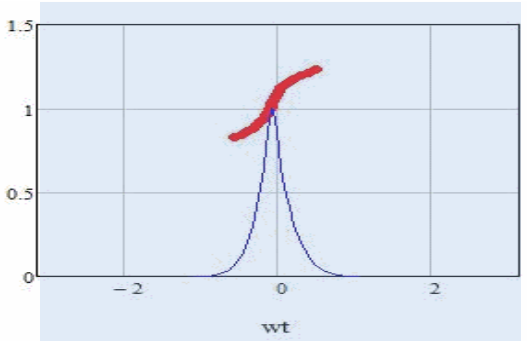
Electron velocity/density



The fully saturated (FS) bunch



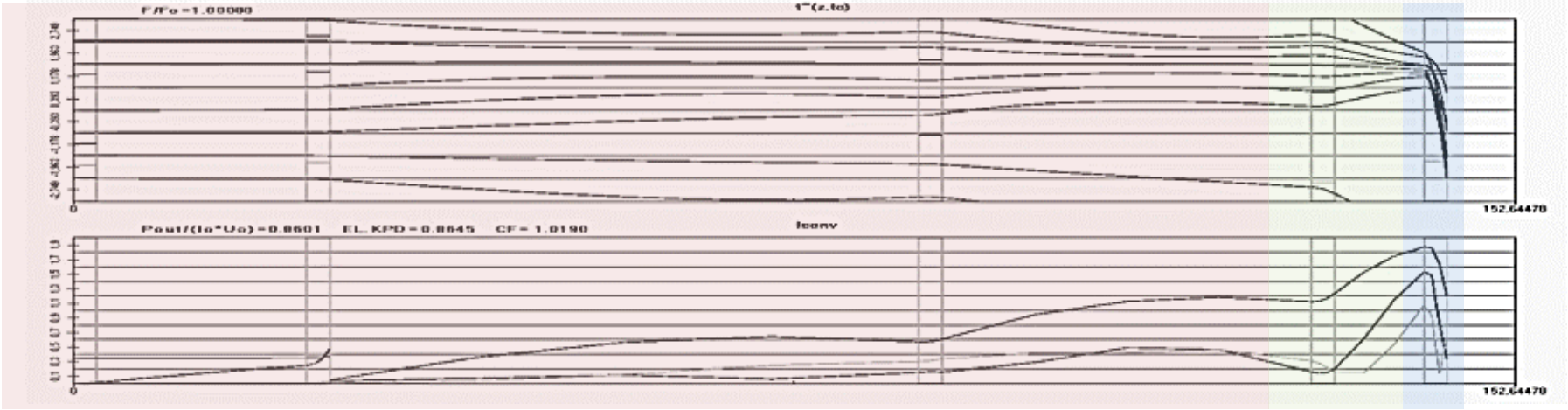
Final compression and bunch rotation prepare congregating FS bunch.

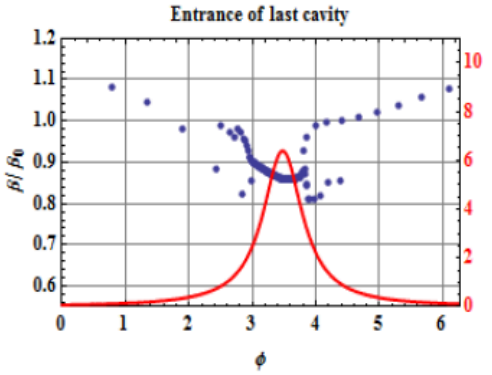


After deceleration all the electrons have identical velocities.

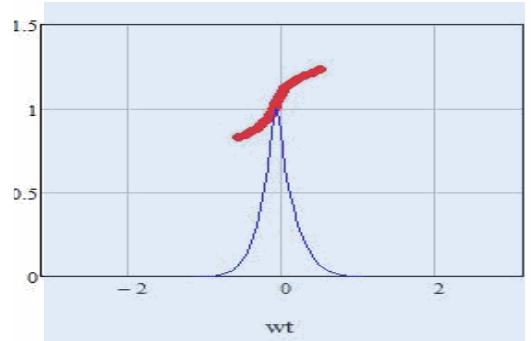
Mission accomplished

Process in the high efficiency klystron





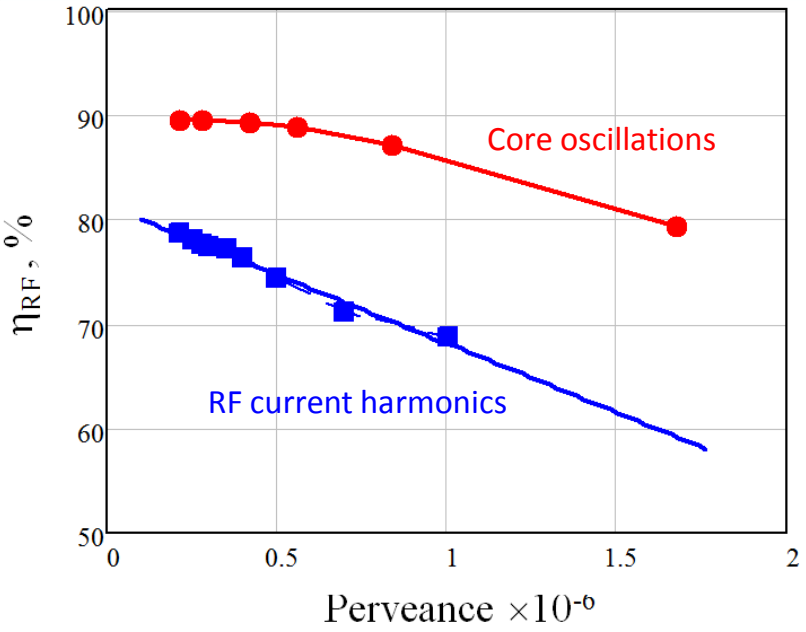
Output of traditional klystron

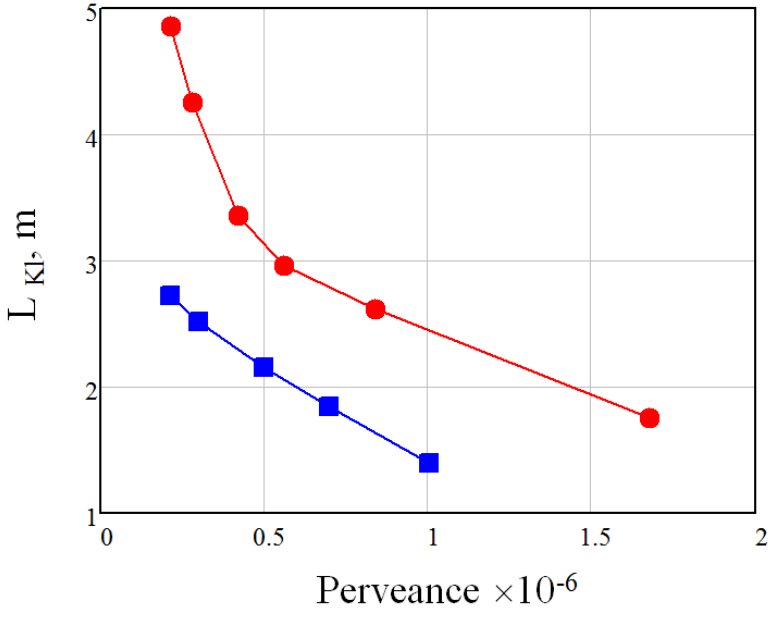


After deceleration all the electrons have identical velocities.

Mission accomplished

Comparison of the two bunching methods.



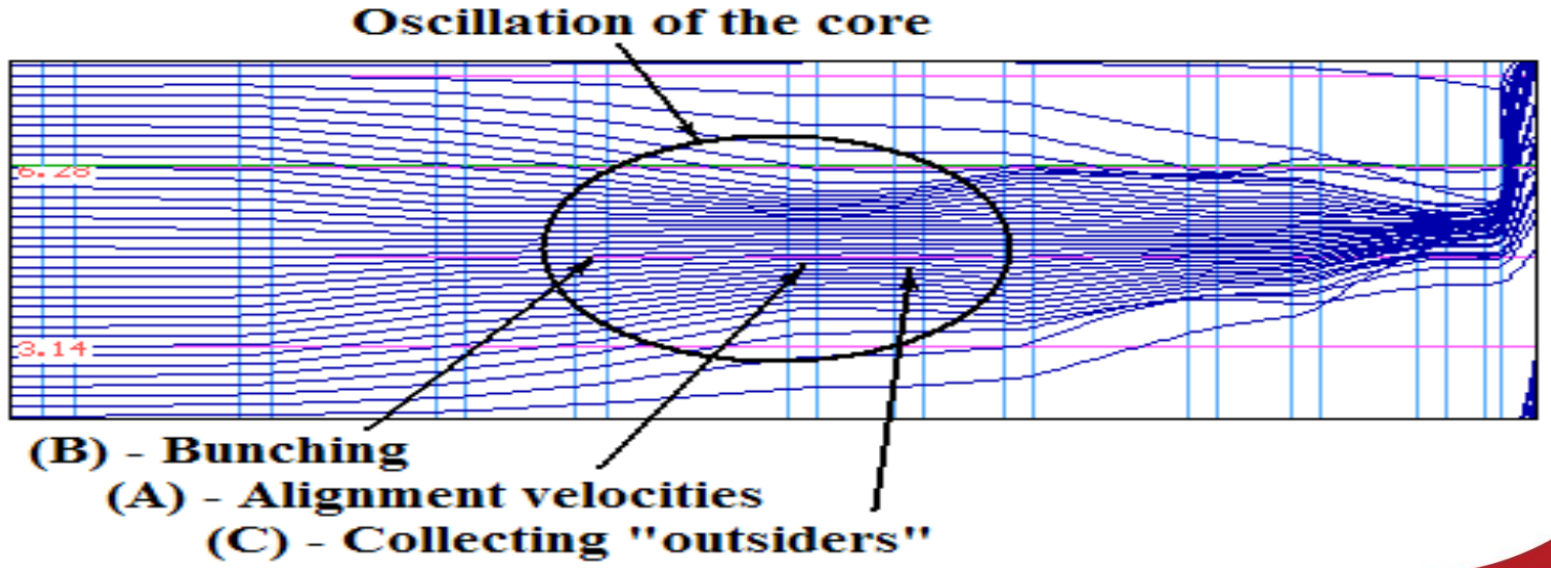


- For the ultimate high efficiency, there is a substantial increase of the bunching length.
- Efficiency degradation up to perveance as high as 1×10-6 appeared to be rather small (about 3%).
- Standard practice of reducing the klystron perveance is not the way to achieve very high, above 80%, efficiency.

Methods to get high efficiency

BAC Method (I. Guzilov)

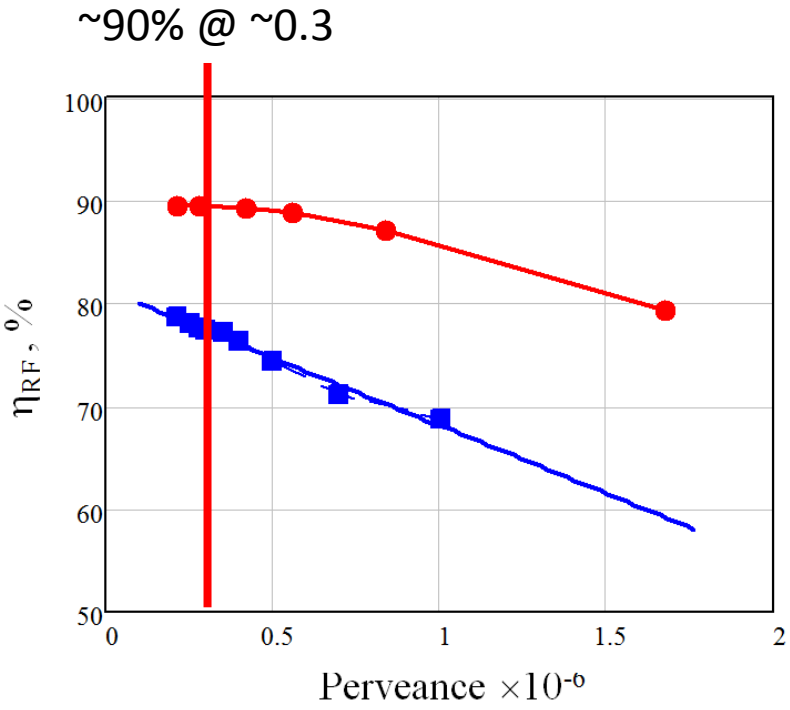
- Again based on core oscillations
- Interaction space is wasted “waiting” for space charge forces to debunch.
- A cavity can achieve the same thing in a shorter space by aligning electron velocities
- Structure **half the length** while maintaining efficiency.



Potential FCC Klystron Specification

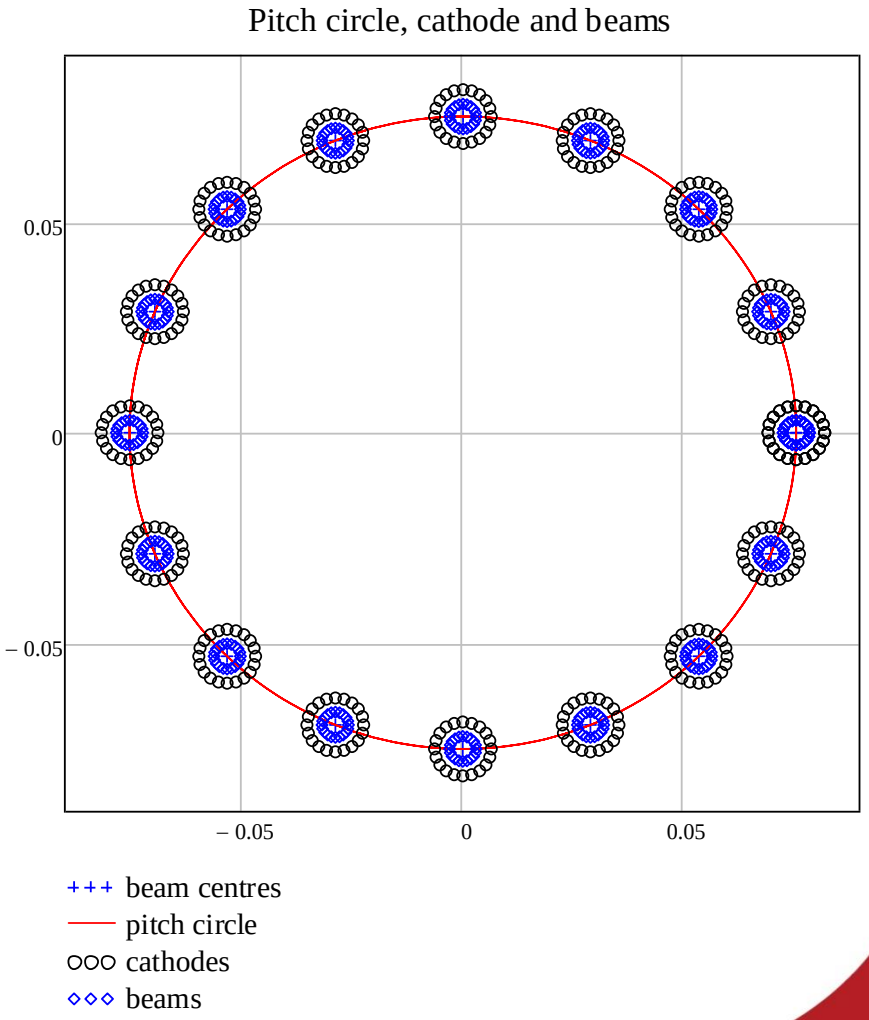
- Using **core oscillation method**

- Frequency: 0.8 GHz
- RF power: 1.5 MW
- Beam voltage: **40 kV**
- Number of beams: **16**
- Total current: 42A
  - Per beam 2.6 A
- Efficiency: **90%**
- Perveance: **0.326 microPerv**
- Duty 100%



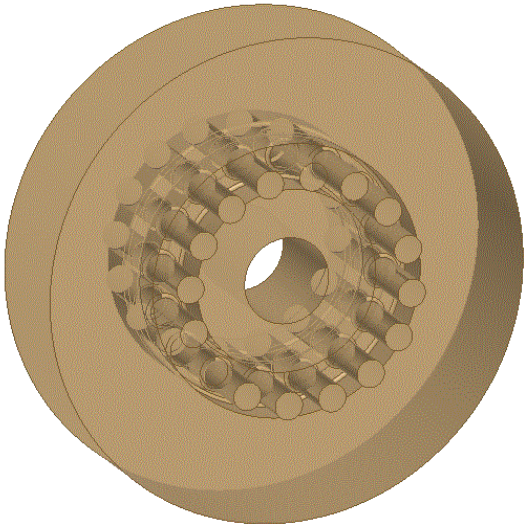
Tube configuration

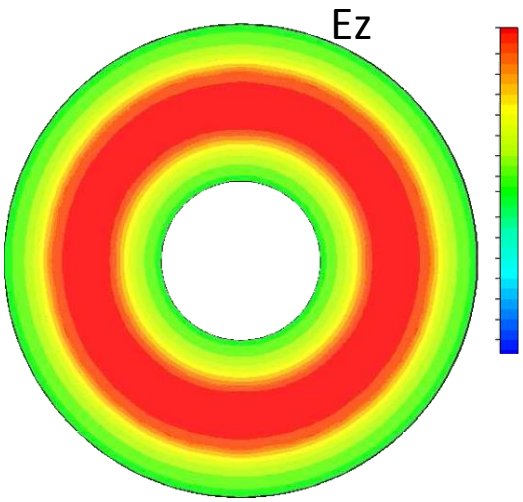
- Cathode loading: 2 A/cm^2
- Beam radius: 3 mm
  - Filling factor 8 mm
- Length: 2.3 m
- Beam circle radius: 75 mm
- Solenoid field (2x): 600 G
- Solenoid radius: 150 mm
- Collector: common
  - Nominal load: 170 kW
  - Peak load: 1.5 MW (no RF)

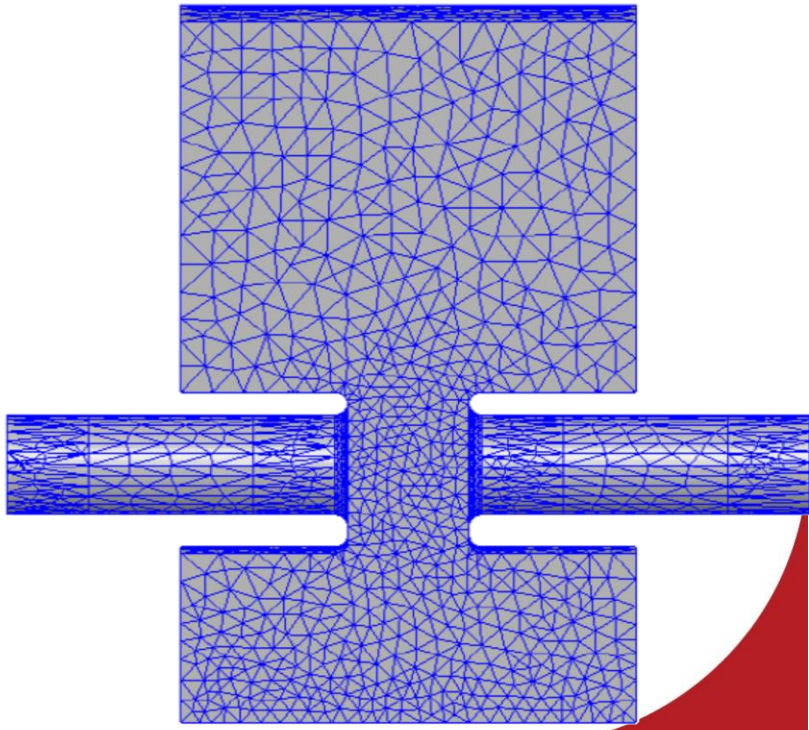


MBK Structure: Cavity

- Coaxial cavity
  - Best trade off between compactness, R/Q and manufacturability
  - R/Q 22 Ohms @ ~800 MHz
    - Single beam equivalent 352 Ohms

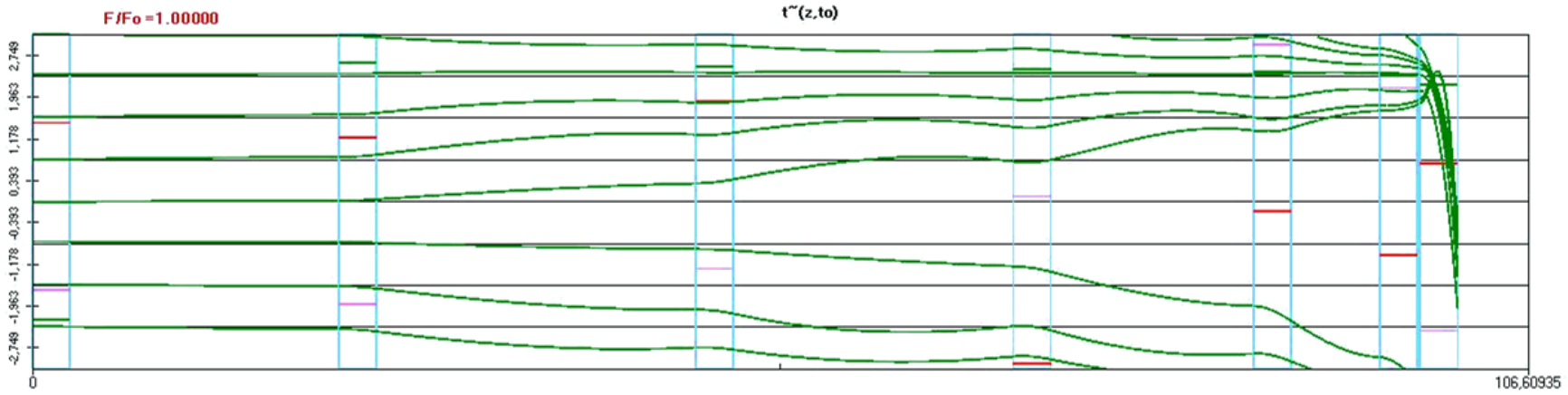


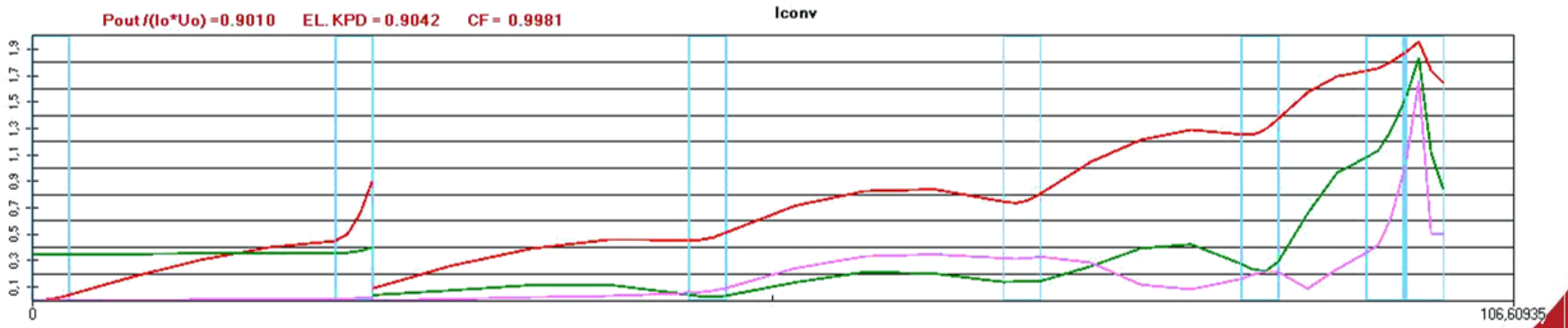




Proposed Interaction Structure

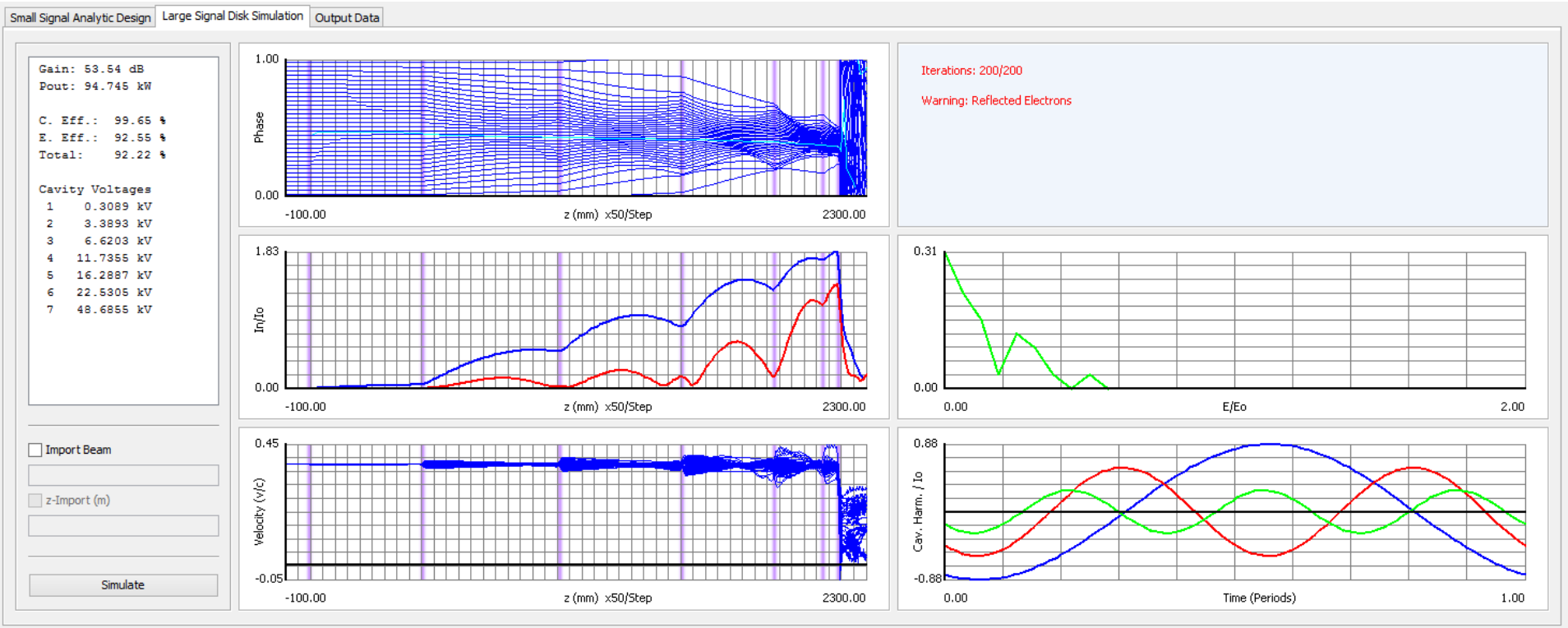
- 3 Oscillations of core.
- 90.42% efficient





AJDisk comparison

- A dubious 92.2% but some validation
- Some reflected electrons
- Greens function method limited at high efficiency



Outlook

Lancaster University

- 90% is theoretical but:
  - No new materials needed
  - No new manufacturing techniques needed
  - No additional complexity
  - **Simply existing technology reconfigured**
  - Would normally expect to lose 5% points (so 85%) from simulation to reality
- Tube also well suited to ESS, potential for prototype?
- Prototypes planned for proof of concept

HEIKA Collaboration
(as of January 2015)

CEA

PEAUGER Franck
PLOUIN Juliette
DALENA Barbara

Thales

MARCHESIN Rodolphe
VUILLEMIN Quentin

MUFA, Moscow

BAIKOV Andrey

JSC 'VDBT'

GUZILOV Igor

Lancaster

LINGWOOD Christopher
CONSTABLE Dave
HILL Victoria

CERN

SYRATCHEV Igor

ESS

MARRELLI Chiara

CCR Inc.

READ Michael

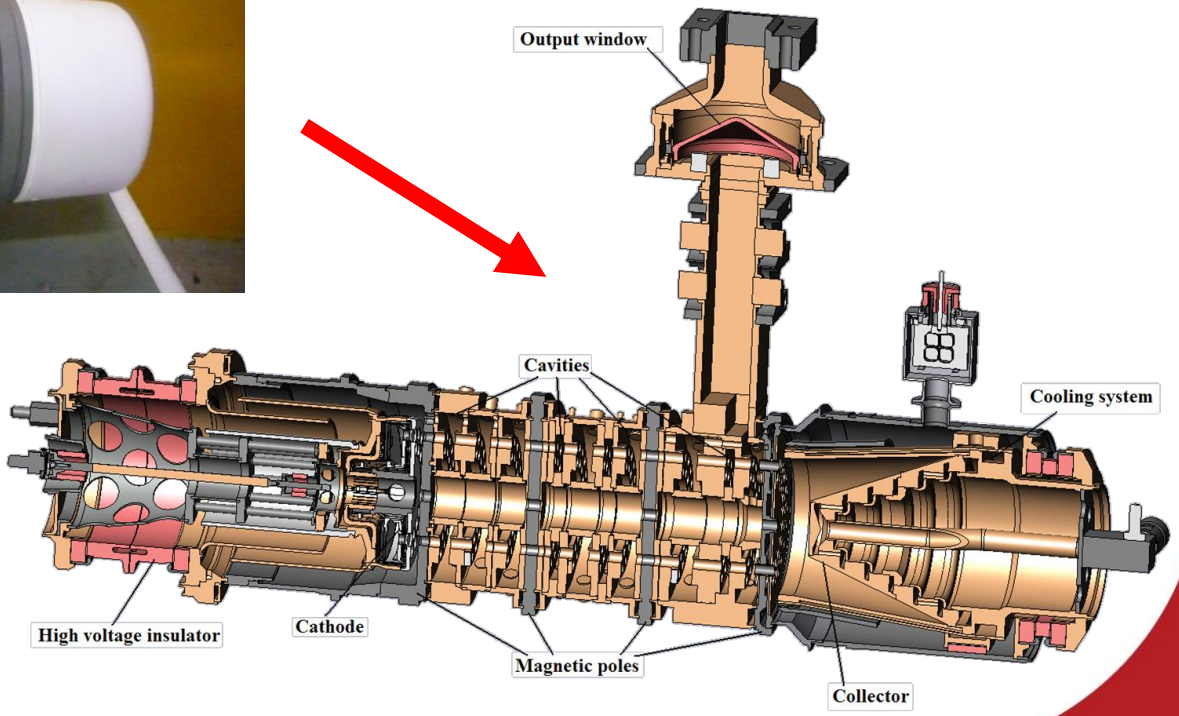
HEIKA's tubes selection

- **L-band**: Low perveance MBK
  1. CLIC: Frequency 1.0 GHz, pulse length 150 microsecond, 20 MW Multi-beam klystron with 40-60 beams. Microperveance per beam 0.3-0.5, operating voltage below 60 kV. Expected efficiency above **85%**.
  2. FCC (ESS): Frequency 0.8 GHz, continuous wave, 1.5 MW Multi-beam klystron with 10-16 beams. Microperveance per beam ~0.2, operating voltage 40-50 kV. Expected efficiency above **90%**.
- **S-band**:
  1. 3 GHz technology demonstrator. 6 microsecond, 6 MW Multi-beam klystron with 40 beams. Microperveance per beam <0.3, operating voltage 52 kV. Expected efficiency **>70%** (with PPM focusing).
- **X-band**: High perveance single beam
  1. 12 GHz klystron with **adiabatic bunching**. 5 microsecond, 12 MW. Microperveance per beam ~1.5, operating voltage 170 kV. Expected efficiency **>75%**.

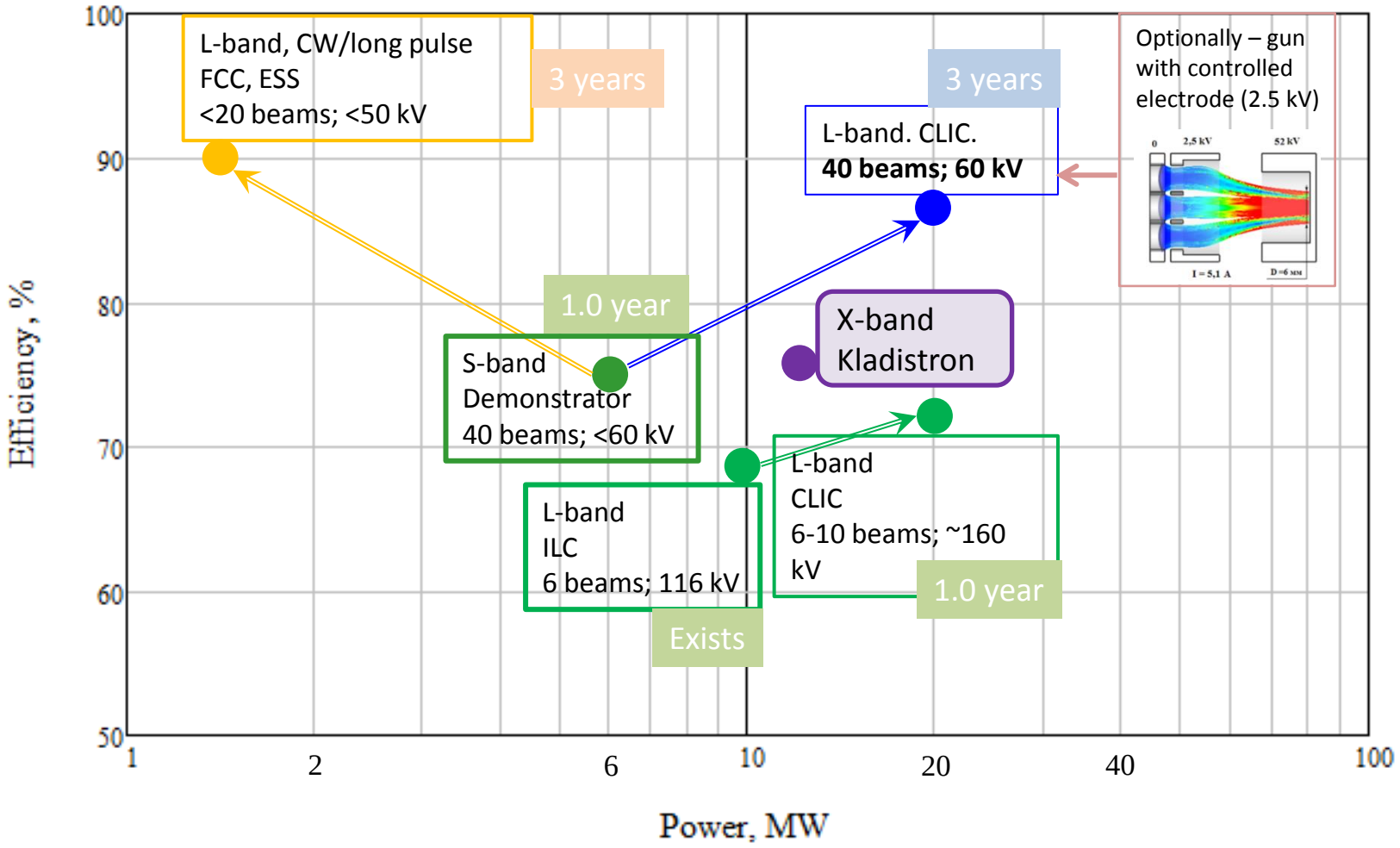
Prototype (KIU-147A)
I Guzilov (JSC)

F	2.856 GHz
Power	6 MW
Voltage	52 kV
Efficiency	**45 %**
Beams	**40**

F	2.856 GHz
Power	6 MW
Voltage	52 kV
Efficiency	**> 76 %**



Roadmap for high-efficiency high RF power klystron development



Conclusion

- Using new bunching theory 90% (at least in simulation) looks possible for FCC/CLIC/ESS klystrons
- Low voltages achievable
- No new technology, simply a design breakthrough

- Prototypes and further validation required
- International collaboration at work