High-efficiency klystron development

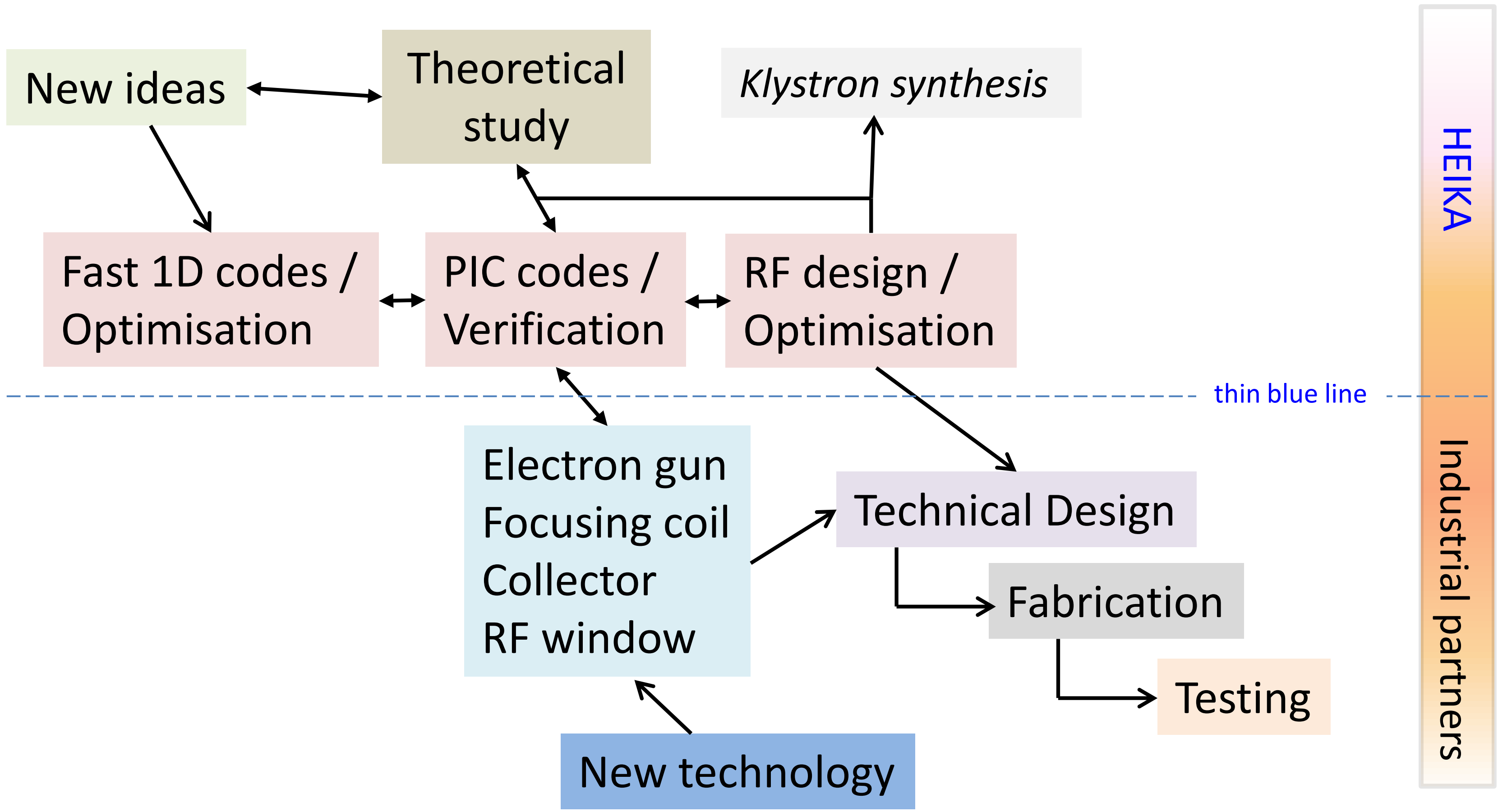
I. Syratchev on behalf of
High Efficiency International Klystron Activity
HEIKA

Motivation for HEIKA

- The increase in efficiency of RF power generation for the future large accelerators such as CLIC, ILC, ESS, FCC and others is considered a high priority issue.
- Only a few klystrons available on the market are capable of operating with 65% efficiency or above. Over decades of high power klystron development, approaching the highest peak/average RF power was more important for the scientific community and thus was targeted by the klystron developers rather than providing high efficiency.
- The deeper understanding of the klystron physics, new ideas and massive application of the modern computation resources are the key ingredients to deign the klystron with RF power production efficiency at a level of 90% and above.

The coordinated efforts of the experts in the Labs and Universities with a strong involvement of industrial partners worldwide is the most efficient way to reach the target … thus HEIKA.

HEIKA map


New ideas
Theoretical study
Klystron synthesis
Fast 1D codes / Optimisation
PIC codes / Verification
RF design / Optimisation
thin blue line
Electron gun
Focusing coil
Collector
RF window
Technical Design
Fabrication
Testing
New technology
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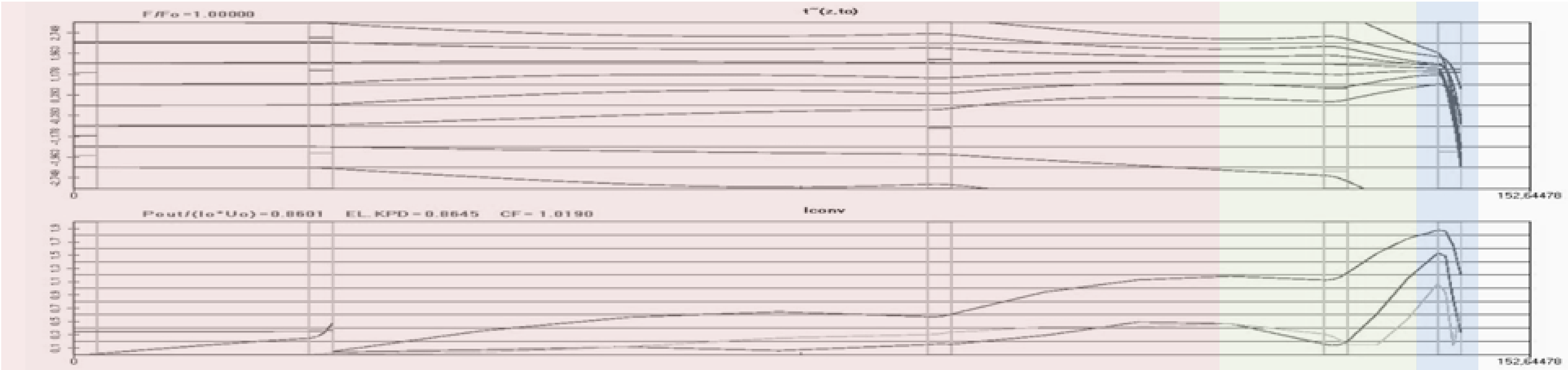
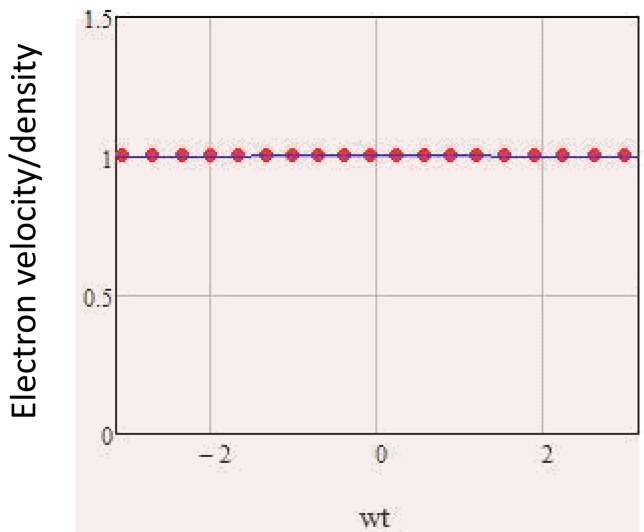
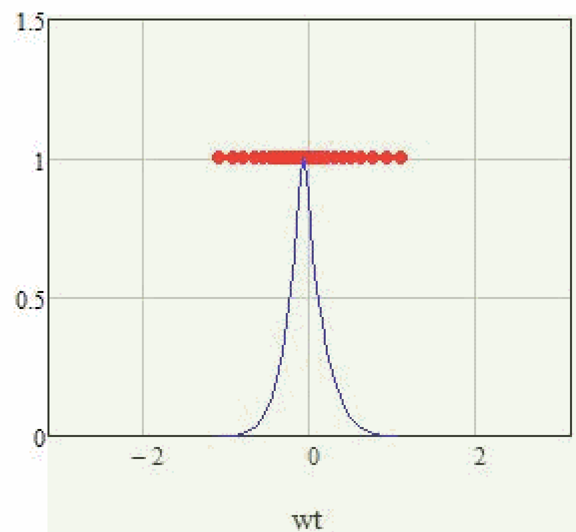
Industrial partners

Personal recollection of the process in the high efficiency klystron (for illustration only)

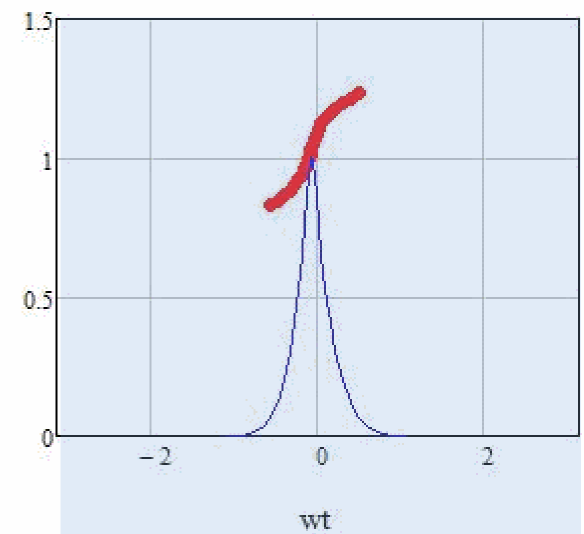




The fully saturated (FS) bunch



Final compression and bunch rotation prepare congregating FS bunch.



After deceleration all the electrons have identical velocities.

Mission accomplished

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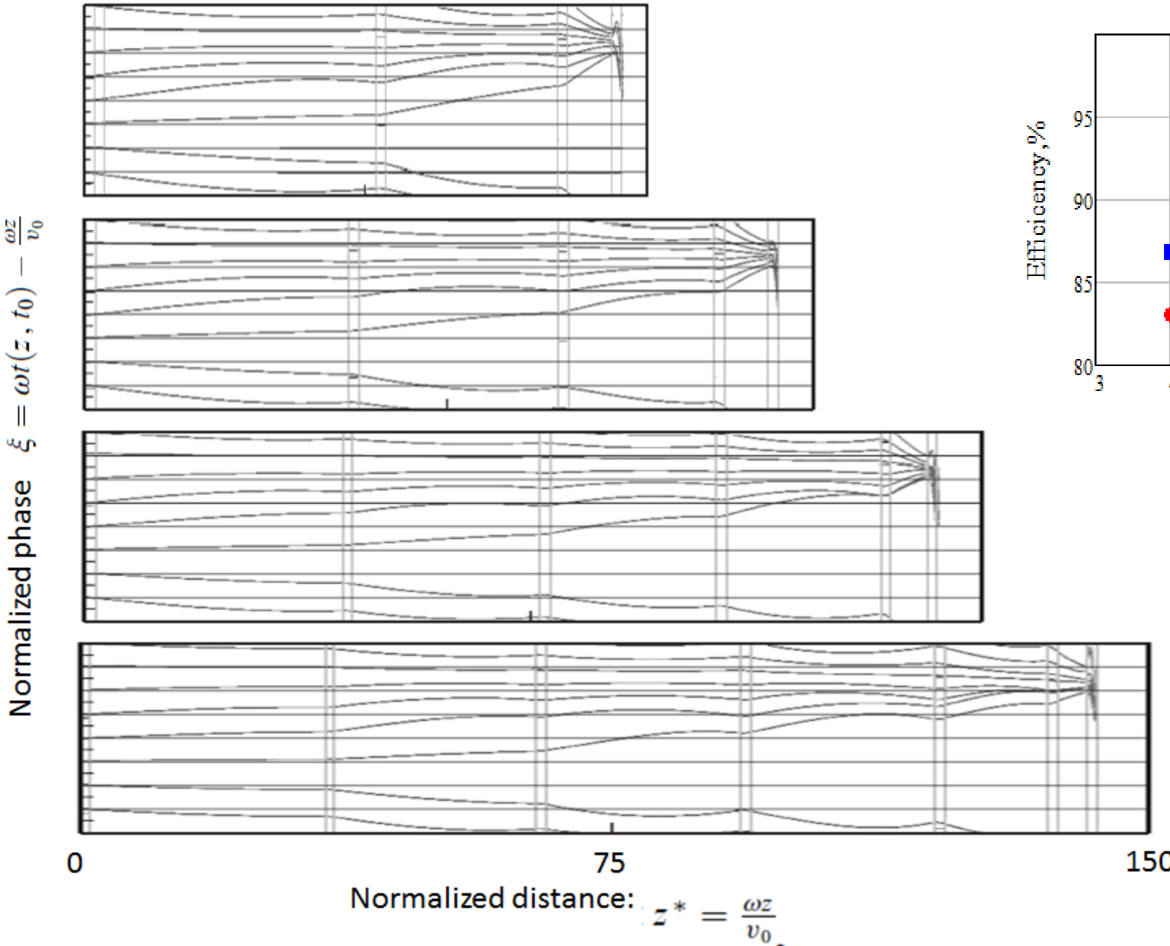
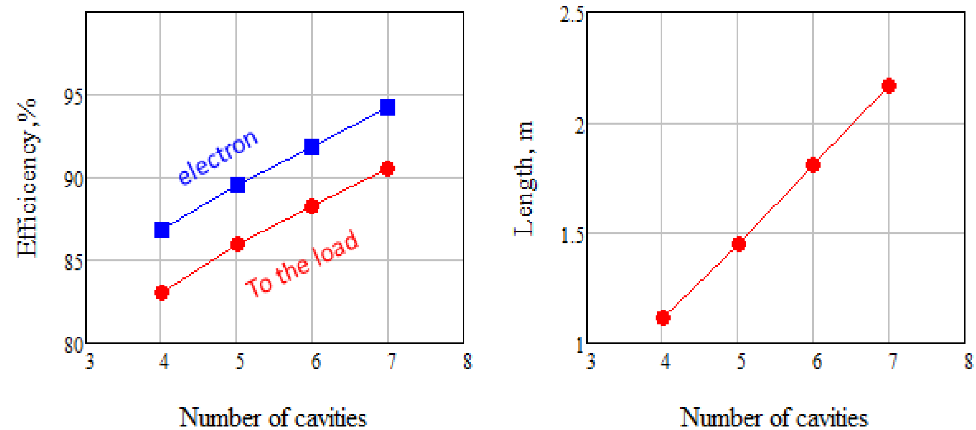
90% efficient klystron.





Towards high power klystrons with RF power conversion efficiency in the order of 90%

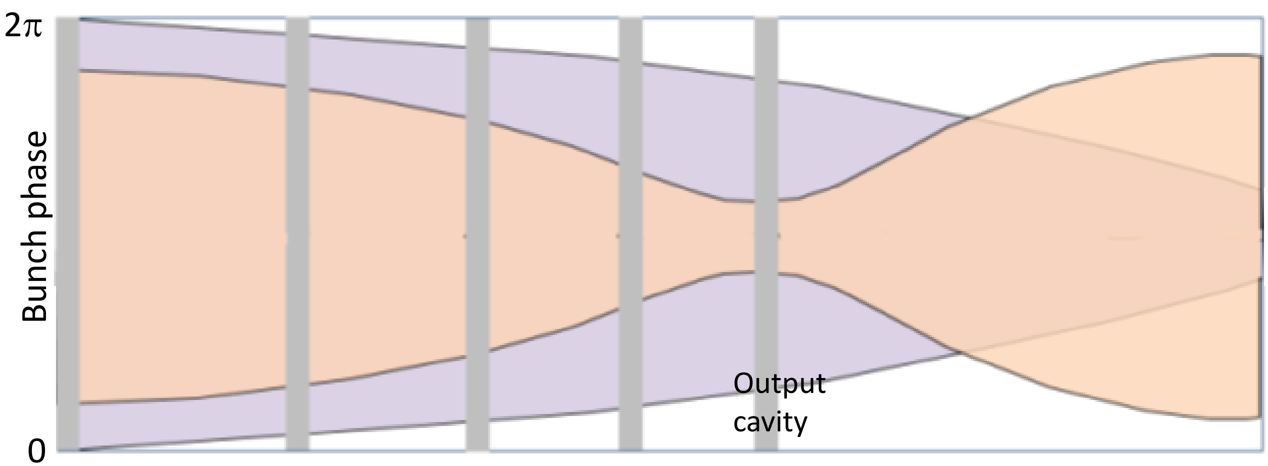
A. Yu. Baikov, *MFUA, Russia*, I. Syratchev, *CERN, Switzerland* and C. Marrelli, *ESS, Sweden*

Submitted to IEEE T-ED 07.06.2015

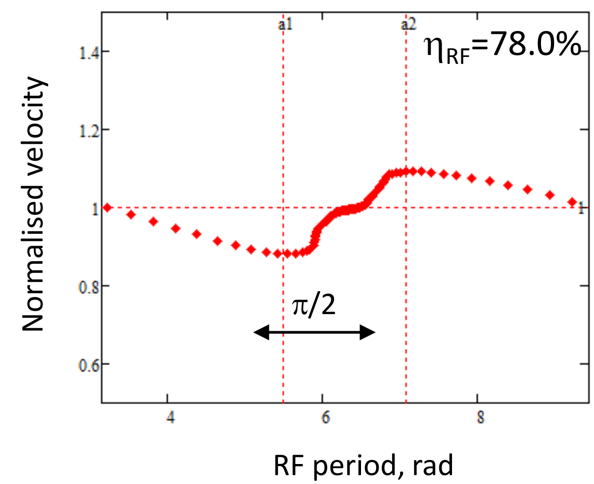
To achieve very high efficiency, peripheral electrons should receive much stronger relative phase shift than the core electrons and this could happens only, if the **core** of the bunch experiences **oscillations** (COM) due to the space charge forces, whilst the peripherals approach the bunch centre monotonously.

Comparison of the two bunching methods #1.

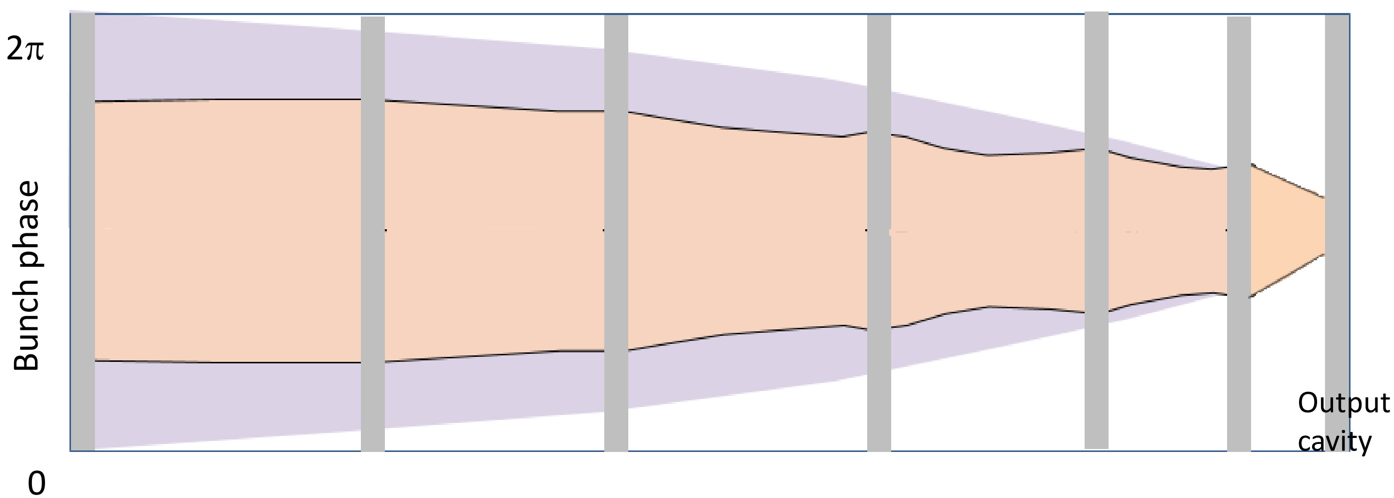
"Classical" bunching

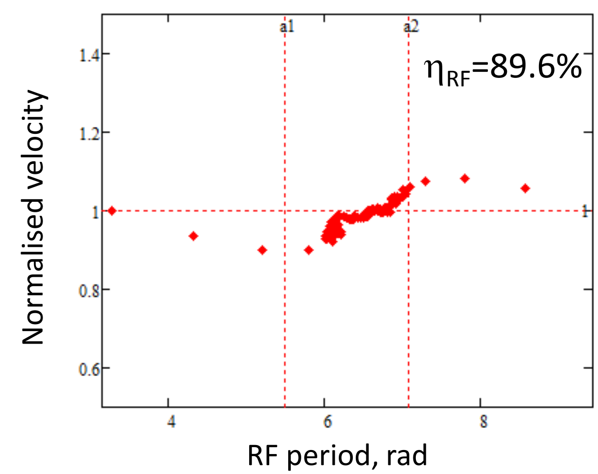


Bunch velocities distributions prior entering the output cavity

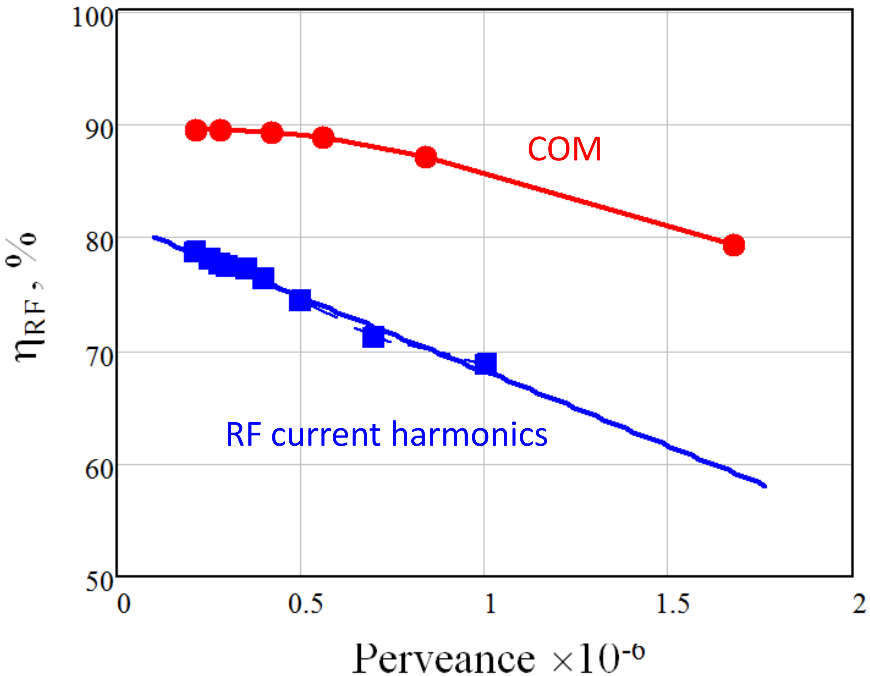


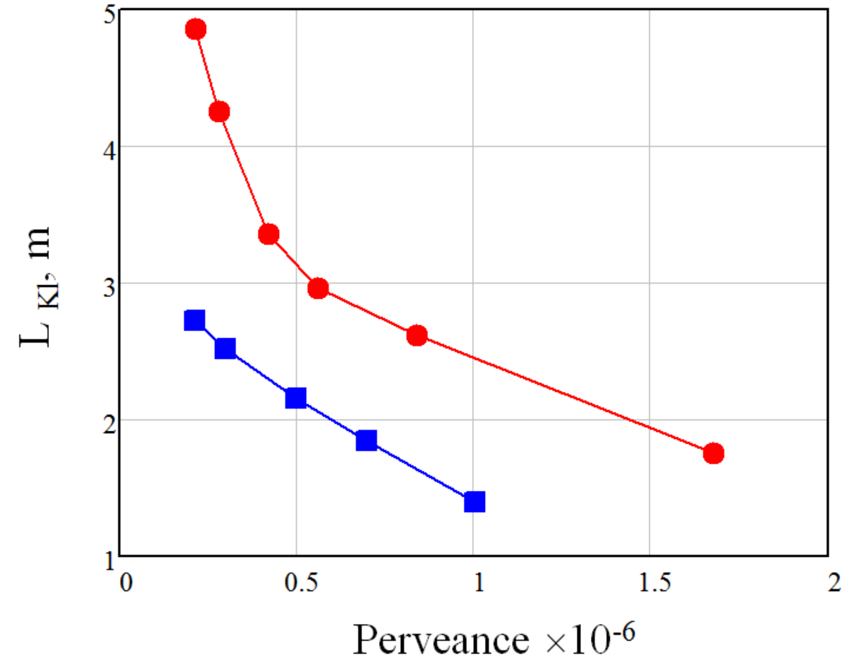
Bunching with core oscillations





Comparison of the two bunching methods #2.



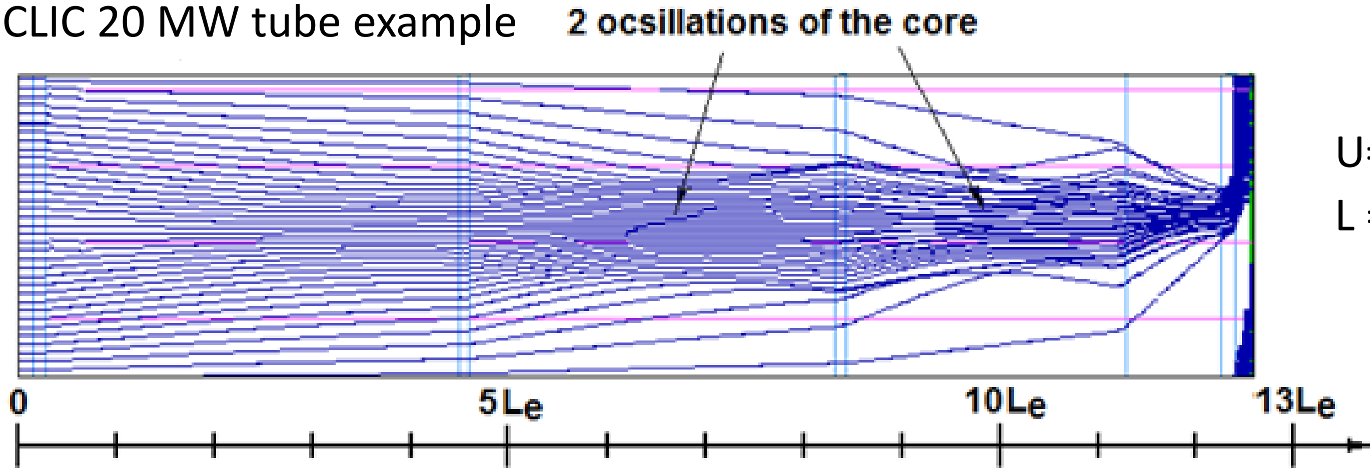


- For the ultimately high efficiency, technical implementation of the bunching method with core oscillations will require substantial increase of the bunching length.
- The observed efficiency degradation up to perveance as high as 1×10^{-6} appeared to be rather small (about 3%).
- This results also imply that reducing the klystron perveance is not the necessary condition to achieve very high, above 80%, efficiency.

Bunching-Alignment-Collecting (BAC) technology

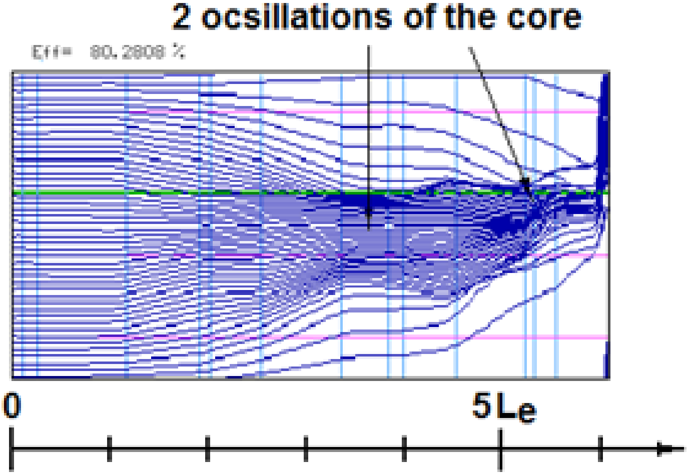
BAC is technical extension of COM, where the impedances of the cavities triplet allows to reduces dramatically the spatial wavelength of the core oscillations, thus for the same efficiency the tube length can be dramatically reduced.

CLIC 20 MW tube example



U=180 kV

L = 3.0 m



U=116 kV

L = 1.2 m

BAC Method of Increasing the Efficiency in Klystrons

I.A. Guzilov
JSC "Vacuum Device's Basic Technologies",
Moscow, 127238, Dmitrovskoe av., 58, Russian Federation,
E-mail: iag@bk.ru

http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6891996

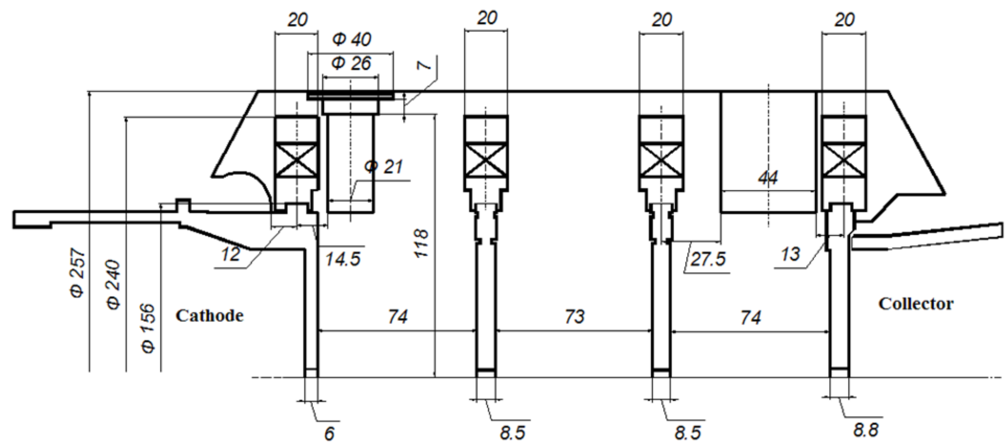
Moscow, Russia

JSC "Vacuum device's basic technologies"

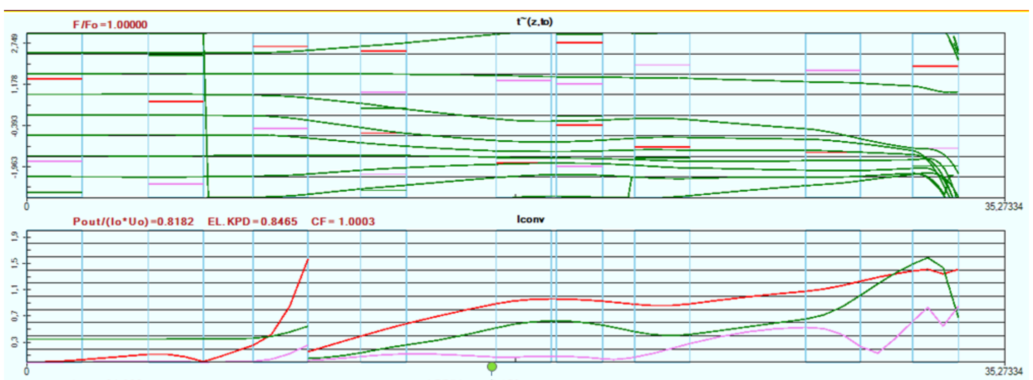
KIU-147. 40 beams, S-band, 6 MW, 52 kV, 45%

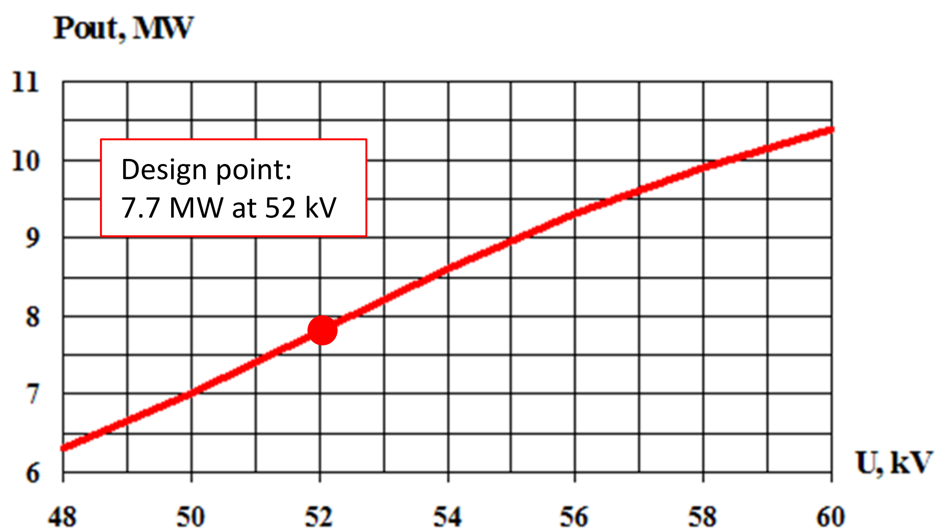
BAC technology demonstrator tube. To be tested in November 2015.

Focusing with permanent magnets (no solenoid)



1. Keep the gun, focusing system and collector
2. Replace the klystron body (the same length).
   Expected efficiency (BAC technology) >77% :





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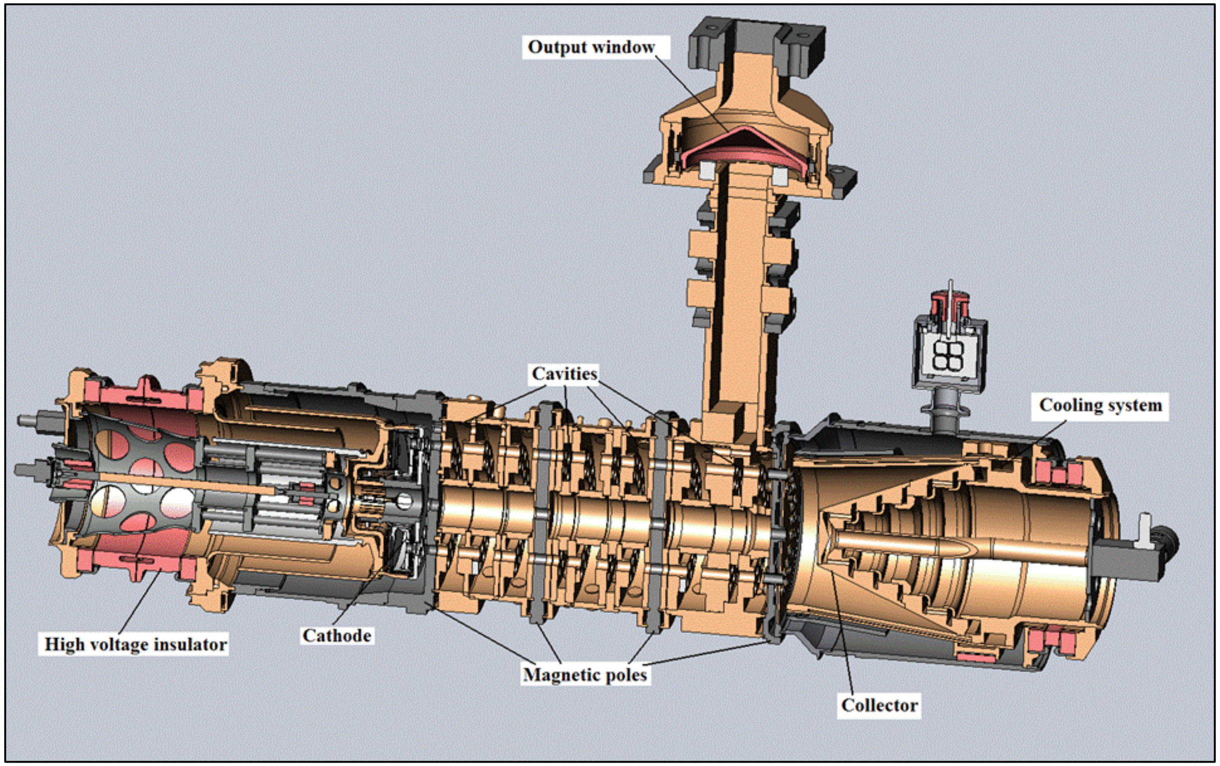
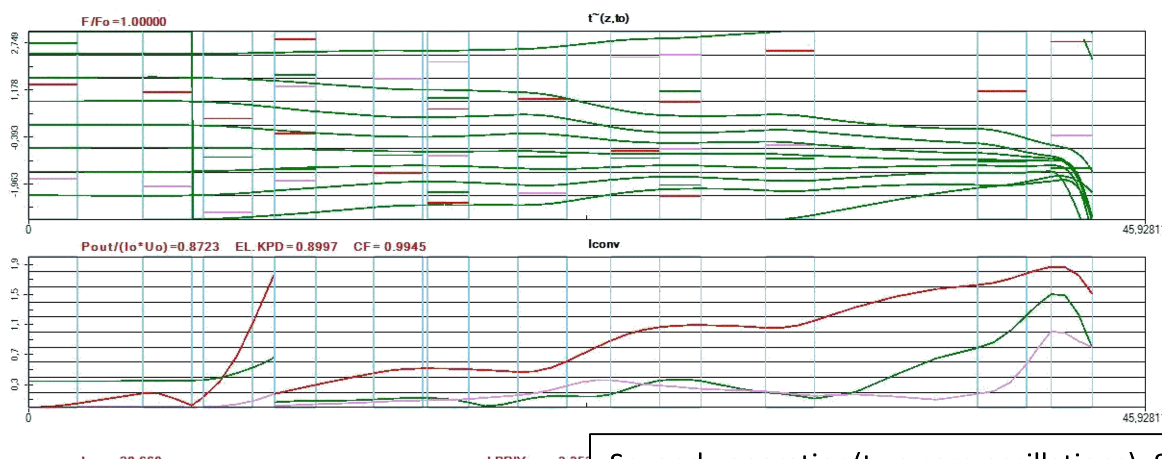
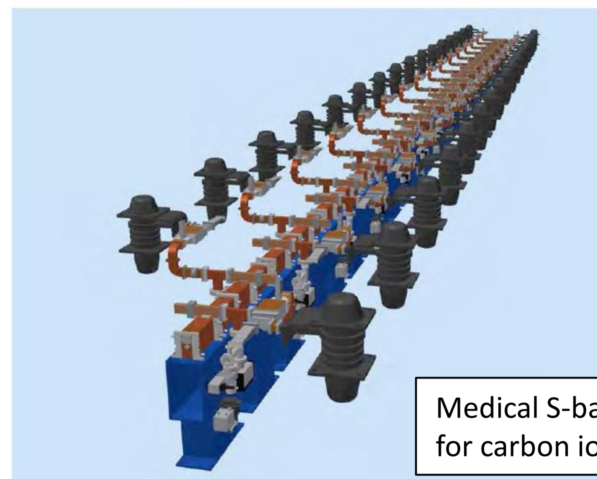
Images of 6 MW, S-band BAC MBK





Second generation(two core oscillations): 87%



Medical S-band linac for carbon ions

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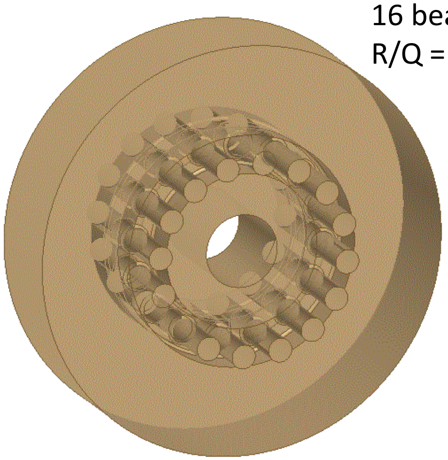
FCC ^{ee} CW, MBK klystron (HEKCW)

HEIKA/HEKCW working team:

I. Syratchev (CERN)
II. G. Burt (Lancaster)
III. C. Lingwood (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)

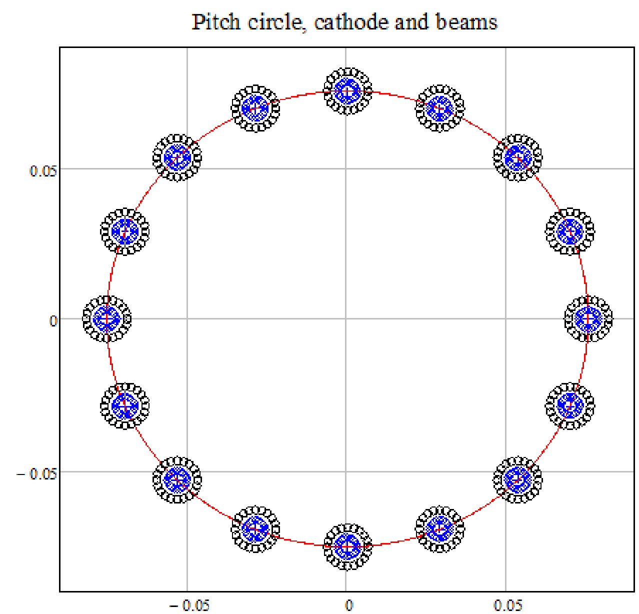
16 beams MBK cavity
R/Q = 22 Ohm/beam



Tube parameters:

- Voltage: 40 kV
- Total current: 42A
- N beams: 16
- μK/beamx10^6 : 0.33
- N cavities: 7
- Bunching method #1: COM

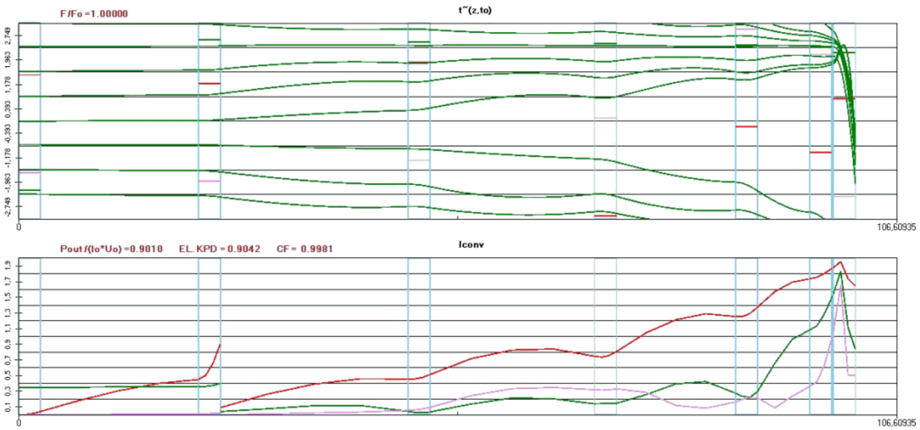
- Cathode loading: 2 A/cm^2
- Beam radius: 3 mm
  - Filling factor 8 mm
- Length: 2.3 m
- Beam circle radius: 75 mm
- Solenoid field (2x): 600 G
- Solenoid radius: 150 mm
- Collector: common
  - Nominal load: 170 kW



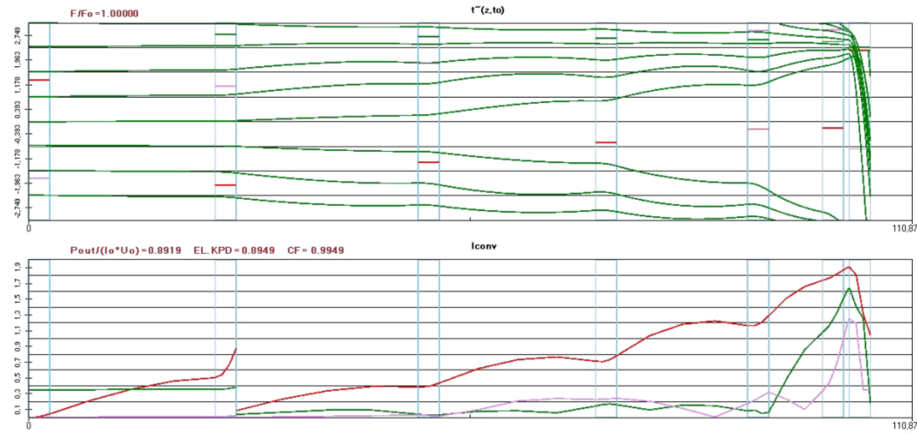
HEKCW RF circuit optimisation

Few tubes were optimised using **KlypWin** (1D code). Two of them were selected for further study.

HEKCW #11-02 (highest efficiency) η= 90.1%

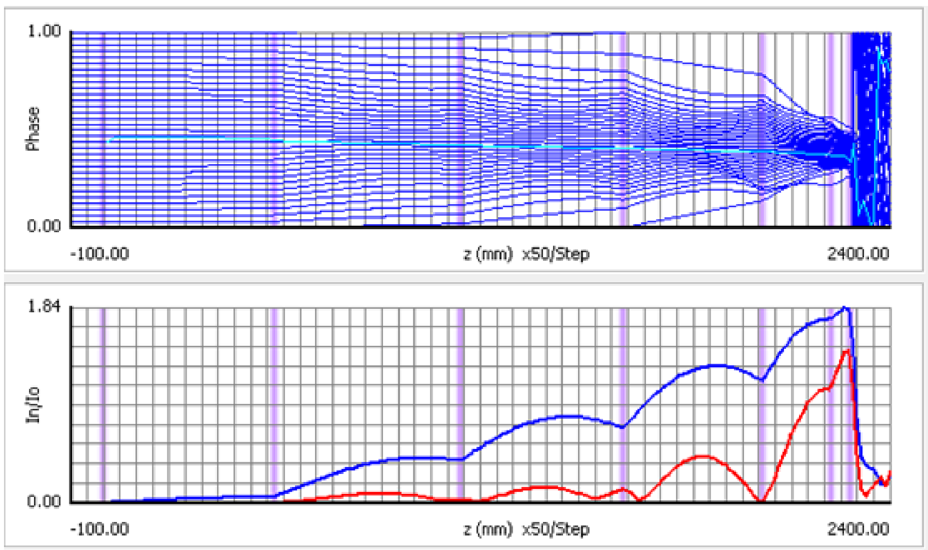


HEKCW #11-07 ('cleanest' phase trajectories) η=89.2%

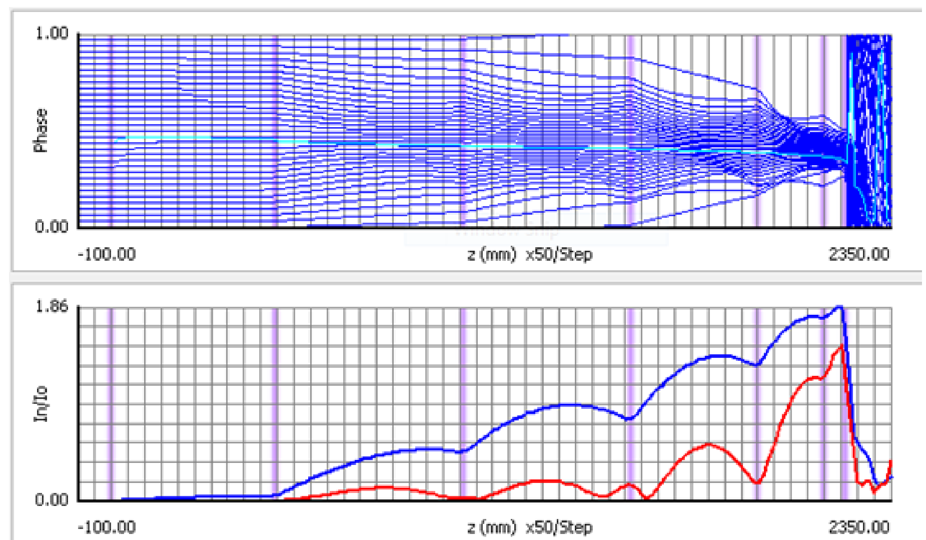


High efficiency confirmed by another non-commercial 1D code **AJDisk**

η= 85.0%



η= 85.5%

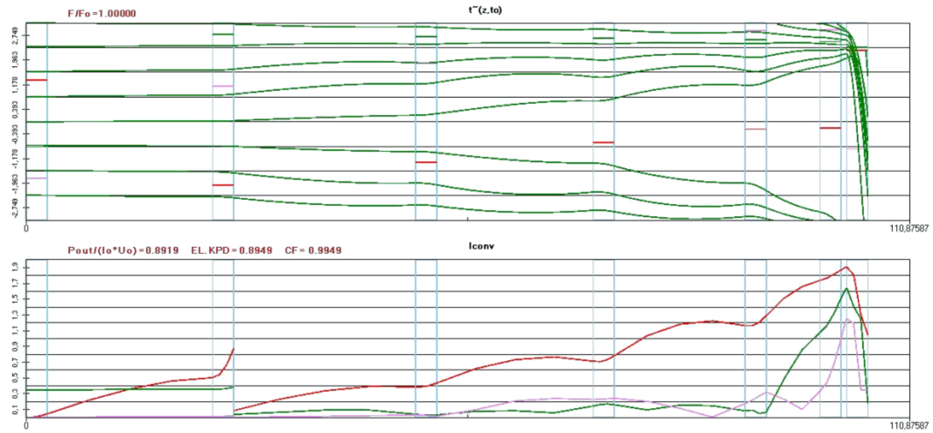


Klystron's General Similitude Principle (GSP)

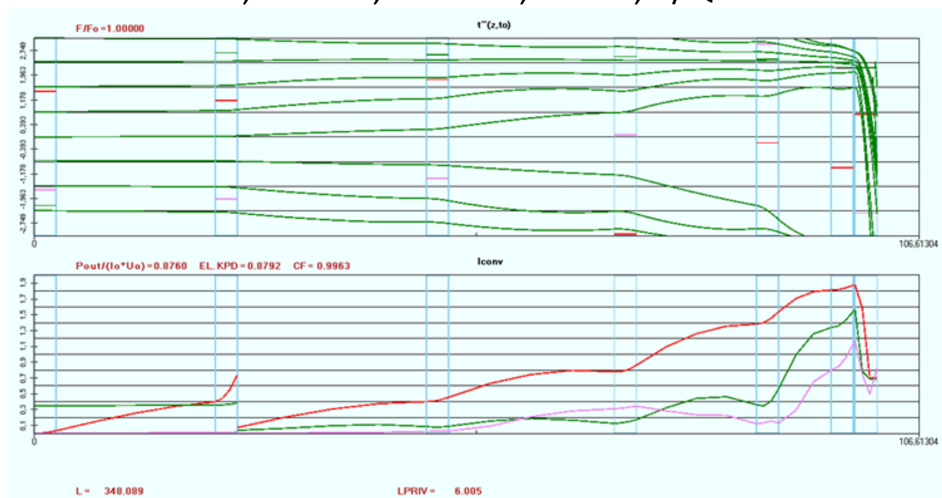
GSP statements:

- For any particular klystron there is a set of generalized parameters.
- Applying special rules of their consequent transformation, the given klystron can be scaled to another tube (with different frequency, RF power, voltage, MBK to single and back and etc.) in such a way, that the efficiency of the original tube will be preserved.

HEKCW, 16 beams, 40 kV, 42 A, R/Q = 352 Ohm

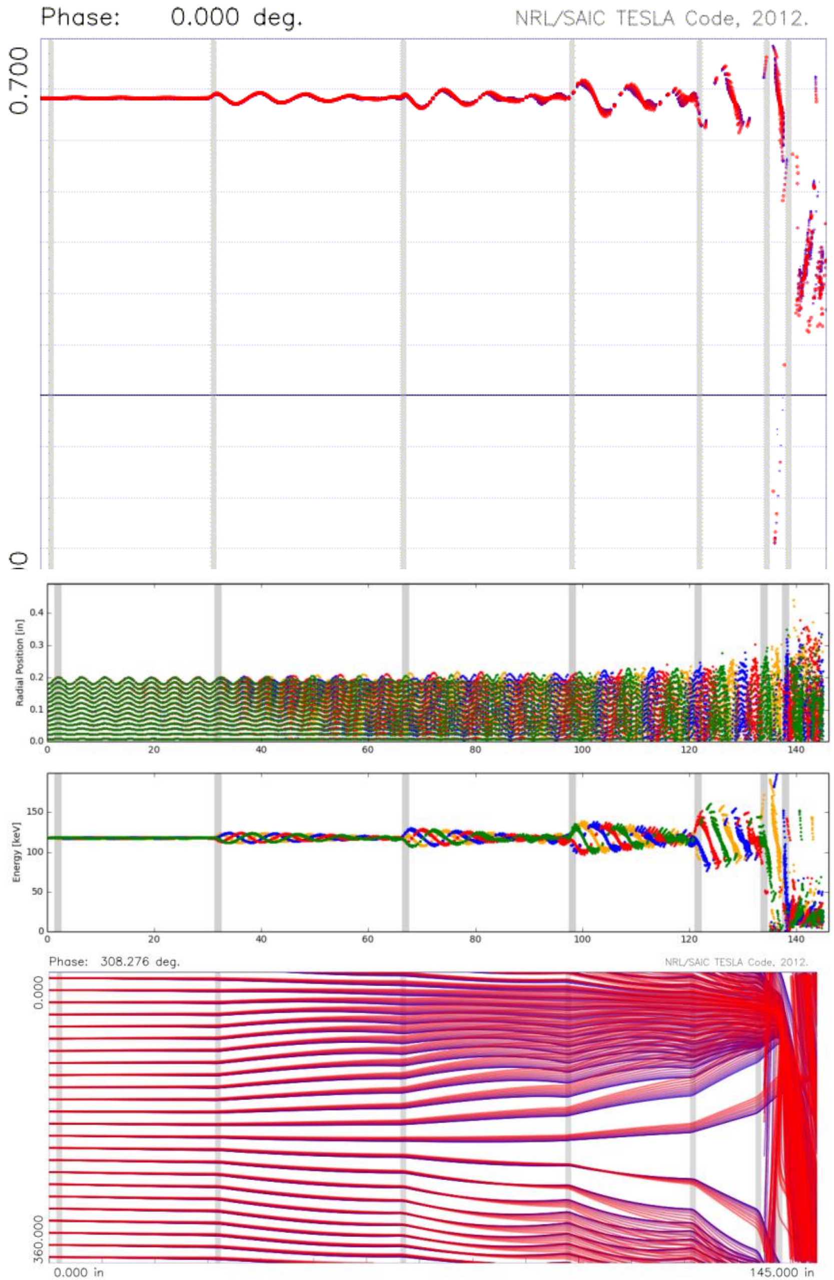


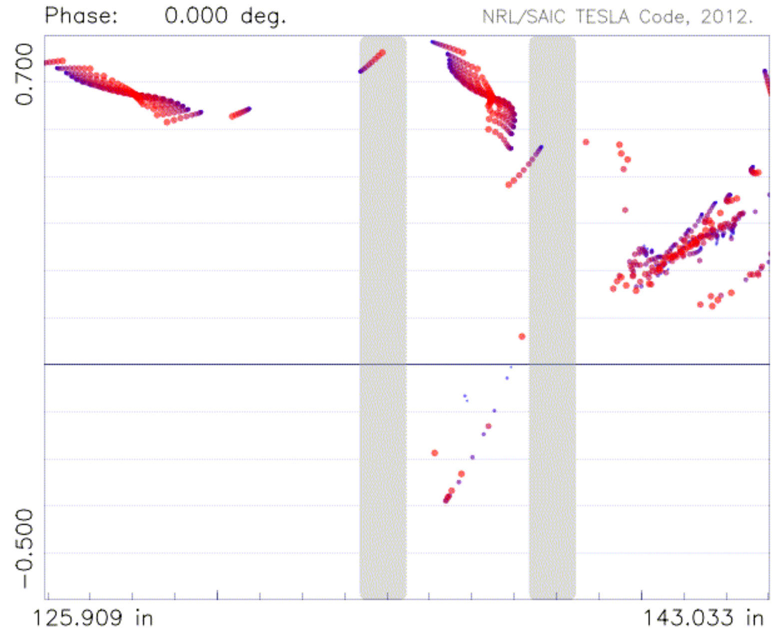
GSP HEKCW, 1 beam, 119.4 kV, 15.1 A, R/Q = 182 Ohm

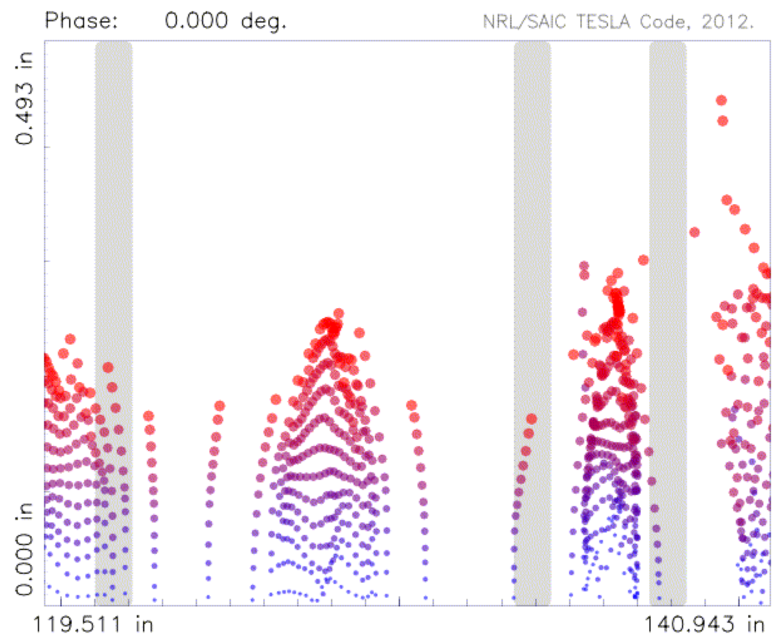


GSP HEKCW is analysed now using 2D PIC codes.

NRL/SAIC TESLA (2.5D). GSP HEKCW first results.







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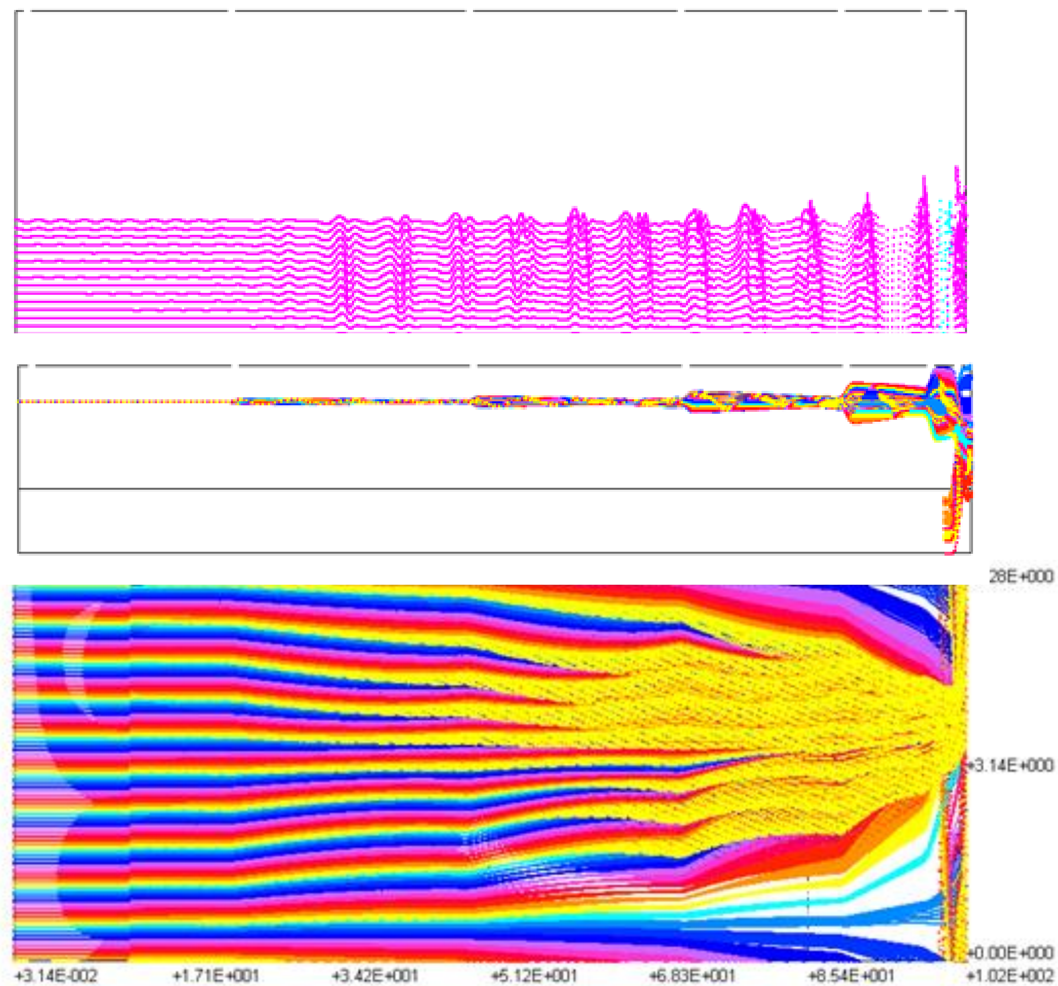
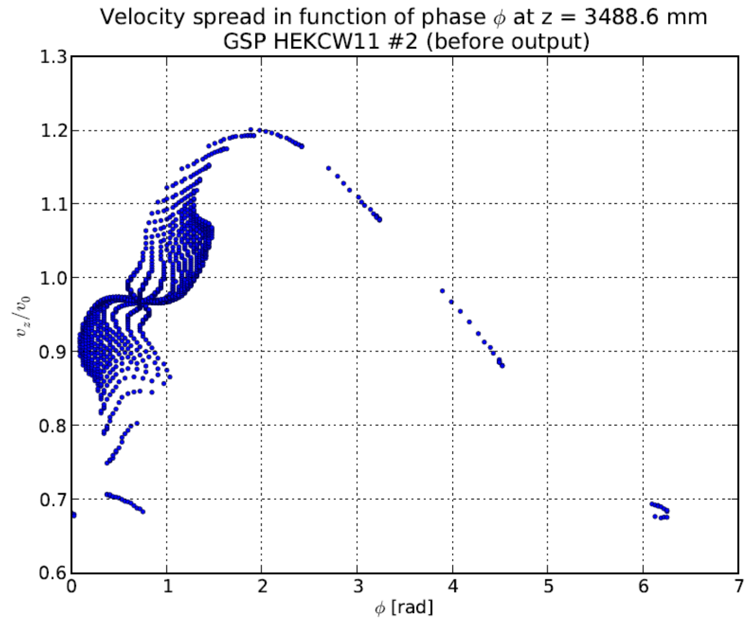
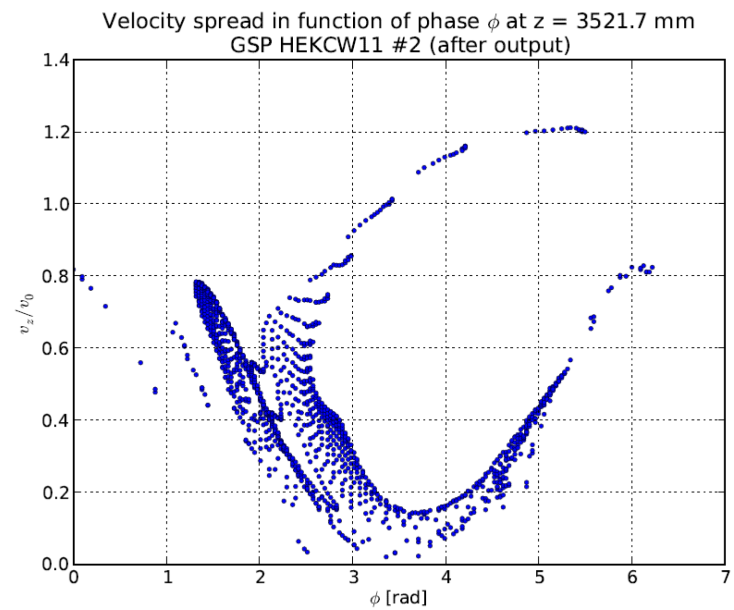
Thales Klys2D. GSP HEKCW first results.







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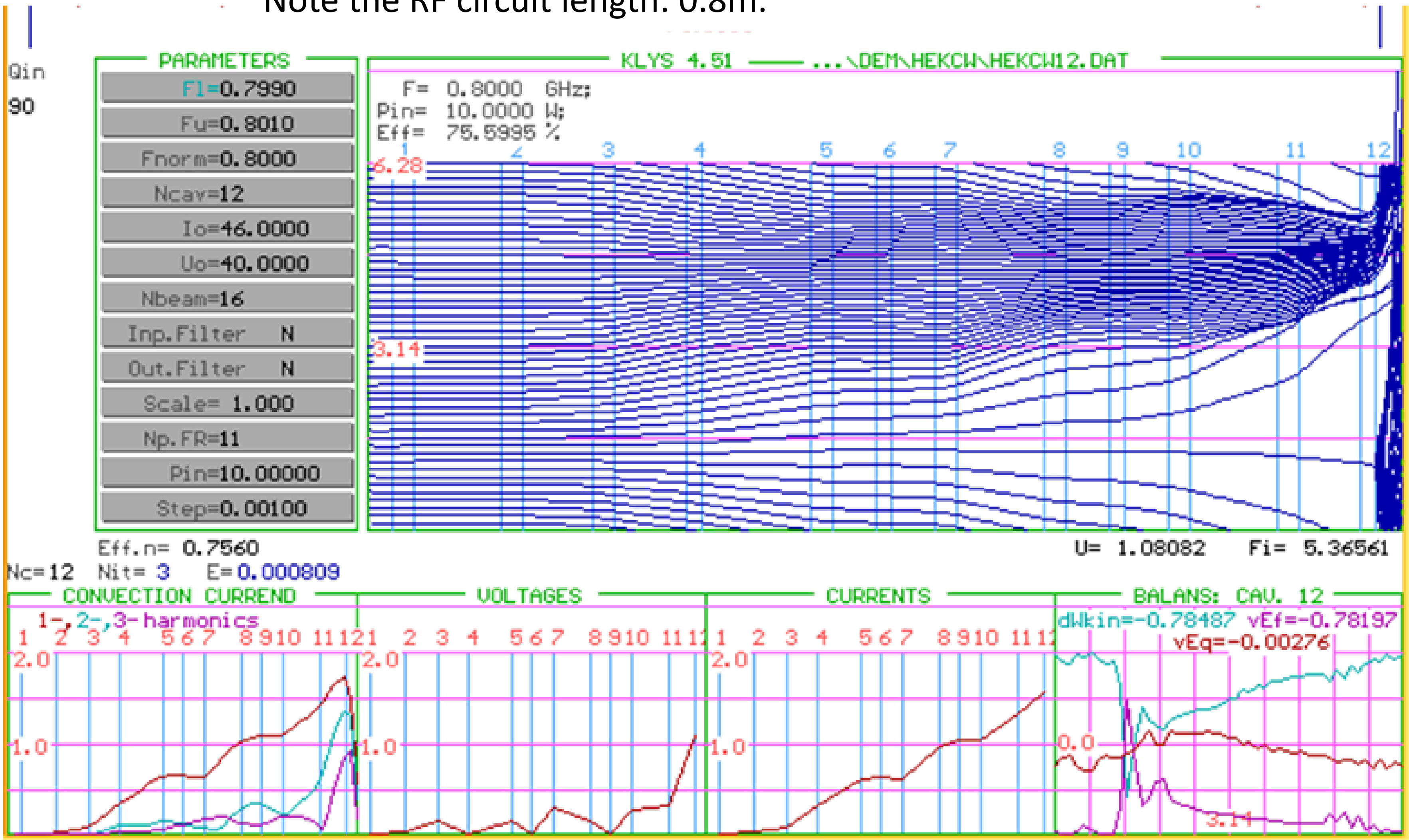
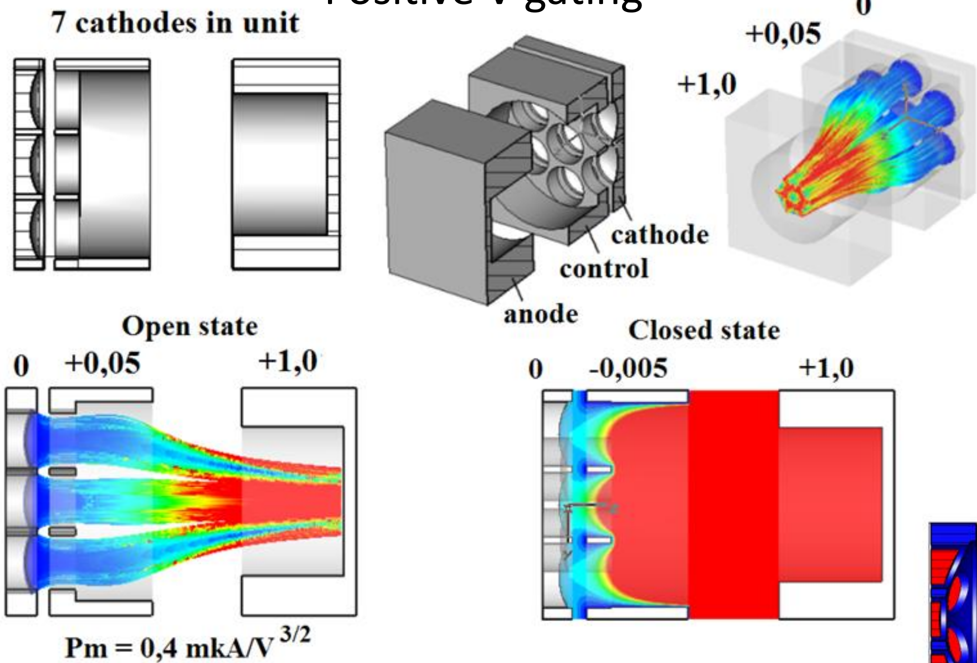
Preliminary design of the BAC HEKCW with 2 core oscillations.
Note the RF circuit length: 0.8m.



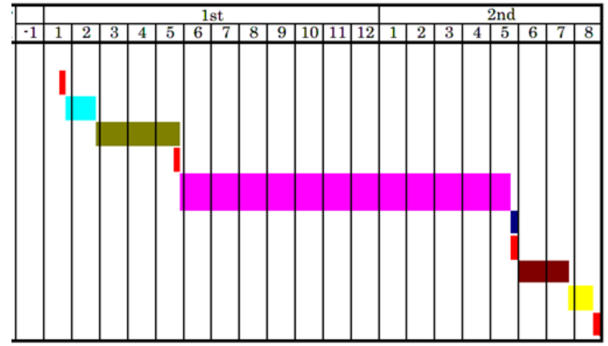
Gated mine-cathode for the HEKCW. Initiative.

Positive V gating

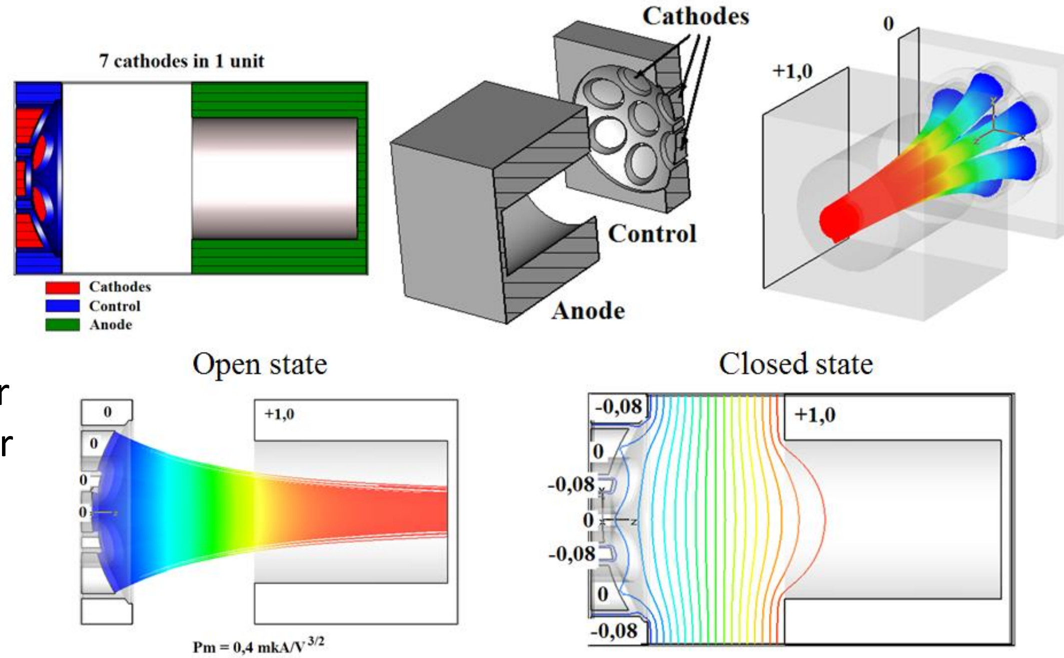


Gate voltage = 0.04 V nominal

Proposal from I Guzilov VDBT, Moscow



Negative V gating



Gate voltage = 0.08 V nominal

- For CW tube, gated cathode is an effective way for fast protection of the collector. Thus, the collector can be designed for the nominal Power (170 kW)
- For the pulsed tube it allows to eliminated the HV switching system in the modulator.

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Klystrons Retrofit program (PMR)

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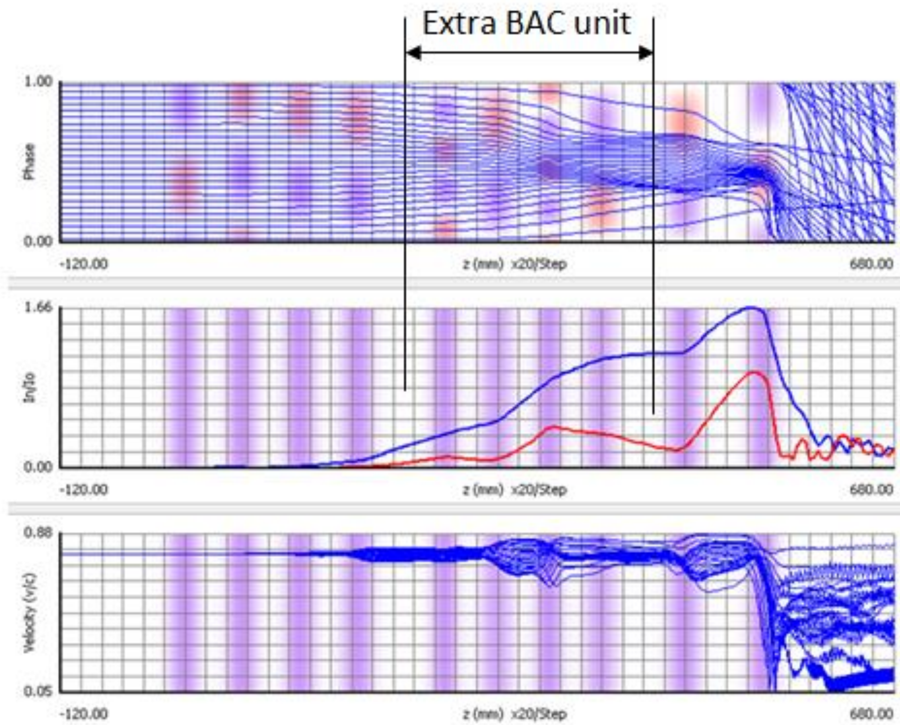
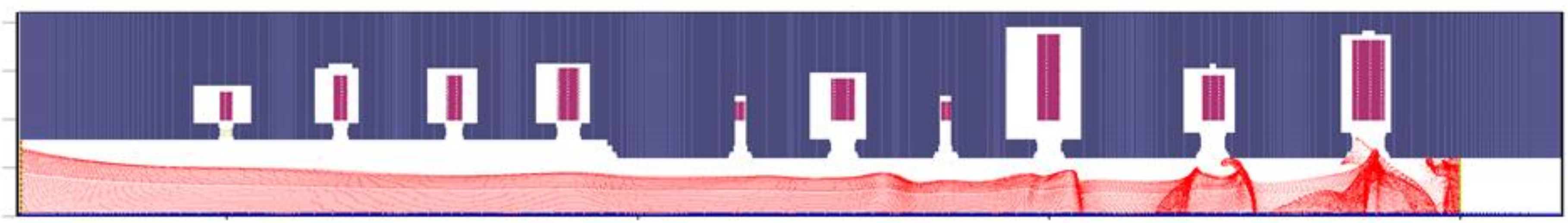
Klystron PMR activity at SLAC (A. Jensen)

The BAC bunching technology was studied at SLAC in attempt to improve the performance of existing S-band SLAC klystron 5045. This is the most mass-produced (>800) high peak RF power (65 MW) tube. First tests are scheduled to be done late 2015.

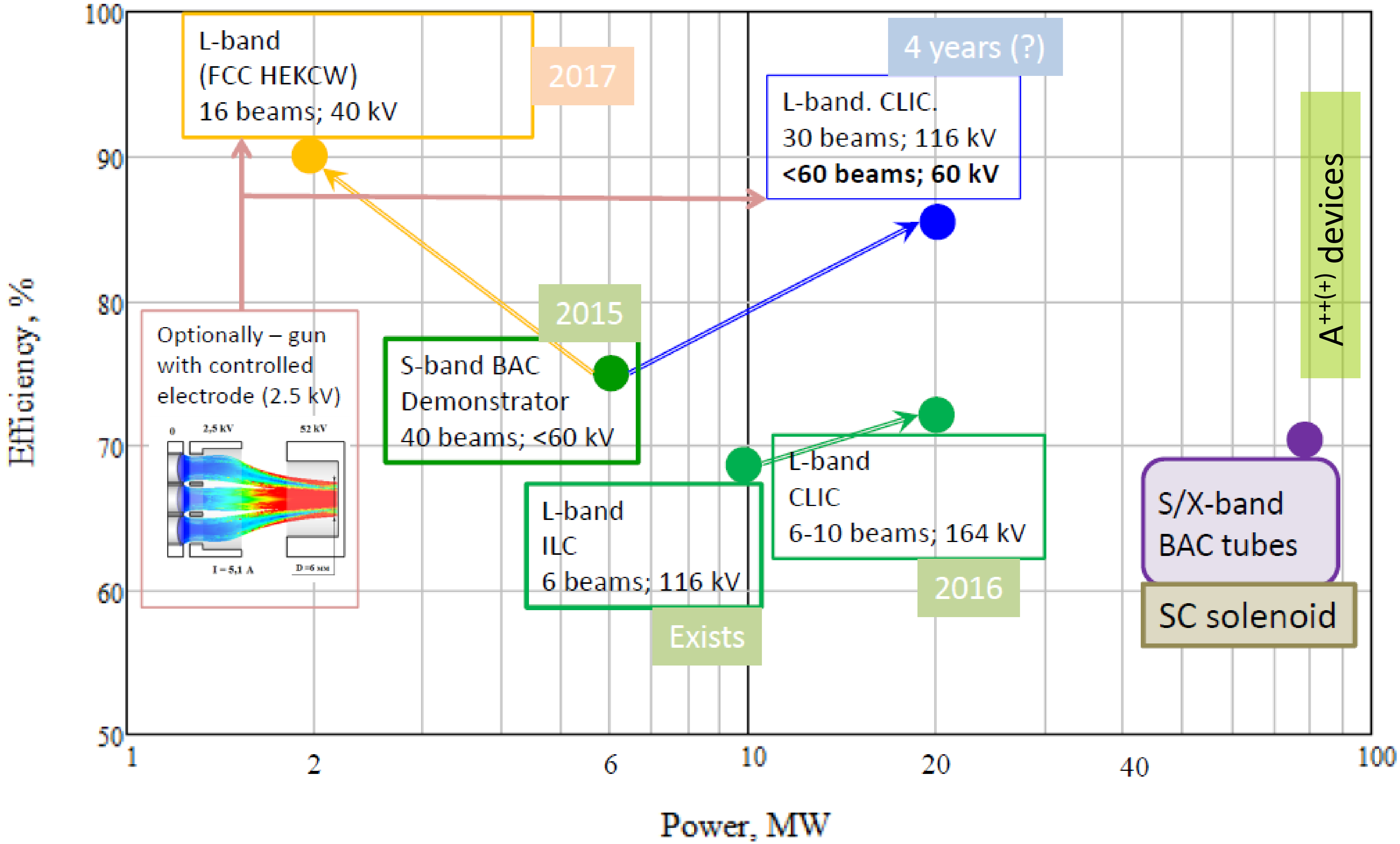
Typical 5045 Operating Parameters

Operating Parameter	Value	High efficiency
Frequency	2.856 GHz	
Beam Voltage	350 kV	
Perveance	2.0 $\mu A/V^{1.5}$	
Peak Output Power	65 MW	92.5 MW
Average Output Power	41 kW	
RF Pulse Width	3.5 μs	
Pulse Rep. Rate	180 Hz	
Gain	50 dB	
3 dB Bandwidth	20 MHz	
Saturated Efficiency	45%	62.5%
Cathode Current Density	8 A/cm^2	





Strategy for high-efficiency high RF power klystron development



I. Syratchev, June 2015, HG Workshop, Beijing.

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