Review of Efficient RF Sources

I. Syratchev, CERN

The context

- Our mandate: Prepare technology for the post-LHC era!
- Economic use of energy resources mandatory!

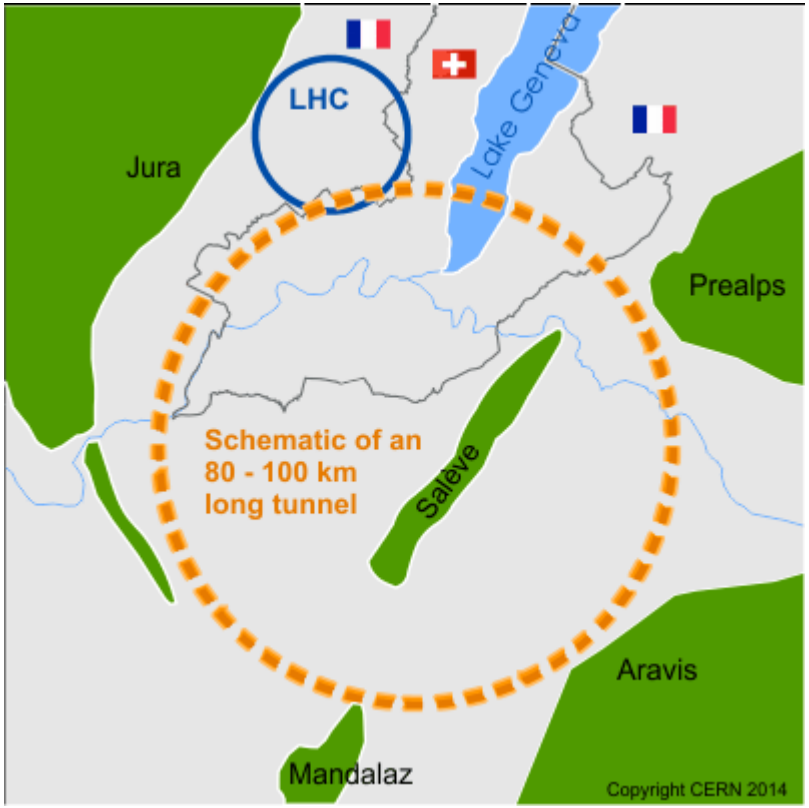
- B. Vierkorn-Rudolph at Workshop Energy for Sustainable Science, ESS 2011: All future (large) accelerators must consider energy efficiency!
- If we don't conceive them for sustainable energy consumption, these projects will not be approved!
- Larger overall efficiency means less consumption and less waste heat production (smaller carbon footprint)!

Workshop Energy for Sustainable Science

Future large scale accelerators with needs for Multi-MW RF power production.

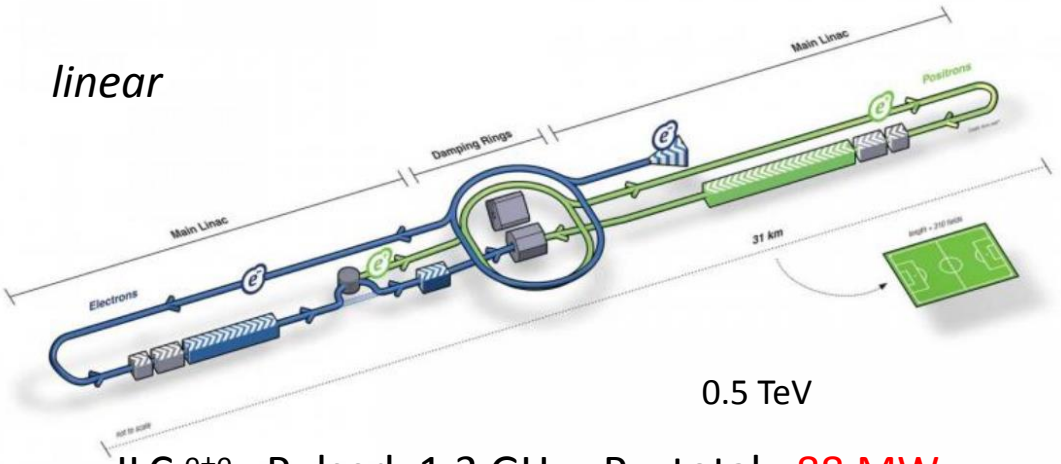
circular

FCC



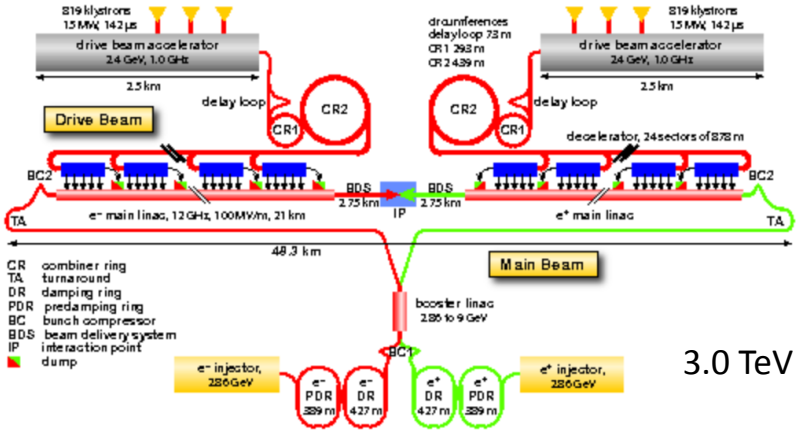
FCC ^{ee}: CW, 0.8 GHz, P_{RF} total= 110 MW

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

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Workshop Energy for Sustainable Science

EnEfficient RF Sources, The Cockcroft Institute, 3-4 June 2014

E. Jensen, CERN

In general, every 1% of RF production efficiency increase brings ~0.3% of the investment cost savings:

- The cooling system
- Power converters
- RF Amplifiers life time, cost and numbers

For machine operation (CLIC 3TeV example), if ηK=0.65→0.75, the possible saving per year (assuming 5500 h operation and $40/MWh): 45 MW×5500 h=250 GWh=900 TJ or $10 Million!

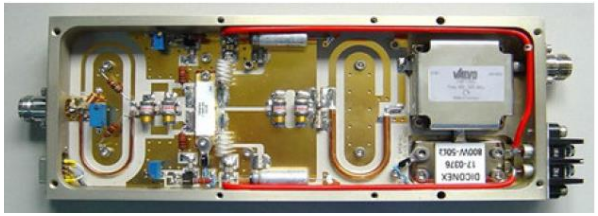
I. Syratchev, April 2015, EuCARD2, Barcelona.

Solid State RF Amplifiers

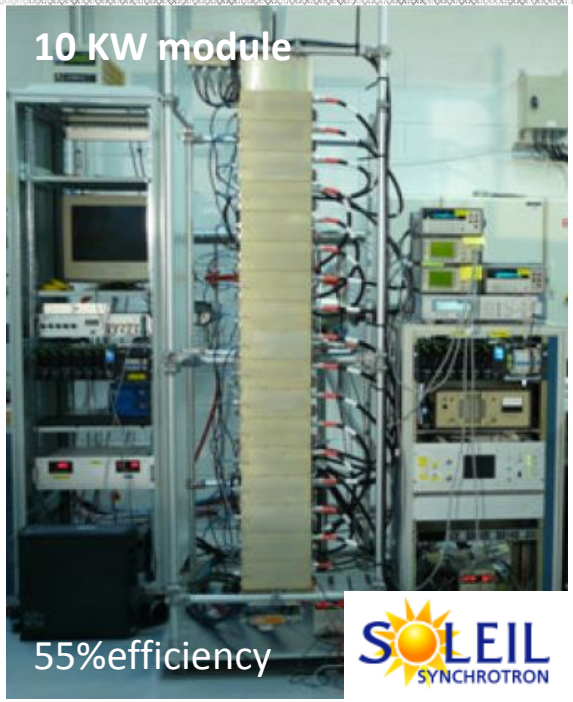
0.5 GHz CW SSA

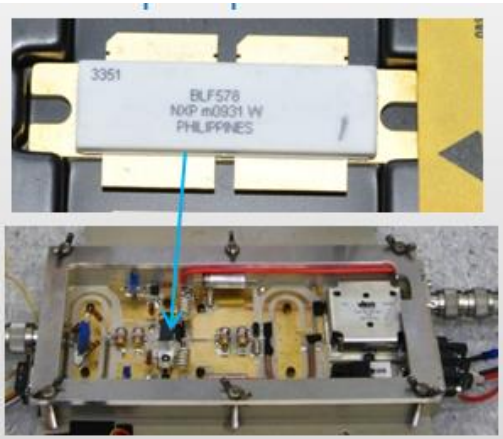
6th generation LDMOS (BLF578) :

650 W modules (Gain 17dB, η ~63%)



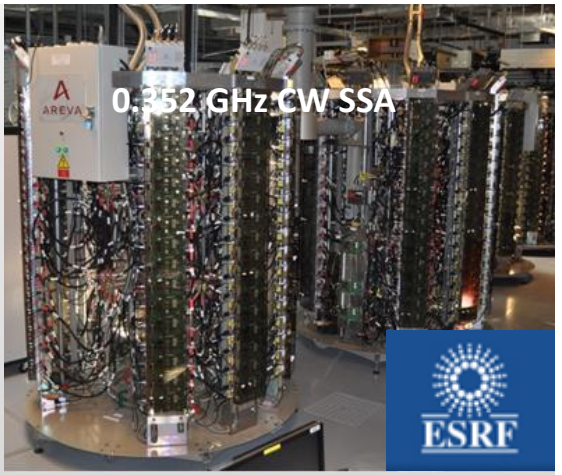
- **SOLEIL 352 MHz SSA State of the Art**
  - P_{mod} ~ 700 W, G > 20 dB, η > 70%
- **500 MHz SSA R&D (BLF578)**
  - P_{mod} ~ 650 W, G ~ 17 dB, η > 60%





650 W RF module

- 6th generation LDMOSFET (BLF 578 / NXP), V_{ds} = 50 V
- Efficiency: 68 to 70 %



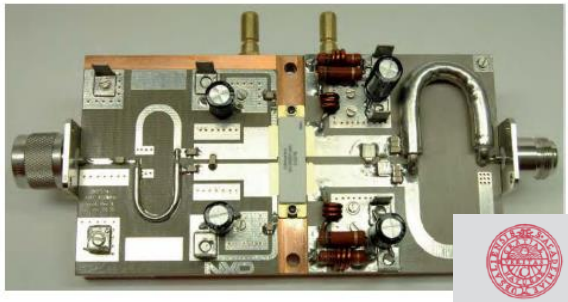
150 kW - 352.2 MHz Solid State Amplifiers for the ESRF booster

Efficiency: > 55 % at 150 kW

> 45 % at 100 kW

The AN10967 demo board

352MHz; 1kW; CW



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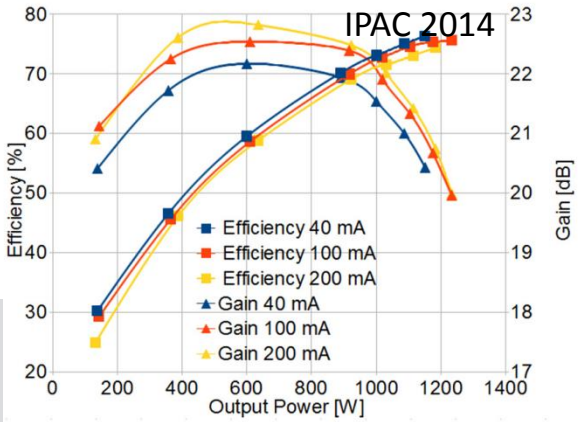
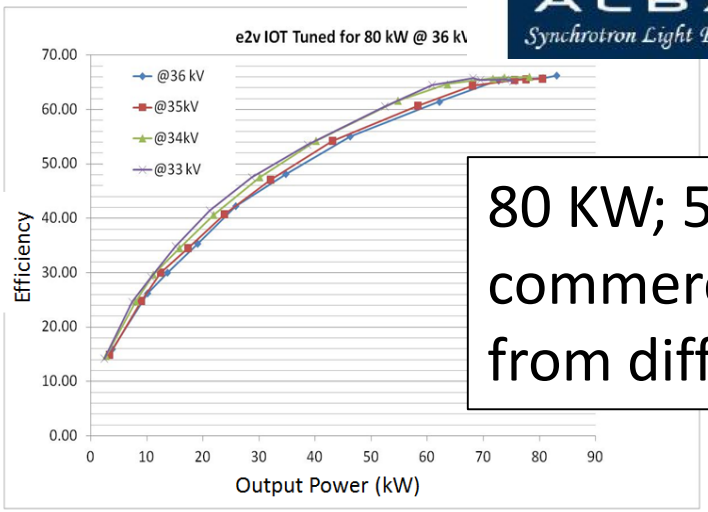
IPAC 2014



Inductive Output Tubes

ALBA
Synchrotron Light Facility

Elettra Sincrotrone Trieste

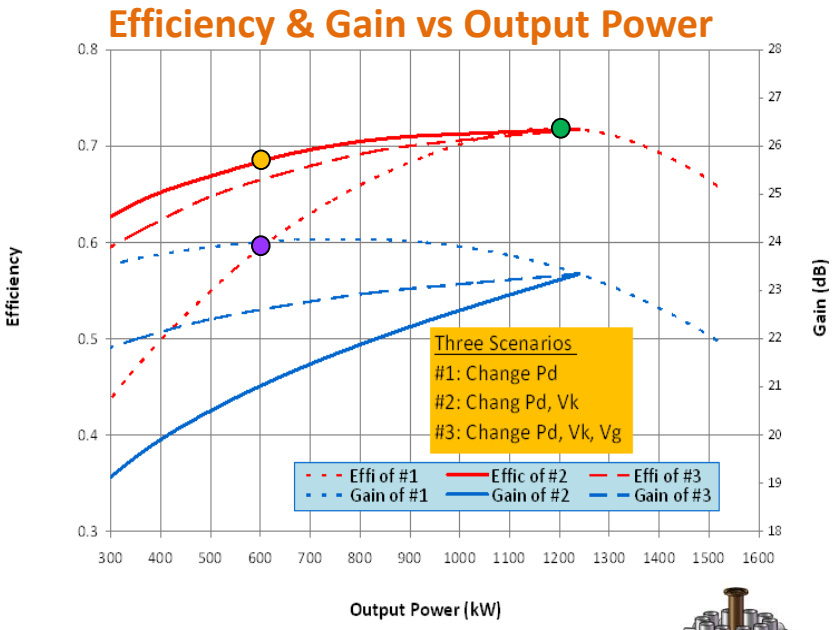


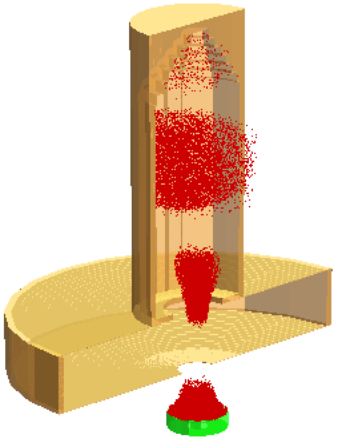
80 KW; 500 MHz IOT are commercially available from different vendors.

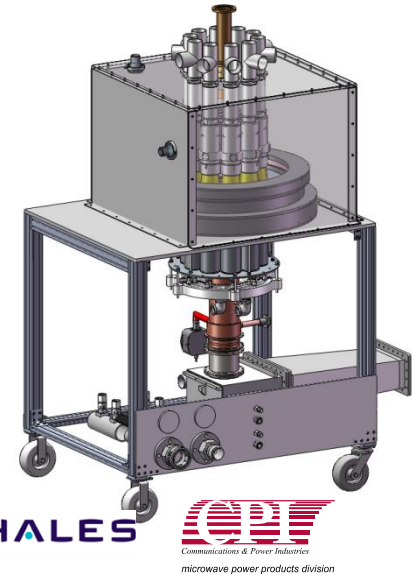
M. Jensen: http://indico.cern.ch/event/340703/timetable/#20150324.detailed

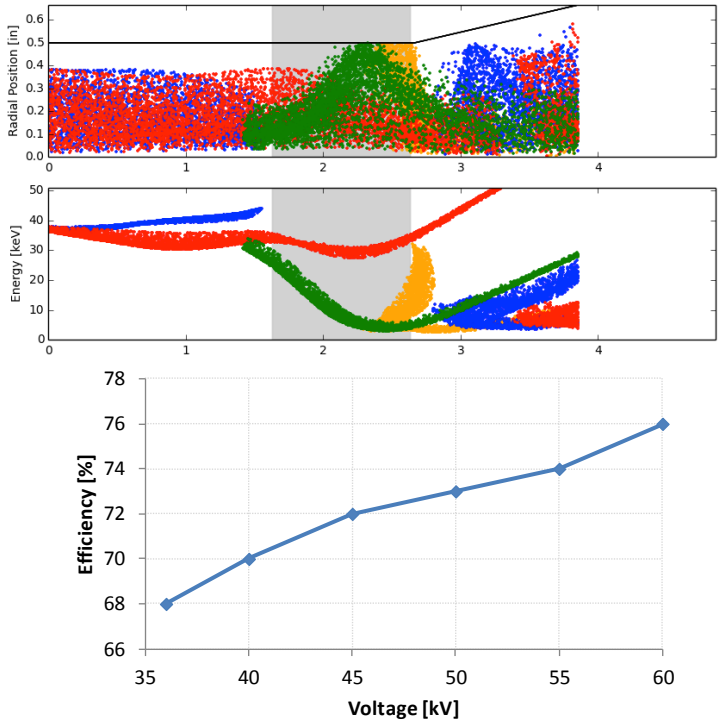
I. Syratchev, April 2015, EuCARD2, Barcelona.

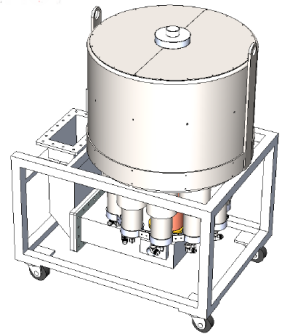
1.2 MW, 0.7 GHz, 10 beams MBIOT (development for ESS)











M. Jensen: http://indico.cern.ch/event/340703/timetable/#20150324.detailed

I. Syratchev, April 2015, EuCARD2, Barcelona.

10 MW, 1.3 GHz MBK klystrons (ILC/X-FEL)

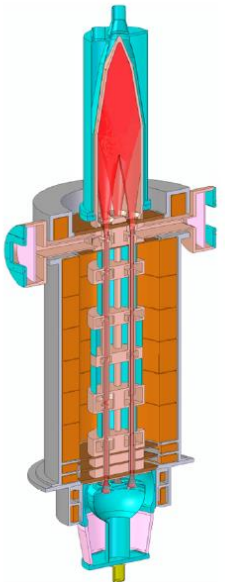
Thales

Toshiba

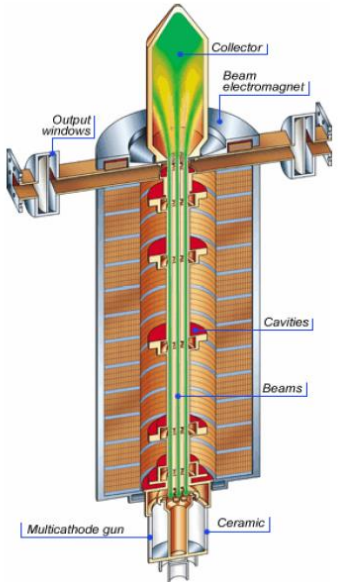
CPI #a

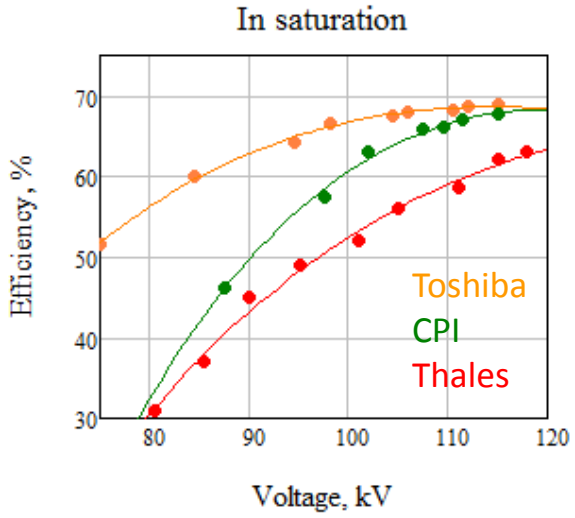
CPI #b

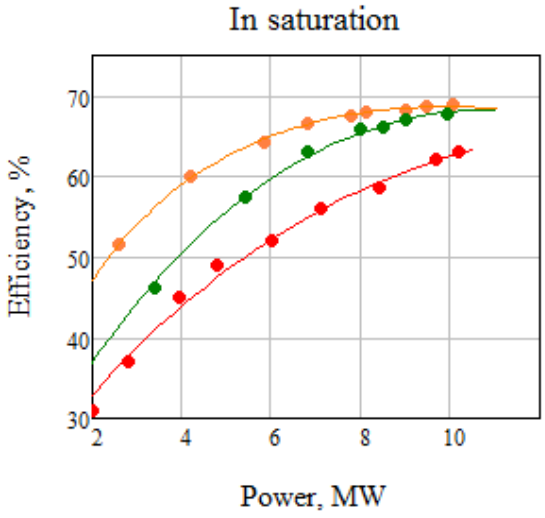
Toshiba

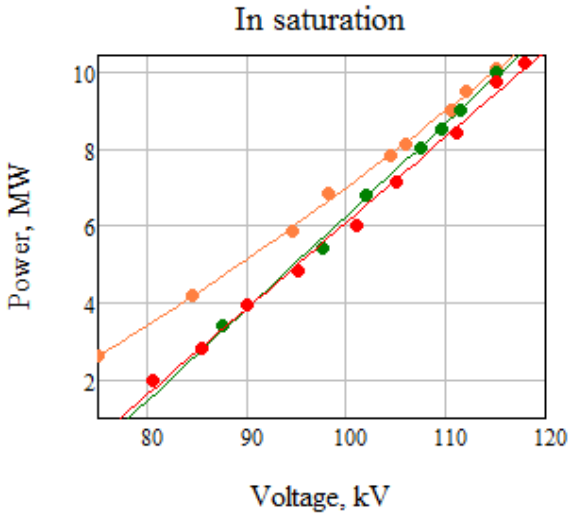


Thales









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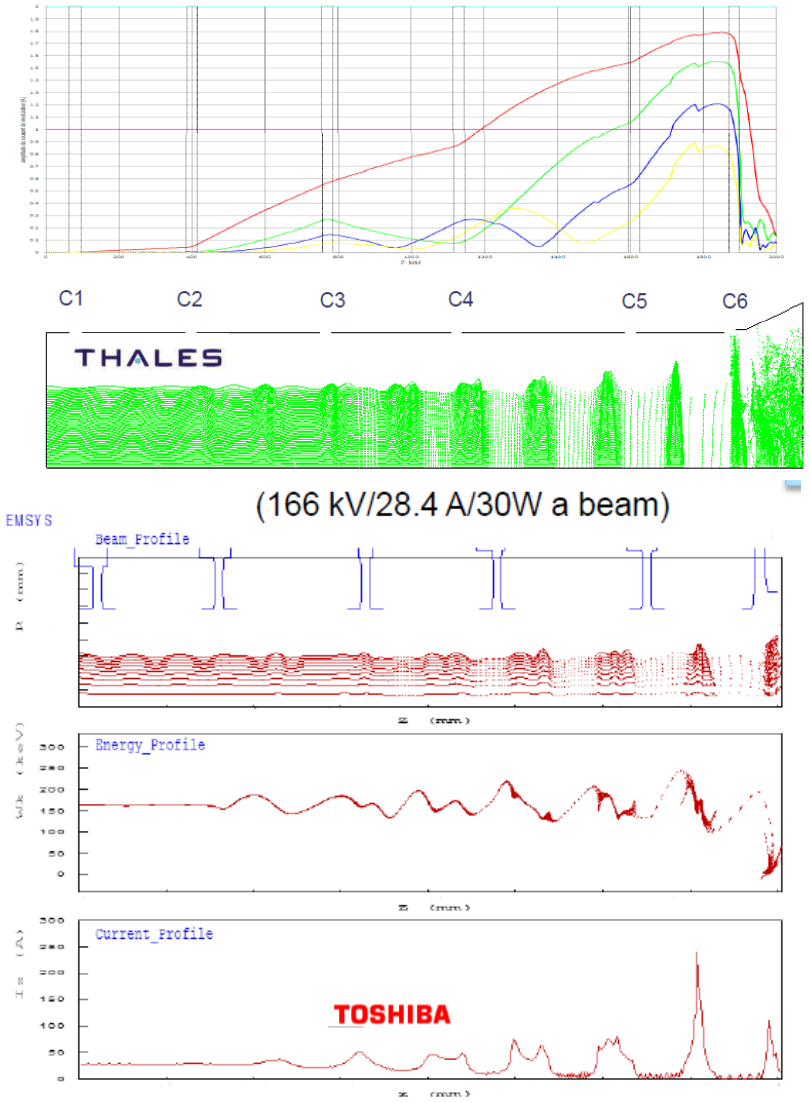
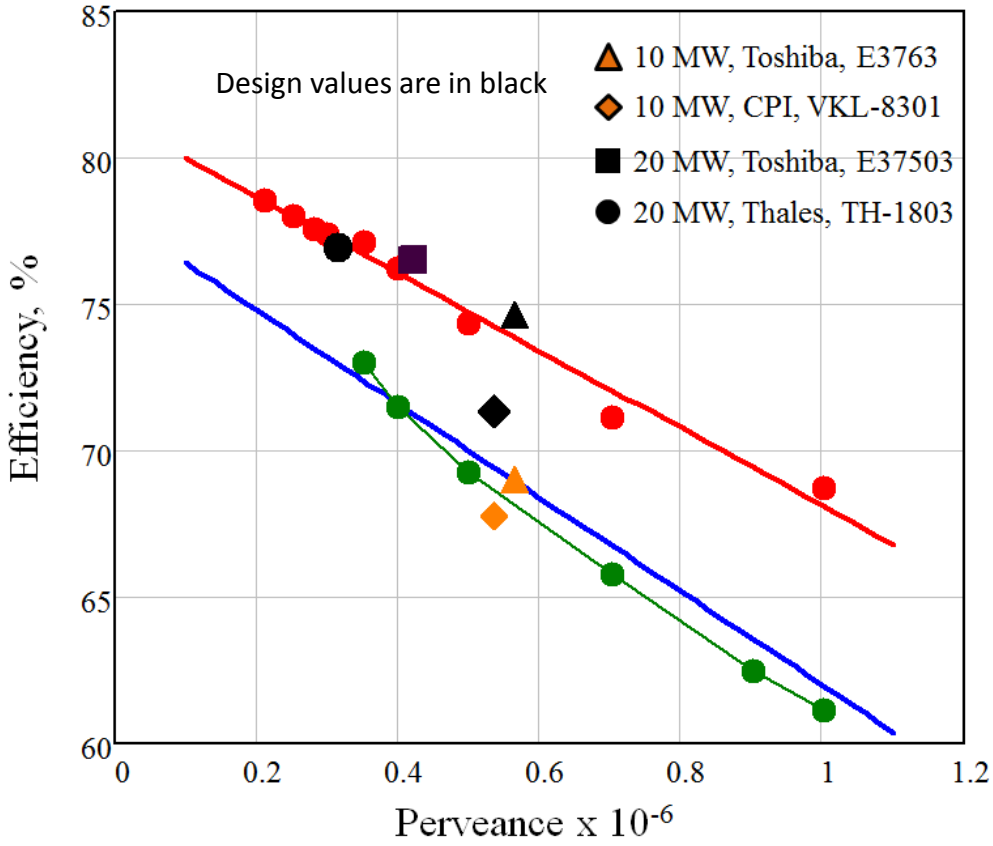
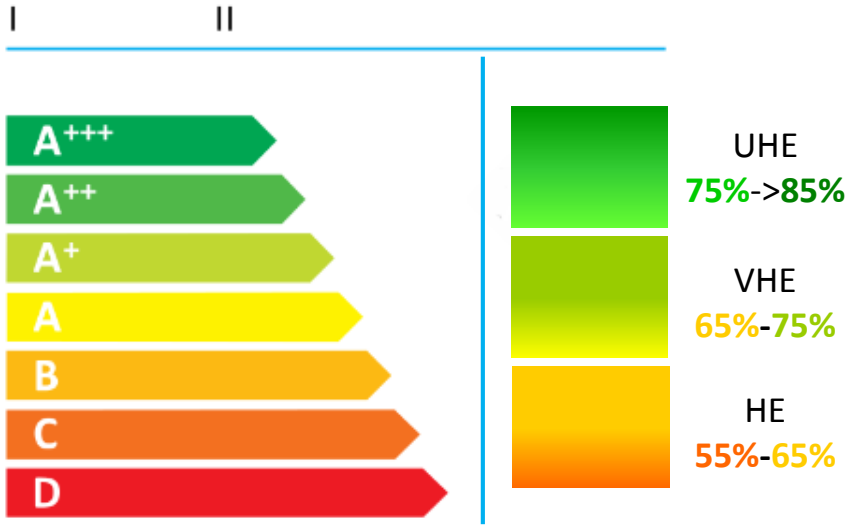
20 MW, 1.0 GHz MBK klystrons (development for CLIC)

- 6 cavities using one harmonic cavity (3rd one)
- 1800 mm from middle gap of cavity 1 to 6

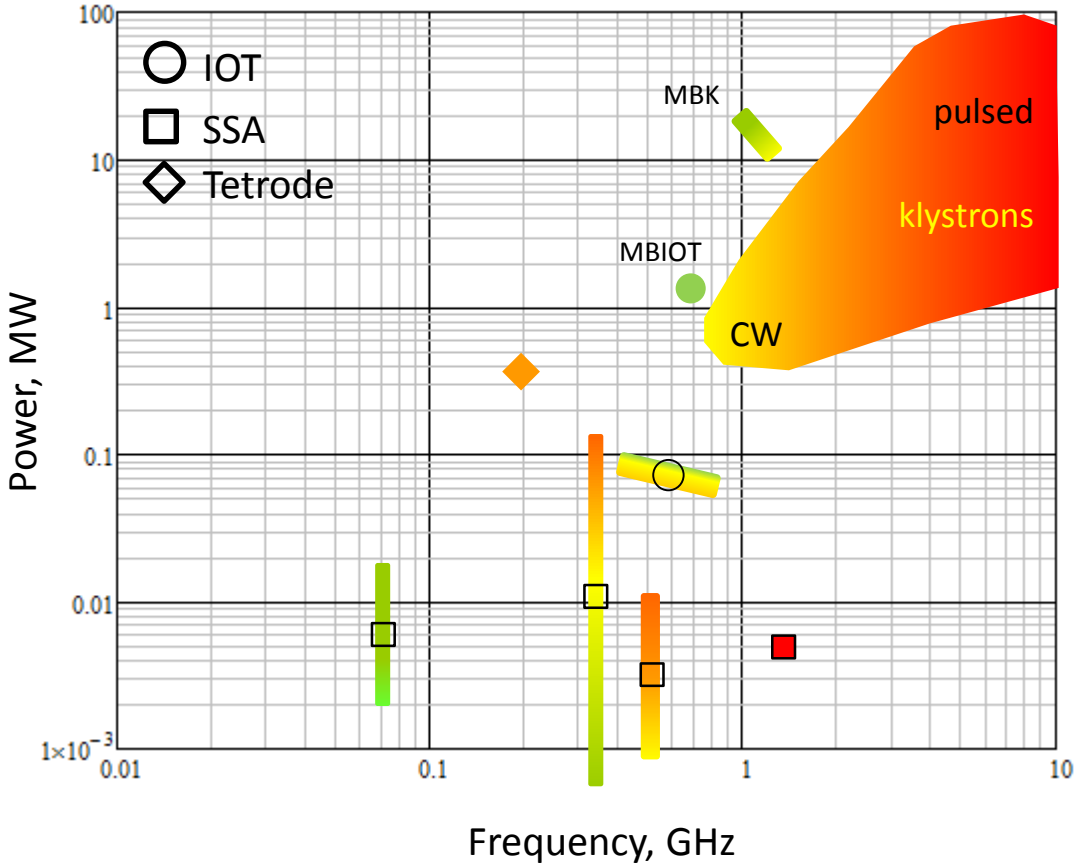




I. Syratchev, April 2015, EuCARD2, Barcelona.



Selected RF amplifiers Power/frequency/efficiency MAP



The $A^{++(+)}$ class high RF power amplifiers today do not exist.

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Towards A$^{++(+)}$ class klystrons

- For decades klystron developers used the same algorithm to design klystron for its highest efficiency. The internal logic of this technique limits the klystron efficiency to about 80 %.
- To go higher in efficiency, the intrinsic properties of the bunching processes and deceleration in the klystron output cavity need to be understood at the level of the electron bunch dynamic.

This development have started recently:

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*

Abstract— 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. The vast majority of existing commercial high power RF klystrons operates in the electronic efficiency range between 40% and 55%. Only a few klystrons available on the market are capable of operating with 65% efficiency or above. In this paper, a new method to achieve 90% RF power conversion efficiency in a klystron amplifier is presented. The essential part of this method is a new bunching technique – bunching with bunch core oscillations. Computer simulations confirm that RF production efficiency above 90% can be reached with this new bunching method. The results of preliminary study of an L-band, 20 MW peak RF power, multi-beam klystron (MBK) for CLIC with efficiency above 85% are presented.

practical recipes for the design of a very high efficiency klystrons still needs to be done. This activity has started recently, integrating the earlier proposed concepts of the 'congregated' bunch and 'regularized bunching' [3]. It has now evolved towards the new idea of the non-monotonic bunching technique together with the new notion of optimal 'lumped bunching length' [4] as a general parameter. This parameter is determined for each particular klystron to maximize its efficiency. In this paper, further studies towards very high RF power conversion efficiency klystrons (around 90%) are presented.

II. State of the Art

The klystron efficiency is defined as the ratio between

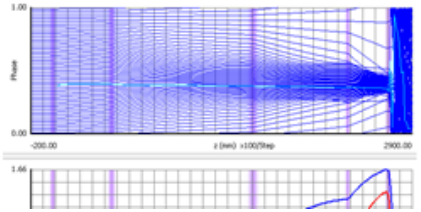
This technology is now being adopted to develop a 20 MW, 1 GHz MBK for CLIC [10]. The direct scaling of existing klystrons towards lower frequency and higher operating voltage, together with slightly reduced microperveance was considered by industry as a straightforward and the tubes have an expected efficiency in the proximity of 70%.

Fig. 1. Commercial 10 MW L-band MBK klystrons, left to right: Thales TH1801, Toshiba E3736 and CPI VKL-8301.

During optimization, for each value of microperveance the output power was kept constant and beam voltage and current were modified accordingly. As a result, the obtained scaling dependency is very similar to that given in (1):

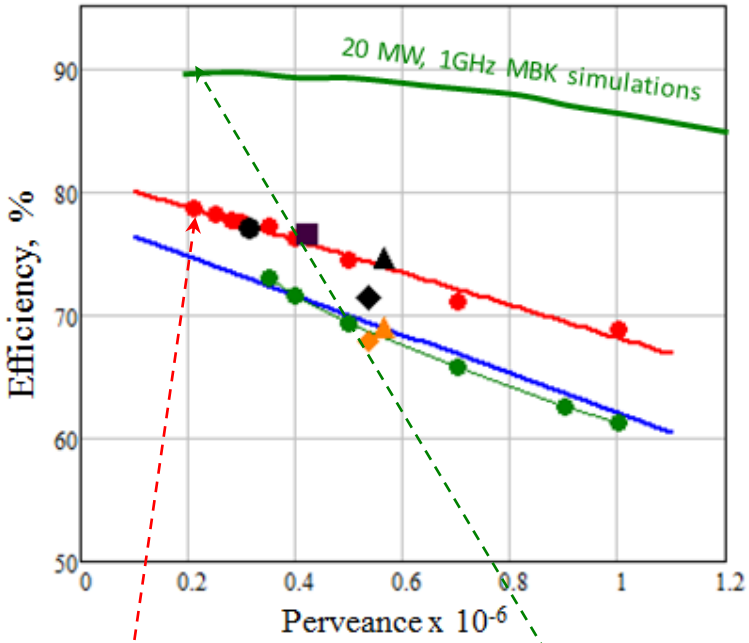
$$\eta_{max} = 81.4 - 13.2 \times \mu K \qquad (2)$$

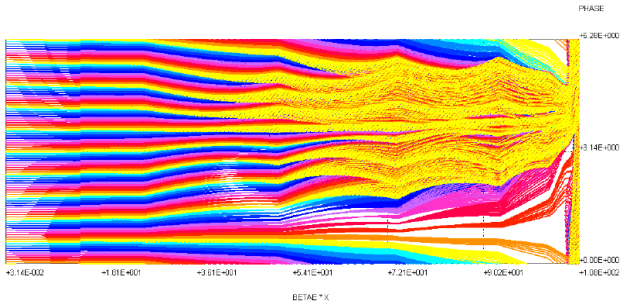
The efficiencies of the optimized MBK klystrons, obtained in simulations using 2.5/3D PIC codes performed by different companies, are shown in Fig. 2. These klystrons have similar configurations: the RF circuit comprises six cavities including one 2nd harmonic cavity. One can see a good agreement (at least for three tubes) between these simulations and scaling dependency shown in (2).



Submitted to IEEE MT&T 30.10.2014

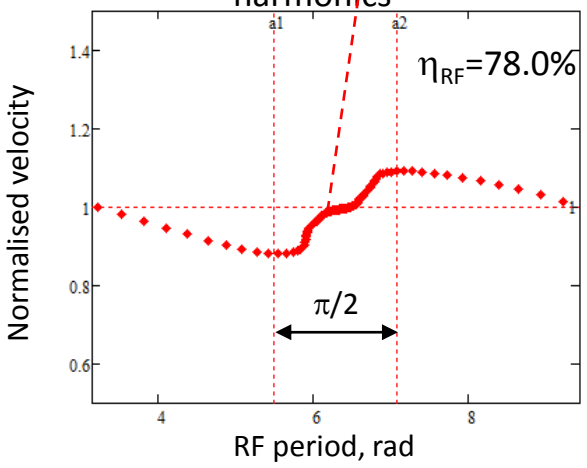
The new bunching concept with core oscillations (COM) allows dramatic improvement of the bunch quality and thus efficiency - up to 90% (and above!)



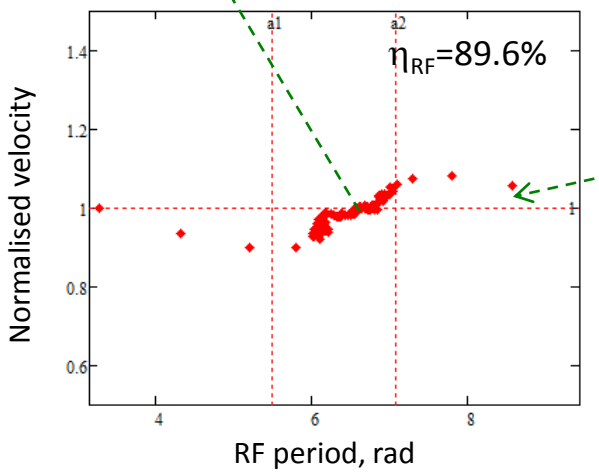


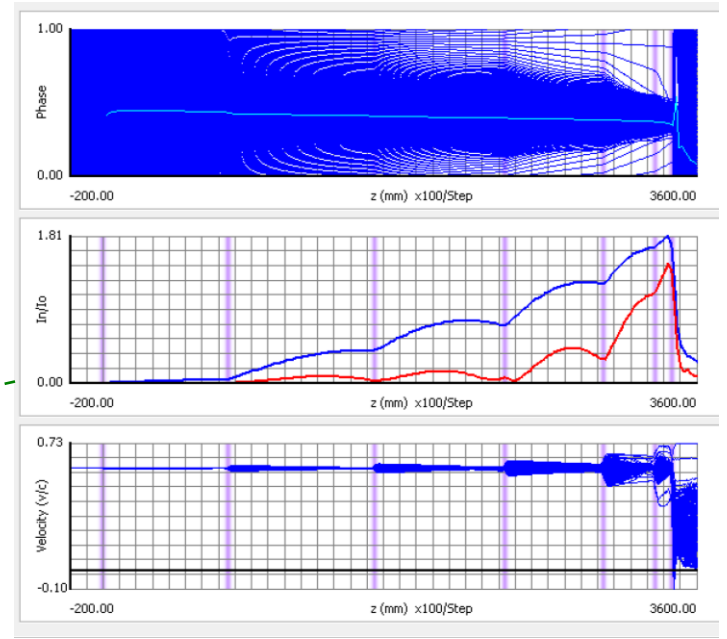
0.8 GHz, 1.5 MW, CW, η= 90%

'Standard' optimisation with maximising the RF current harmonics



Optimisation with bunch core oscillations method





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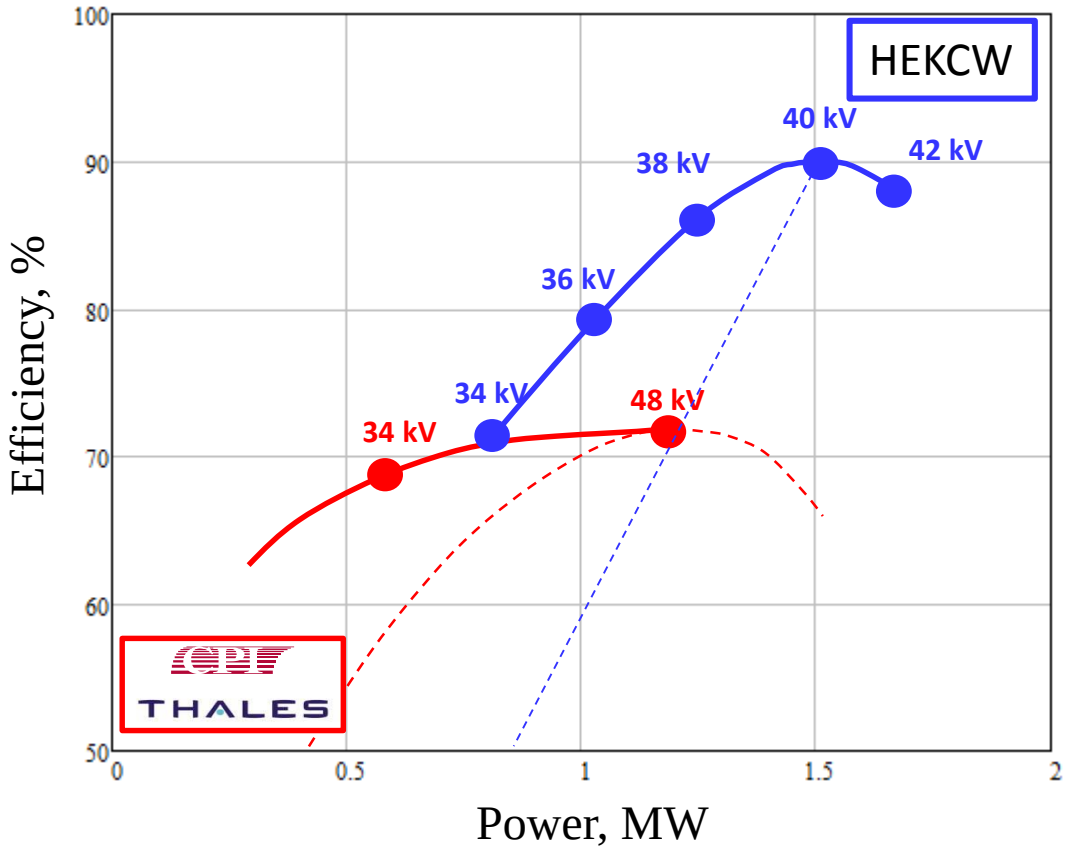
Comparison of the simulated performances of the MBIOT and HEKCW MBK



Dotted lines – only changing P drive
Solid lines – changing P drive and Voltage

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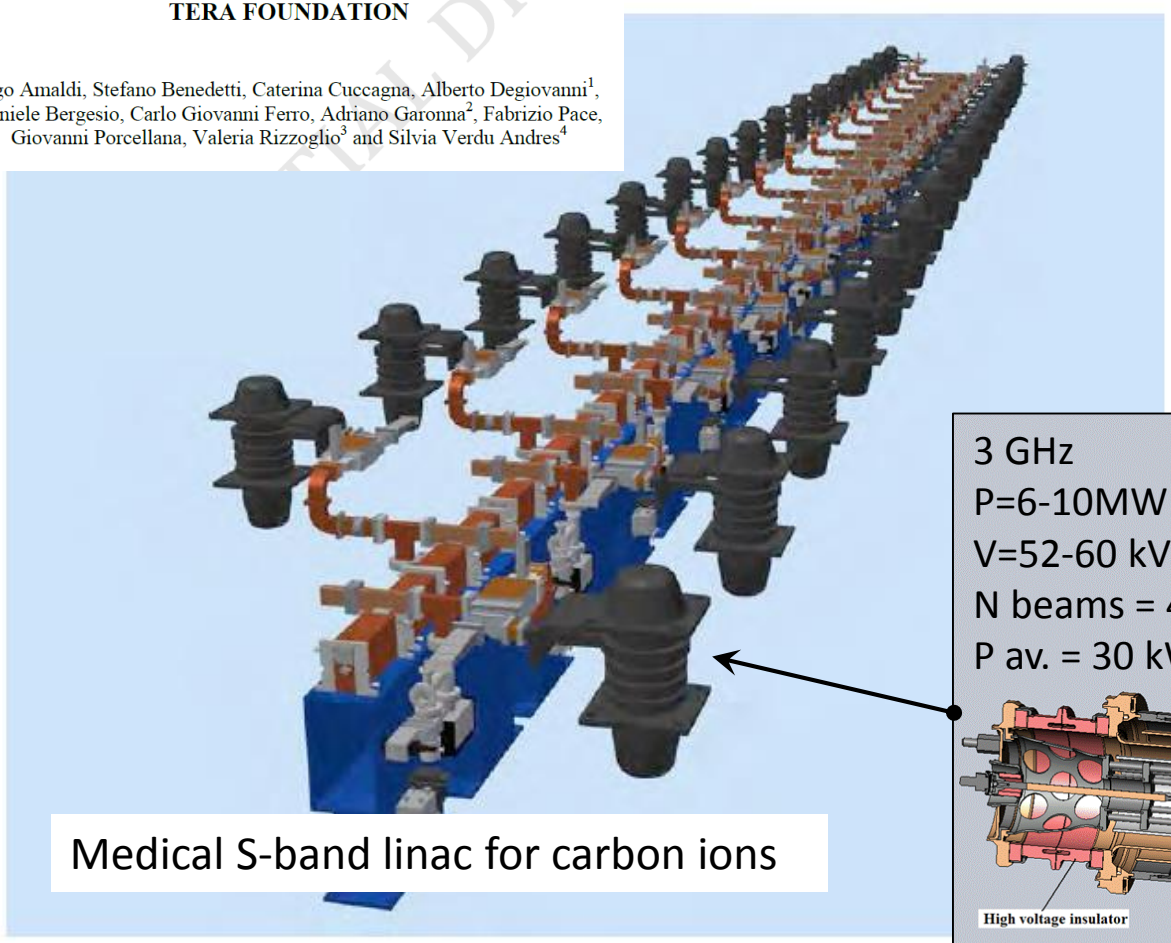
New bunching technology (BAC) demonstrator. To be tested in November 2015.

CABOTO TECHNICAL REPORT

AUGUST 2014

TERA FOUNDATION

Ugo Amaldi, Stefano Benedetti, Caterina Cuccagna, Alberto Degiovanni[1], Daniele Bergesio, Carlo Giovanni Ferro, Adriano Garonna[2], Fabrizio Pace, Giovanni Porcellana, Valeria Rizzoglio[3] and Silvia Verdu Andres[4]

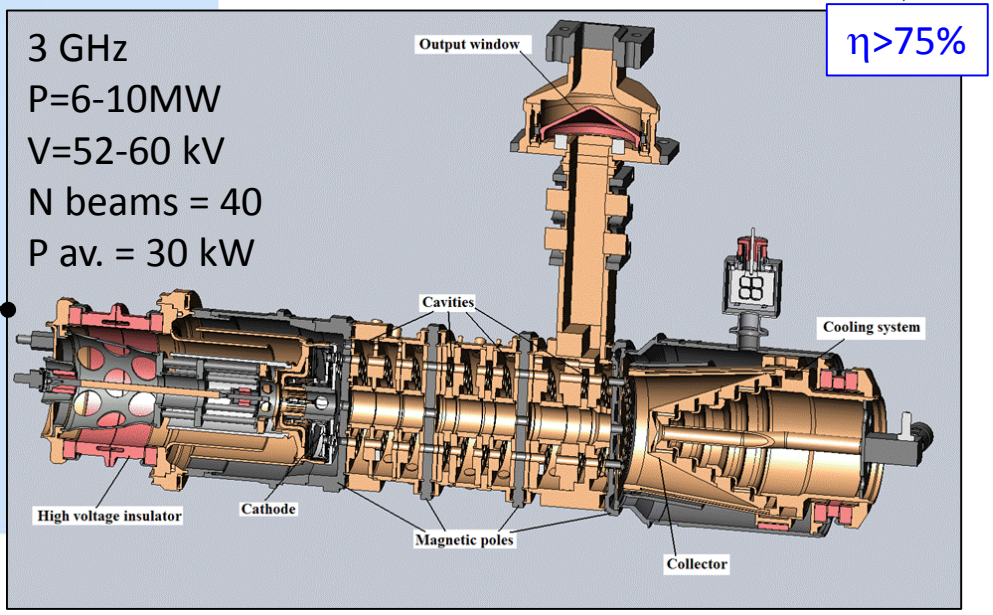


Medical S-band linac for carbon ions

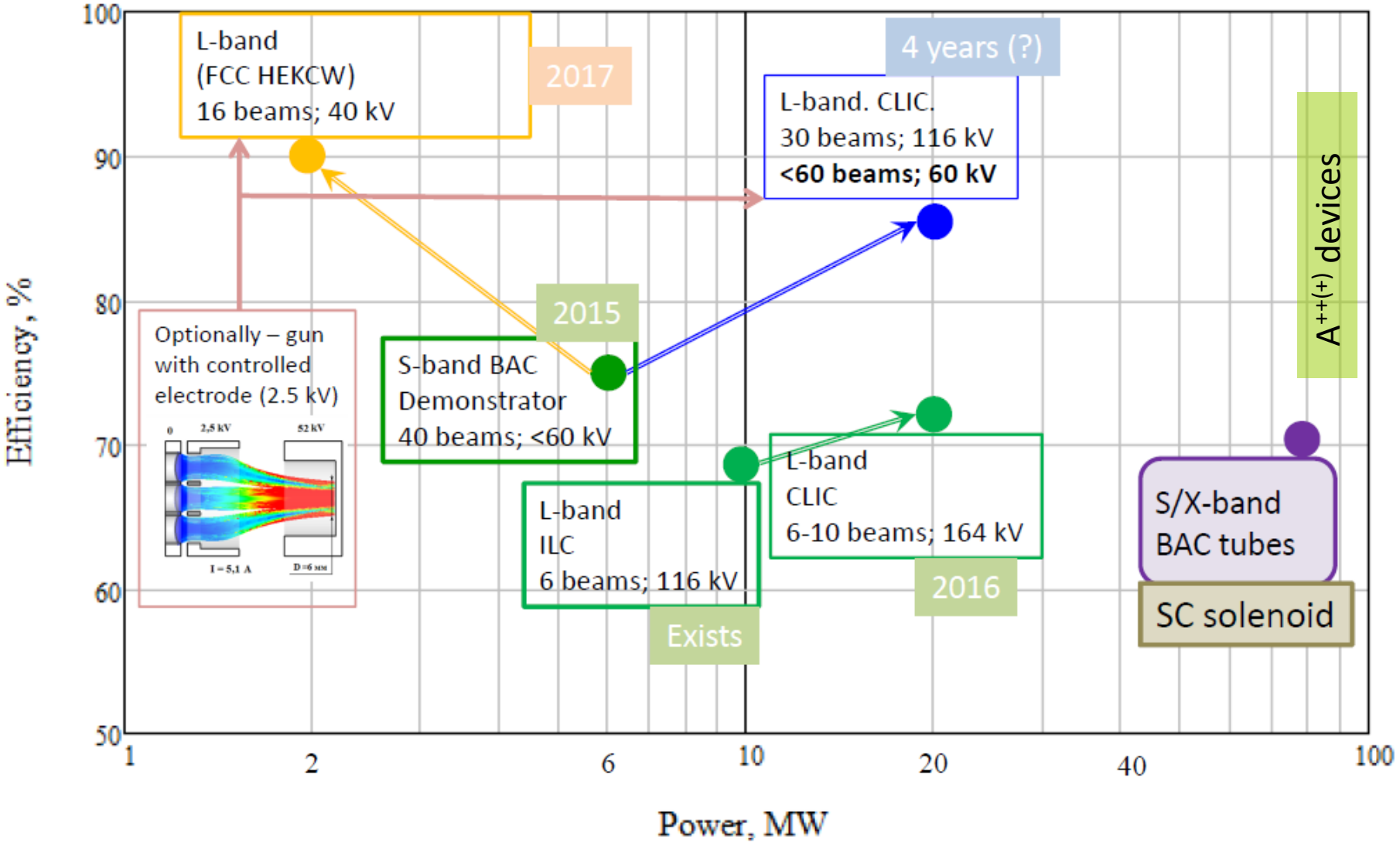
η=45%

η>75%

3 GHz
P=6-10MW
V=52-60 kV
N beams = 40
P av. = 30 kW



Strategy for high-efficiency high RF power klystron development



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Thanks for your attention
… and stay tuned