Developments Towards Higher Efficiency of RF Systems

Erk Jensen/CERN

The work and results I present here stems from a truly collaborative effort.
It is not my own work, but I wish to highlight their successful effort.

I acknowledge some by name – forgive me for not being complete!

Introduction

- This is not a summary talk.
- The RF relevant FCC machine parameters have well converged – they clearly indicate the need for ***Higher Energy Efficiency***.
- These parameters have been scrutinized in a recent RF review and are well converging towards a baseline design.
- Energy efficiency can be improved by
  - Optimizing cryogenic consumption
  - Optimizing the RF power generation:

    The highlight I have chosen to present concerns very high efficiency klystrons, based on novel ideas ("bunch core oscillations", "BAC" and "congregated bunch").

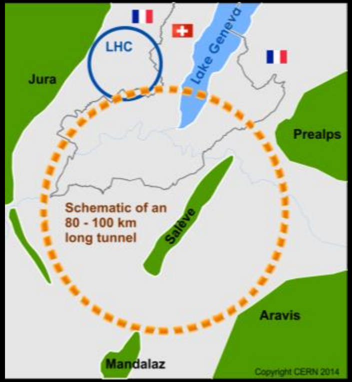
Motivation: FCC parameters

	FCC-hh	Z	Z	W	H	$t\bar{t}$
Beam energy [GeV]	**50,000**	**45.6**		**80**	**120**	**175**
Beam current [mA]	0.5	1450		152	30	6.6
Bunches / beam		30180	91500	5260	780	81
Bunch spacing [ns]	25	7.5	2.5	50	400	4000
Bunch population [10^{11}]	1.0	1.0	0.33	0.6	0.8	1.7
Crossing angle at IP [mrad]		30				
Bunch length [mm] (total)	300	6.7	3.8	3.1	2.4	2.5
Energy loss / turn [GeV]		0.03		0.33	1.67	7.55
Total RF voltage [GV]	0.032	0.4	0.2	0.8	3	10
RF frequency [MHz]	400					
cells×cavities×beams	1×25×2	1×150×2	1×75×2	2×150×2	2×400×2	2×1340
Luminosity/IP for 2IPs [10^{34} $cm^{-2}s^{-1}$]	5…30	207	89.4	19.1	5.1	1.3
SR power (total) ≈ total RF power [MW]	**5**	**100**				
Electric power for RF [MW]	**≈ 10**	**≈ 165**				
Total cryogenic power [MW]	**0.4**	**2**	**2**	**5**	**23**	**39**

Energy consumption – orders of magnitude

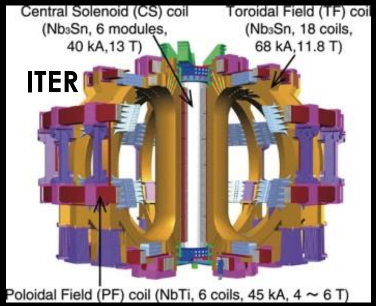
generation	consumption	storage
1d cyclist „Tour de France" (4h x 300W): **1.2 kWh**	1 run of cloth washing machine: **0.8…1 kWh**	Car battery (60 Ah): **0.72 kWh**
1d Wind Power Station (avg): **12 MWh**	1d SwissLightSource 2.4 GeV,0.4 A: **82 MWh**	ITER superconducting coil: **12.5 MWh**
1d nucl. Pow. Plant Leibstadt (CH): **30 GWh**	1d FCC-ee at $t\bar{t}$ with 1.3E34 **9 GWh**	all German storage hydropower: **40 GWh**

cyclist, 300 W



FCC-ee: 384 MW

car battery



nucl. plant 1.3 GW

EuCARD² network "*EnEfficient*"

- EuCARD² ("***Eu**ropean **C**oordination for **A**ccelerator **R**&**D***") is co-funded by its partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453, and runs from 2013 to 2017.
- Work Package 3 of EuCARD² is the networking activity "EnEfficient", which stimulates developments, supports accelerator projects, thesis studies and similar in the areas of
  - Energy recovery from cooling circuits
  - Higher electronic efficiency RF power generation
  - Short term energy storage systems
  - Virtual power plant
  - Beam transfer channels with low power consumption
- More details under www.psi.ch/enefficient

M. Seidel/PSI

FCC-ee: estimate of energy consumption

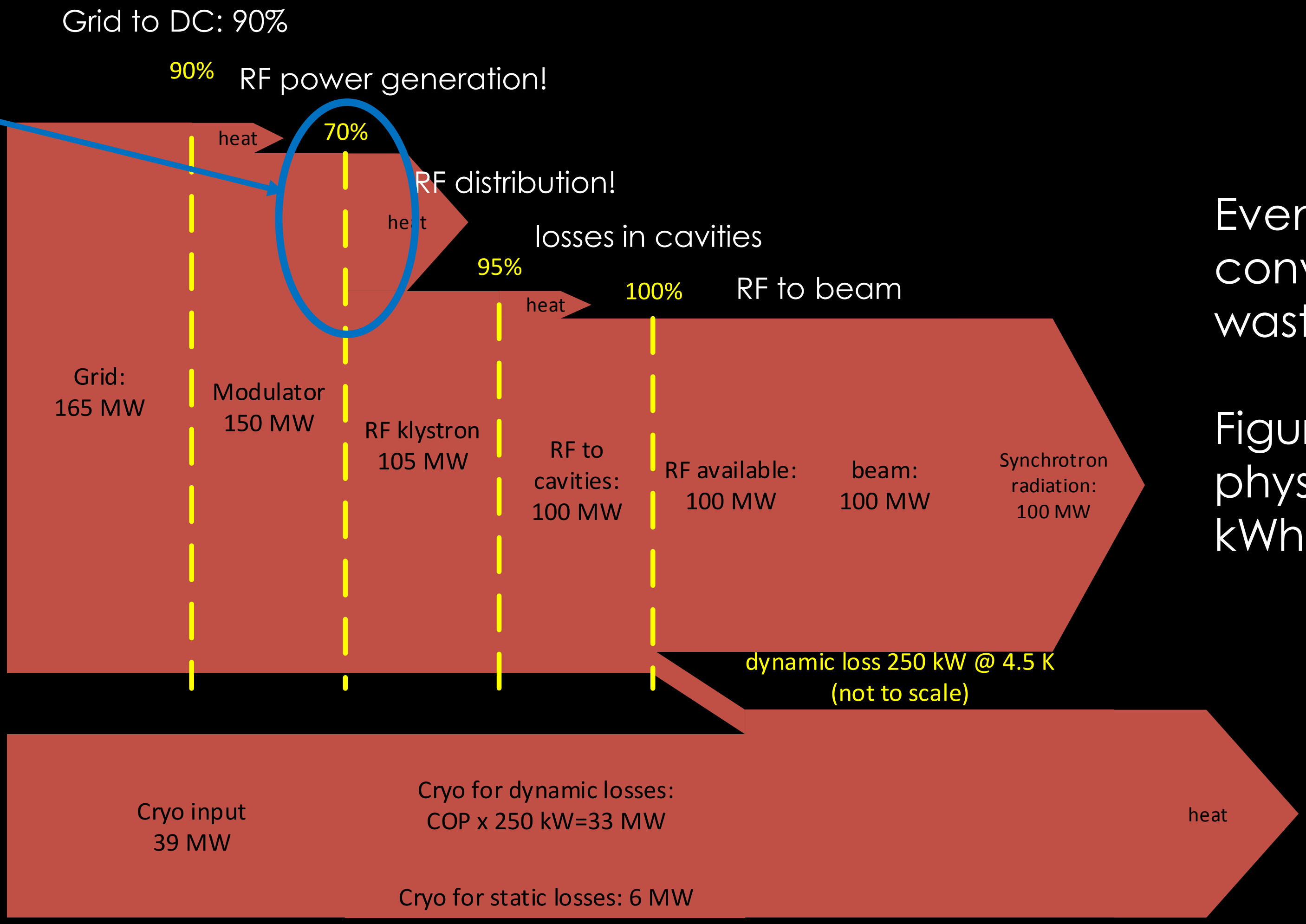
Initial estimates (target values)	Z	W	H	$t\bar{t}$
Electric power for RF [MW]	≈ 165			
Total cryogenic power [MW]	**2**	**5**	**23**	**39**
Collider magnets [MW]	3	10	24	50
Booster [MW]	4	5	8	12
Injector complex [MW]	10			
Detectors (2) [MW]	10			
Cooling & ventilation [MW]]	47	49	52	62
General services [MW]	36			
Total [MW]	277	290	328	384
1d FCC running	6.5 GWh	7 GWh	8 GWh	9 GWh

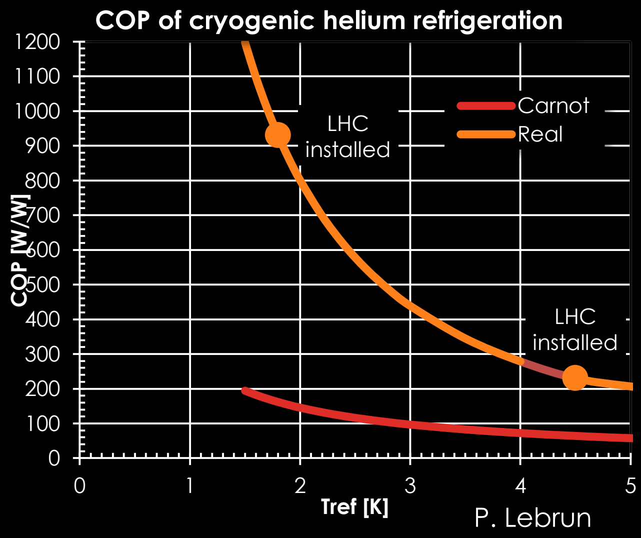
- The FCC – like other planned future large accelerators – has an energy consumption in the range relevant for society and public discussion
- Electric Energy is expensive ($\approx 40€/\mathrm{MWh}$) and valuable – transforming it to heat is destroying exergy, increasing global entropy and thus has significant environmental impact.
- In the following, I will concentrate on the largest consumer for FCC-ee: **RF!**

F. Zimmermann, O. Brunner et al.

Example $t\bar{t}$: orders of magnitude

Note: largest impact by RF power generation



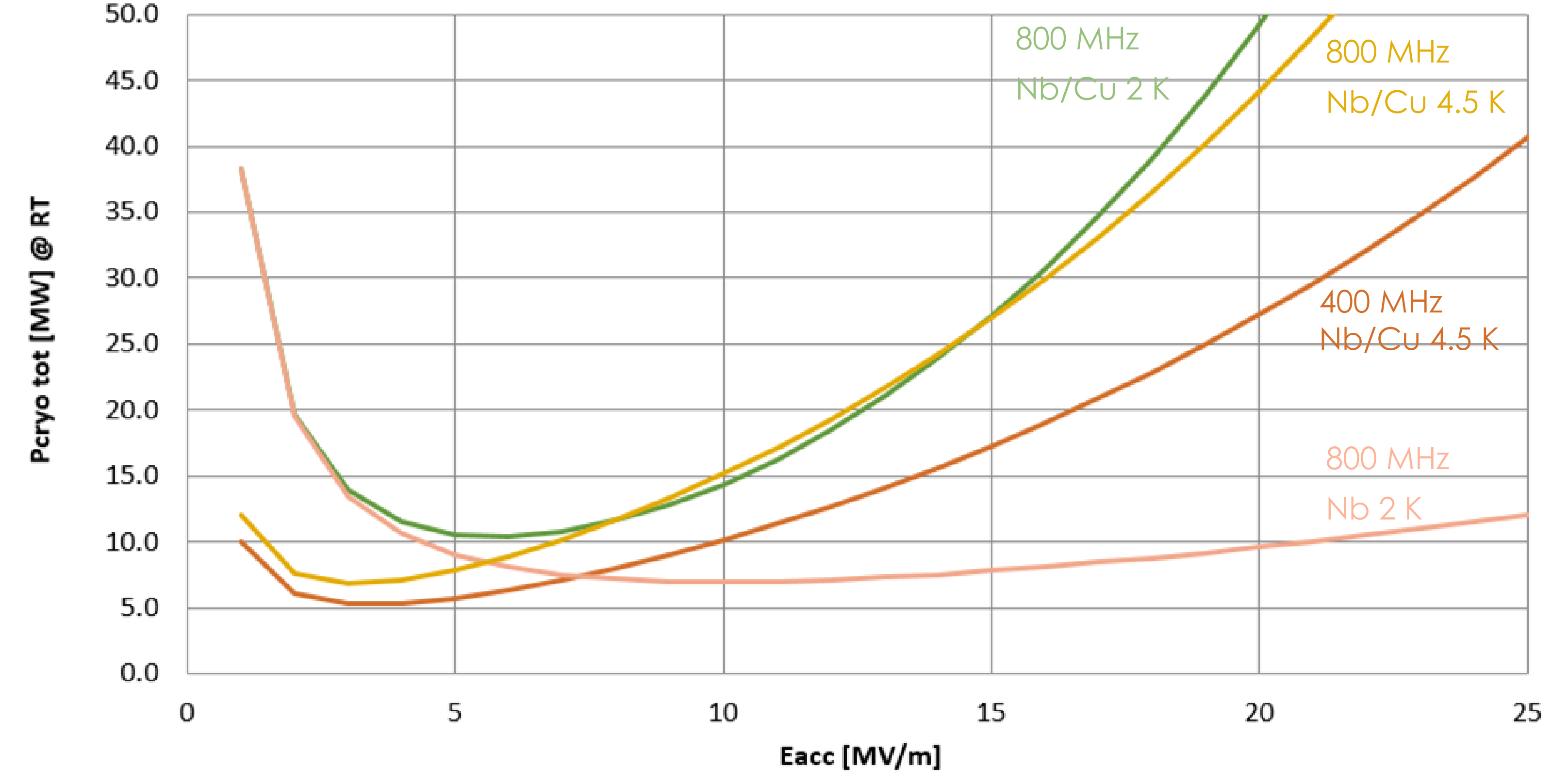


Eventually, all is converted to waste heat!

Figure of merit: physics results per kWh!

Cryogenic system optimization

- In the example above ($t\bar{t}$), 20% of the total power for the RF system is used to cool the cavities – this was already a result of an initial optimization.



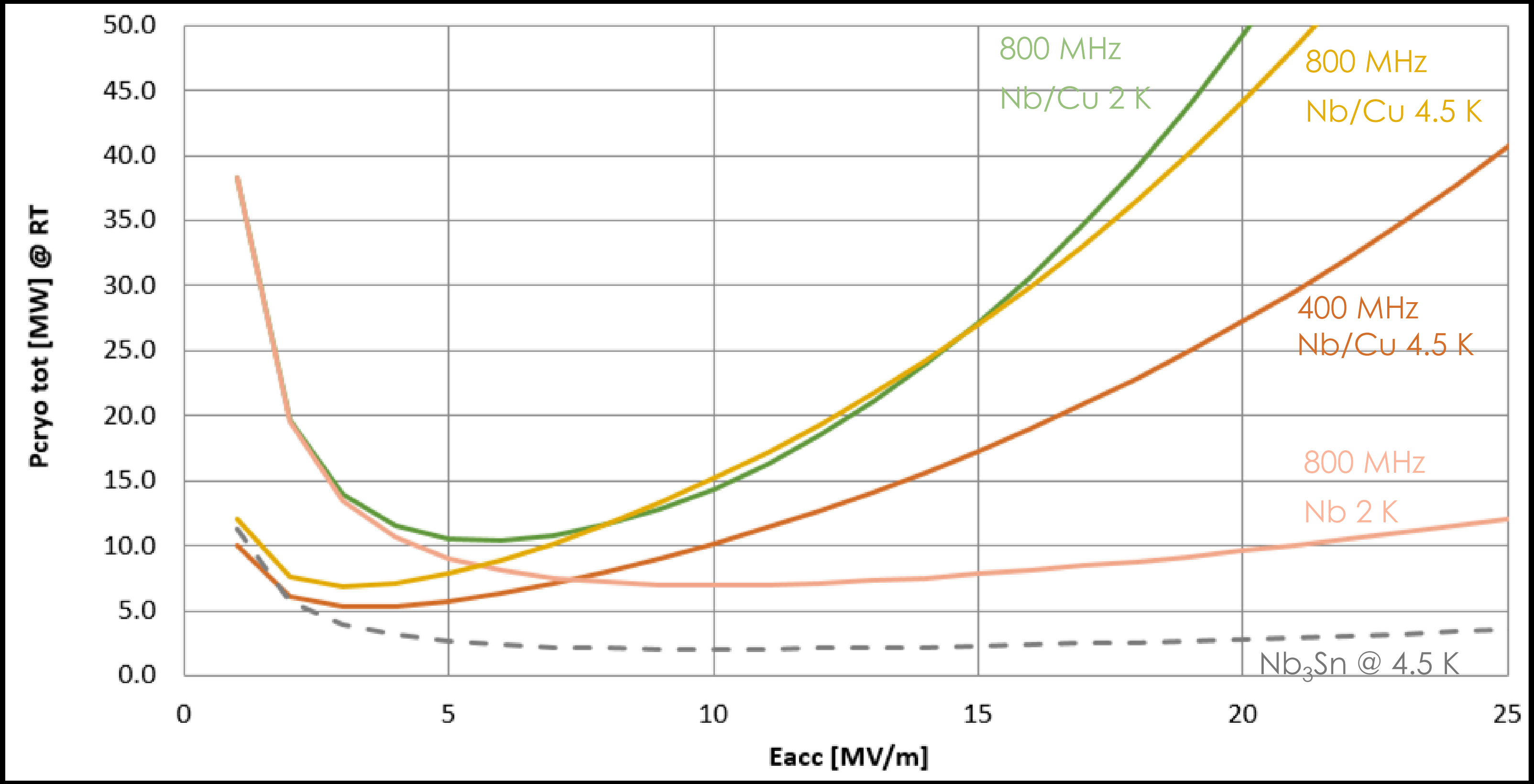
These results allowed to converge to baseline parameters! They also indicate:

- With present day technology, to contain cryogenic losses, fields should remain moderate.
- 4.5 K or 2 K operation – no significant difference at 800 MHz, 10 MV/m.

S. Aull, O. Brunner, A. Butterworth, R. Calaga, N. Schwerg, M. Therasse et al.

Cryogenic system optimization

- … But this also indicates what significant improvement could be obtained when Nb_3Sn-like (A15) materials can be successfully used!!!



This is the mouth-watering for tomorrow afternoon's session "Material, cavities and cryomodules R&D" – Giulio & Tiberio, 13:30

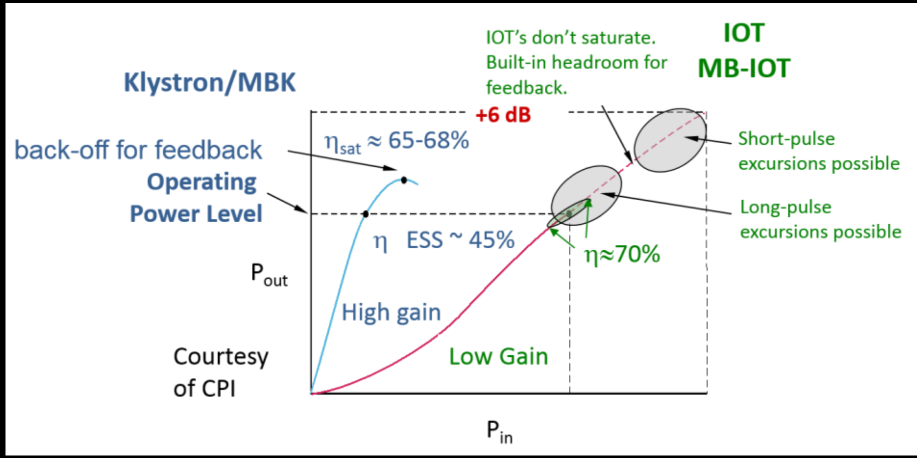
S. Aull, O. Brunner, A. Butterworth, R. Calaga, N. Schwerg, M. Therasse et al.

RF generation: What means 69% instead of 70%?

- I had assumed above: 70% efficiency for RF power generation.
- With 105 MW RF output and at 70% efficiency, this means that ***1 percentage point less*** means
  - Input power up from 150 MW to 152.2 MW, waste heat up from 45 MW to 47.2 MW.
  - 2.2 MW more electricity consumed (assuming 5000 h: 10 GWh/year or 400 k€/year)
  - 2.2 MW more heat produced and wasted in the environment.
  - The electrical installation has to be larger by 1.45%!
  - The cooling and ventilation has to be larger by 4.8%!
- All the above are significant!
- Work on increasing the useable efficiency is worth every penny invested!

RF power generators - efficiencies

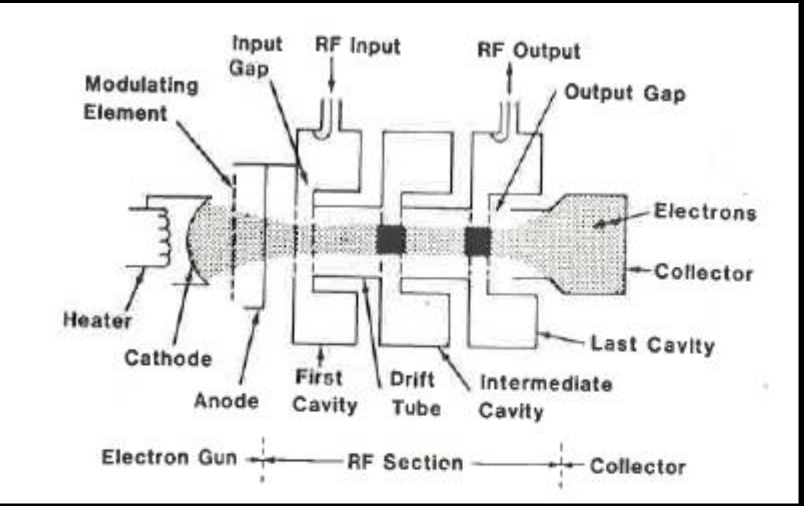
	Tetrodes	IOTs	Conventional klystrons	Solid State PA	Magnetrons
f range:	DC – 400 MHz	(200 – 1500) MHz	300 MHz – 1 GHz	DC – 20 GHz	GHz range
P class (CW):	1 MW	1.2 MW	1.5 MW	1 kW @ low f	< 1MW
typical η:	85% - 90% (class C)	70%	50%	60%	90%
Remark	Broadcast technology, widely discontinued			Requires P combination of thousands!	Oscillator, not amplifier!



M. Jensen: EnEfficient RF Sources, 2014, Daresbury

How does a klystron work?

- A continuous electron beam is accelerated by a DC voltage and guided by magnets,
- A small power RF input causes an RF voltage in the input gap, where the velocity of the electrons will be modulated with the RF.
- Passing though a subsequent drift tube, this velocity modulation will lead to density modulation (bunching).
- The density modulation causes an RF component of the current which will excite large power in the output gap.
- With just input cavity and output cavity, the maximum possible efficiency of a klystron is 58%.
- Additional cavities (near the operation f and possibly at harmonics) will help the bunching process.
- The best efficiency reached this way is around 70%.



From A.S. Gilmour, Jr. “Microwave Tubes”, Artech House 1986, who took this from Microwave Tube Manual by Varian Associates, Air Force Publication Number T.0.00-25-251, 1979

This is where we stood in 2013…

… and then Igor Syratchev (CERN) met Igor Guzilov (VDBT*) and Andrey Baikov (МФЮА**)

*JSC VDBT: "Vacuum Device's Basic Technologies"
** МФЮА (MFUA.ru): Moscow University of Finance and Law

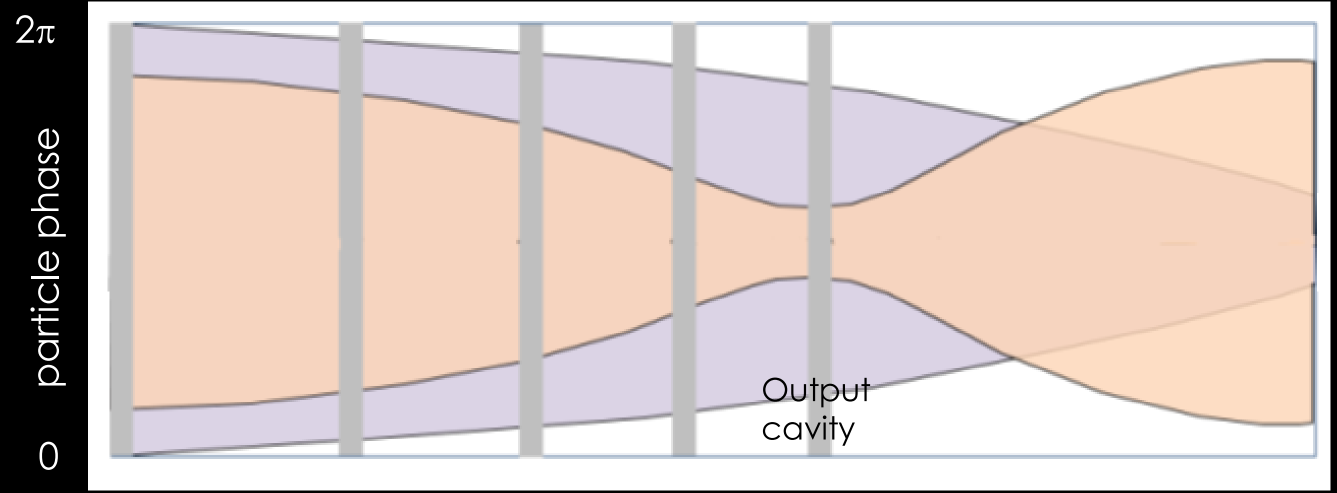
Remember Washington*? I said:

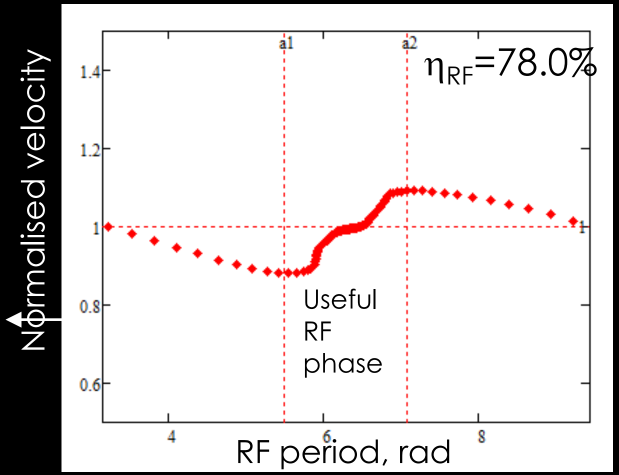
- 2014 saw a breakthrough in klystron theory:
  - The "**congregated bunch**" concept was re-introduced [V.A. Kochetova, 1981]
    (later electrons faster when entering the output cavity).
  - The concept of "**bunch core oscillations**" was introduced [A. Yu. Baikov, et al.: "Simulation of conditions for the maximal efficiency of decimeter-wave klystrons", Technical Physics, 2014]
    (controlled periodic velocity modulation)
  - The "**BAC**" method was invented [I.A. Guzilov, O.Yu. Maslennikov, A.V. Konnov, "*A way to increase the efficiency of klystrons*", IVEC 2013]
    (Bunch, Align velocities, Collect outsiders)
- These methods together promise a significant increase in klystron efficiency (approaching 90%)
- An international collaboration has started – prototypes are being designed. (SLAC plans to convert an existing 5045 klystron – simulations are encouraging)

*) FCC-week, Washington DC, 23-27 March 2015

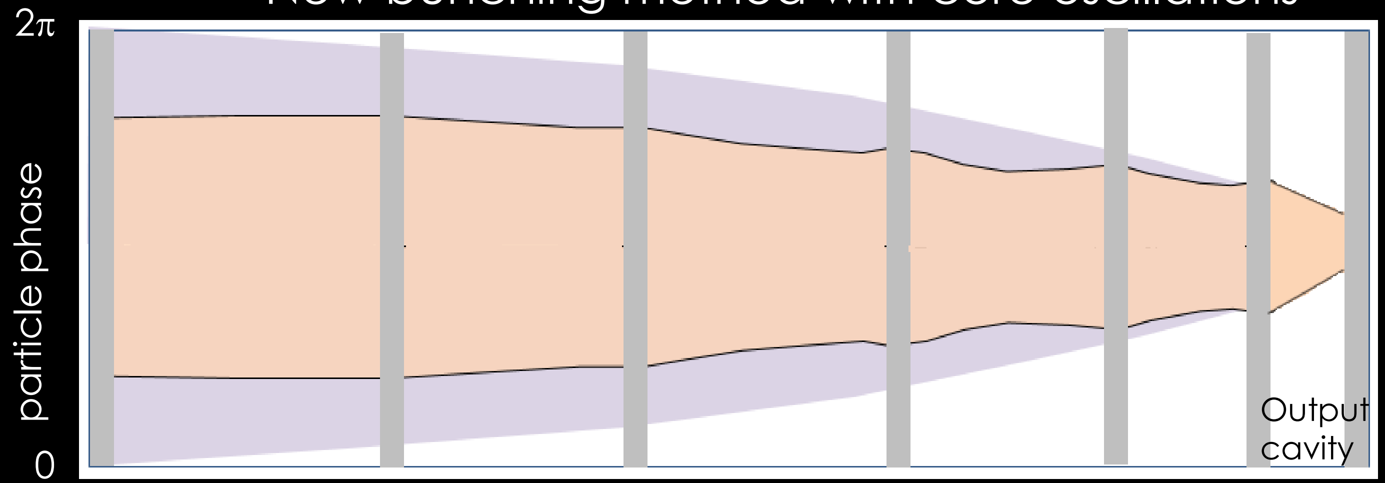
"Bunch core oscillations" explained

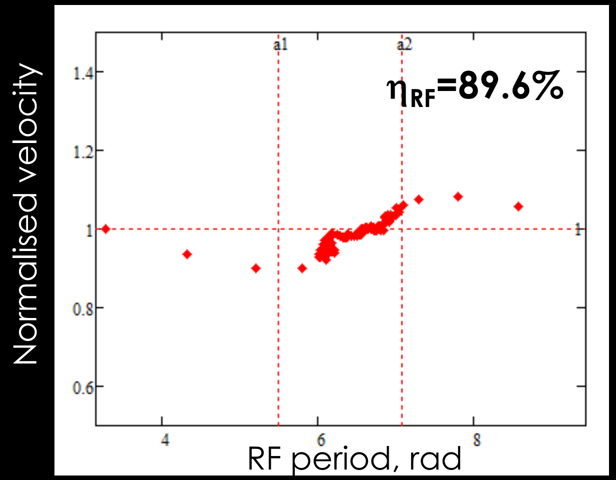
"Classical" bunching





New bunching method with core oscillations





HEIKA collaboration

- HEIKA – "High Efficiency International Klystron Activity" is evaluating and implementing this "breakthrough".
- HEIKA Members: Labs (CERN, ESS, SLAC, CEA), Universities (MFUA, Lancaster), Industry (Thales, L3, CPI, VDBT)
- It studies theoretically and experimentally high efficiency klystrons for both pulsed (e.g. CLIC, ESS) and CW applications (FCC).
- HEIKA is well integrated with the "EnEfficient" network in EuCARD^2 as enabler.

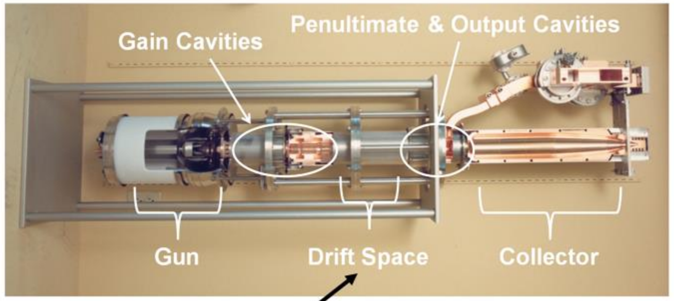
I. Syratchev (CERN), A. Baikov (MFUA), I. Guzilov (VDBT), J. Neilson, A. Jensen (SLAC), G. Burt, D. Constable, C. Lingwood (U Lancaster), A. Mollard (CEA), R. Marchesin (Thales), Q. Vuillemin (Thales/CERN), C. Marrelli (ESS), R. Kowalczyk (L-3com), (Toshiba), T. Grant (CPI)

The plan(s)

- VDBT to build a POP prototype with the following parameters:

Parameter	specification
RF frequency	$2.99855\ \mathrm{GHz}$
Peak power	$> 6\ \mathrm{MW}$
RF gain	$> 45\ \mathrm{dB}$
Efficiency	$> 60\%$ (aiming at $> 70\%$)
Voltage	$\leq 60\ \mathrm{kV}$ (aiming at $52\ \mathrm{kV}$)
pulse length × rep rate	$\geq 7.5\ \mu\mathrm{s} \times 300\ \mathrm{Hz} = 2.25 \cdot 10^{-3}$

- SLAC had the idea to refurbish an existing 5045 klystron (2.856 GHz)
  - Increase of η from 45% to 55%
  - Increase output power from 65 to 85 MW!
- … design a klystron for FCC!



The 5045 is being retrofitted to add BAC cavities in the drift space.

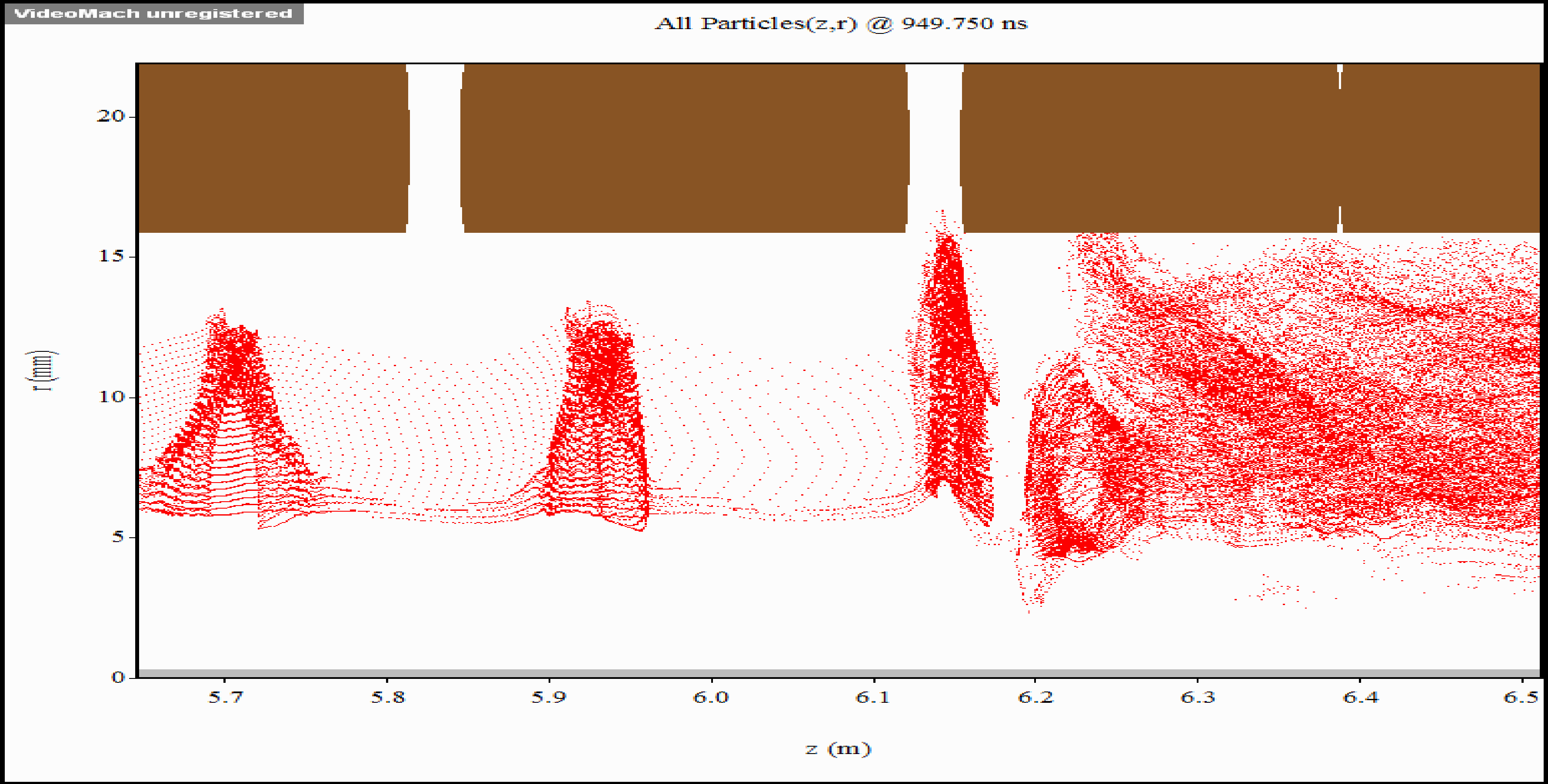
Aaron Jensen et al., IVEC2015

FCC klystron – initial target parameters

Operating frequency	800 MHz initially
Target RF Output power	1.5 MW (CW)
Voltage	40 kV
N-beams×Current	$16 \times 2.6\ \mathrm{A} = 42\ \mathrm{A}$
Target Efficiency	90%
Perveance	$16 \times 0.33\ \mu\mathrm{K} = 5.25\ \mu\mathrm{K}$
Number of cavities	8
Cathode loading	$< 2\ \mathrm{A\,mm^{-2}}$
Length	2.3 m

PIC simulations showed that this is not easy at all – efficiency limited to about 80%

The way out: hollow beams!

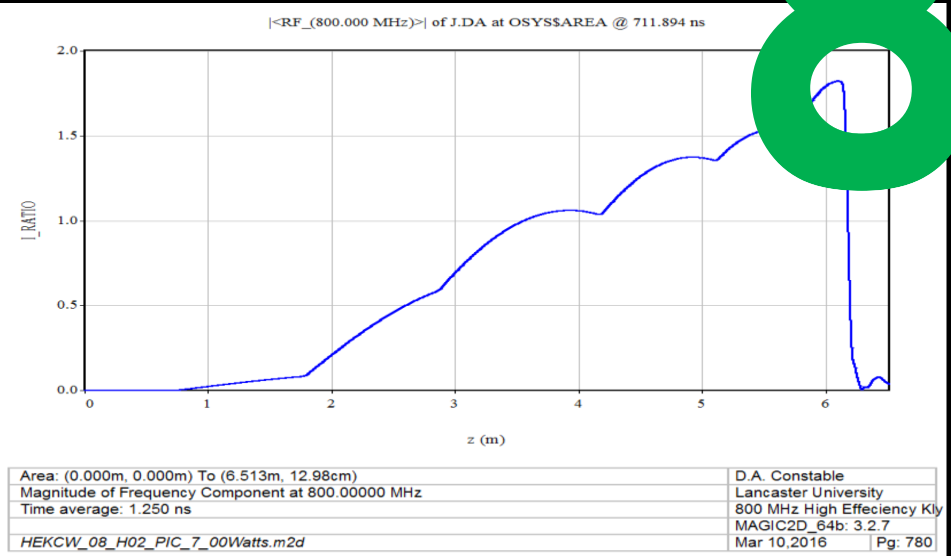


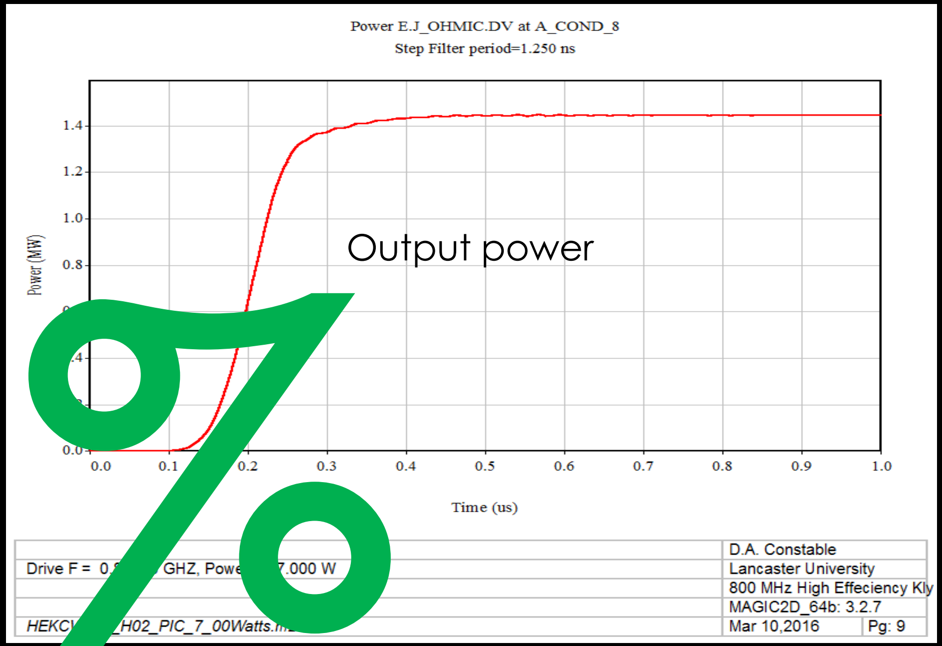
D. Constable, C. Lingwood (U Lancaster) & HEIKA collaboration

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
- Efficiency…..

86%



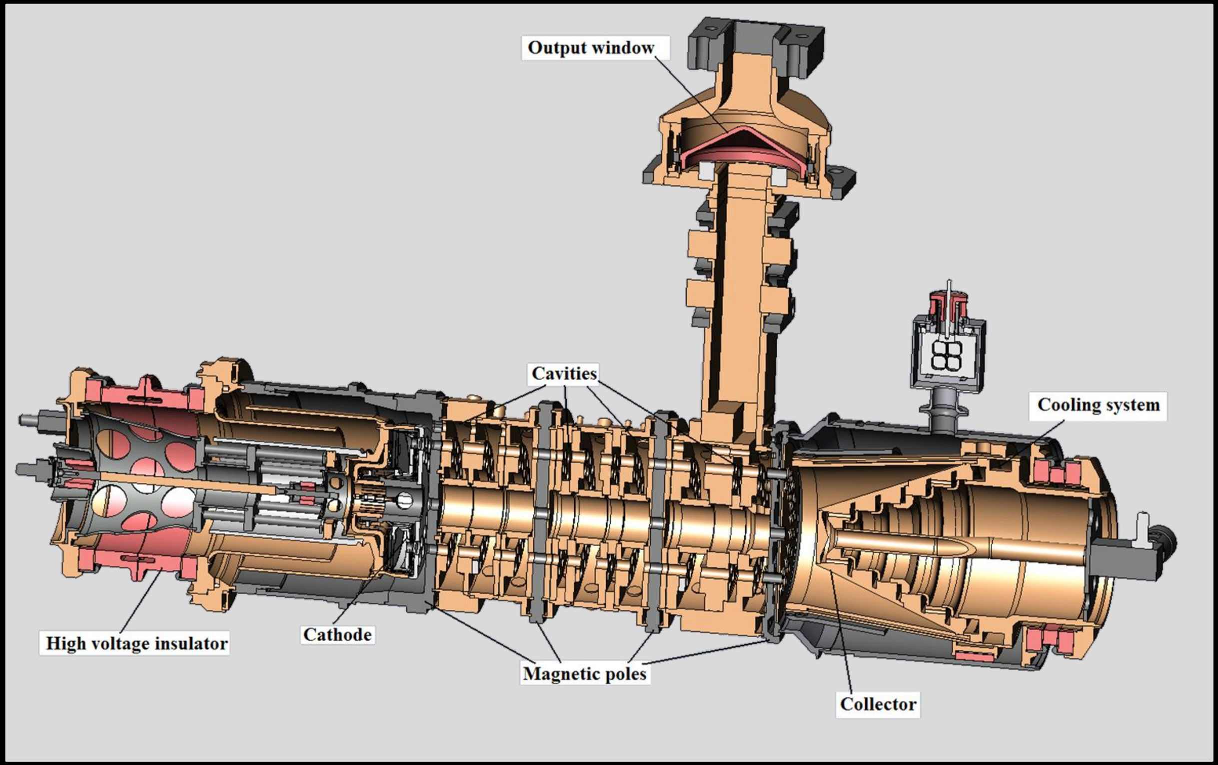


More of these exciting results tomorrow afternoon, session “RF Efficiency Optimization” – Giulio & Tiberio, 15:30

D. Constable, C. Lingwood (U Lancaster) & HEIKA collaboration

Progress with the VDBT prototype

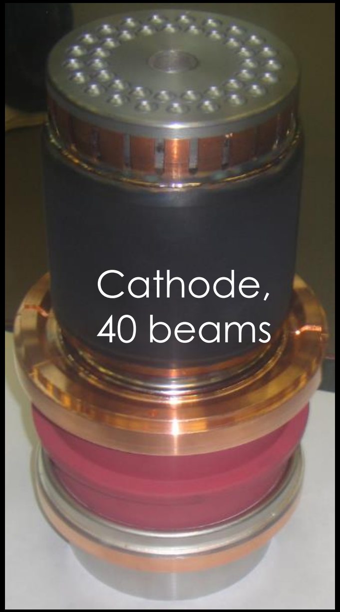
Shown in Washington: the concept

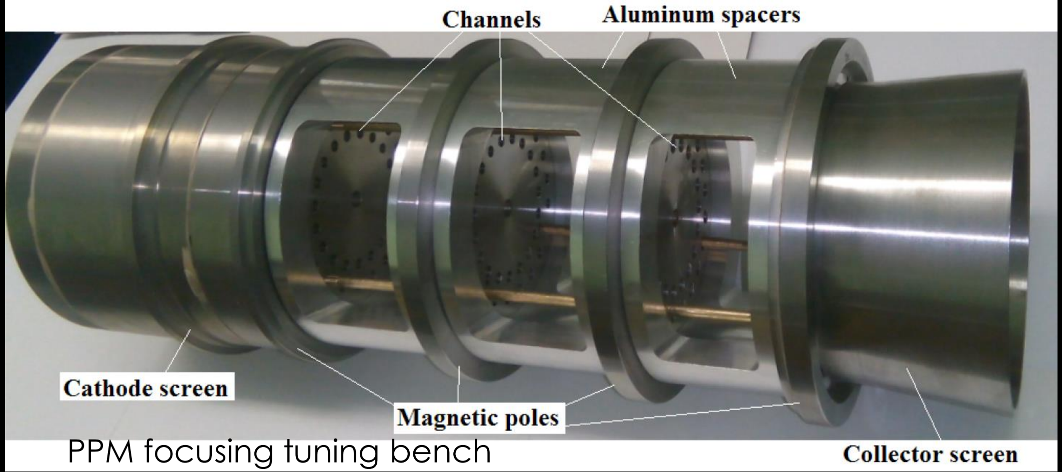


The engineering design and fabrication of parts started in 2015

I. Guzilov (VDBT)

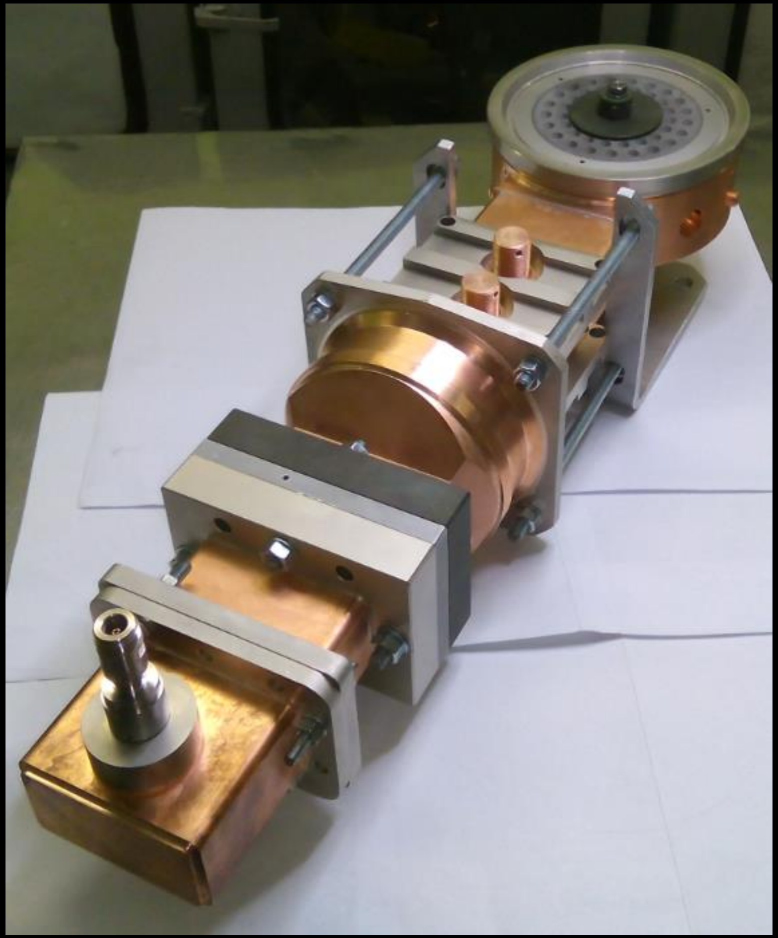
VDBT Prototype – status Aug 2015



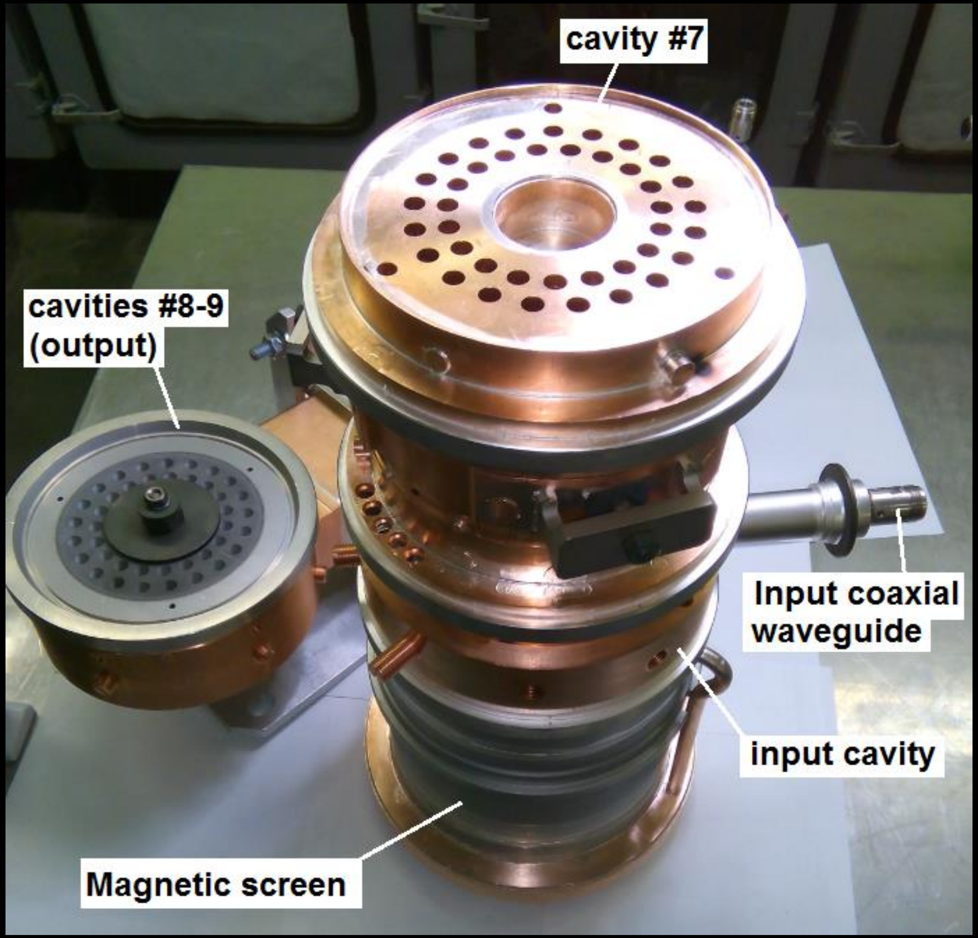


I. Guzilov (VDBT)

VDBT Prototype – status Dec 2015



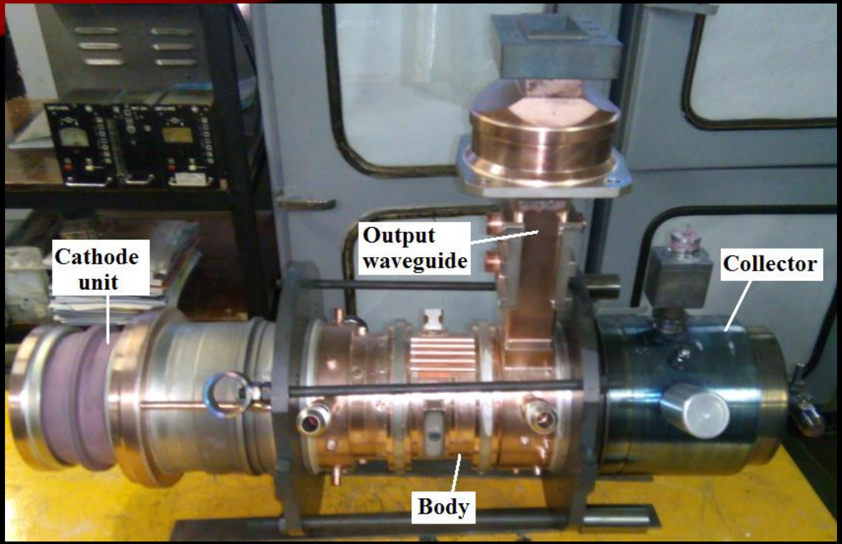
Cavities 8 and 9 and output waveguide



Cavities during assembly

I. Guzilov (VDBT)

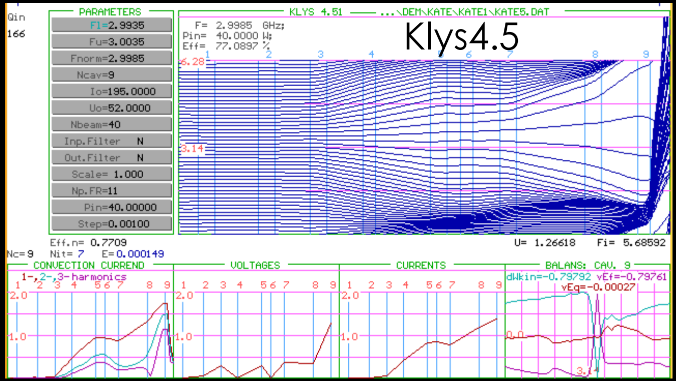
Progress with the VDBT prototype

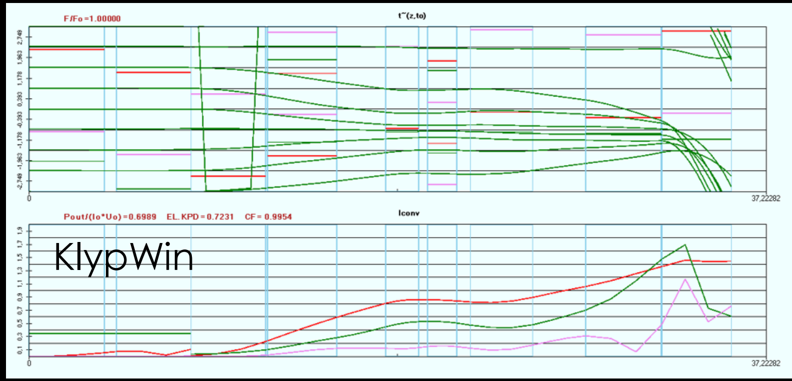


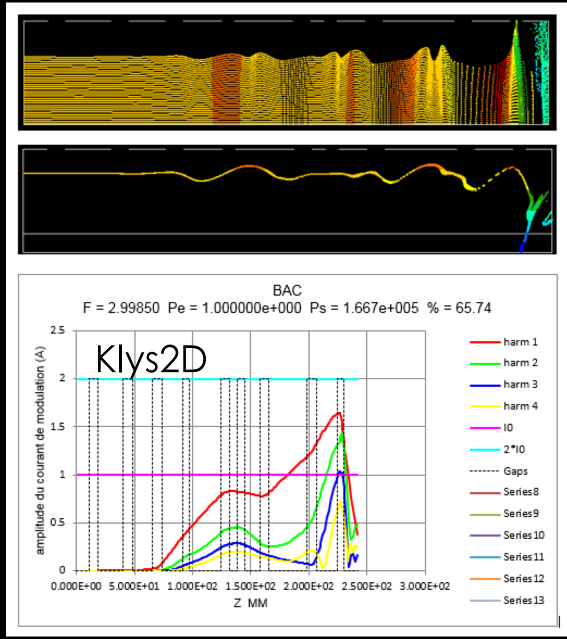
Assembled prototype ready for testing

- Predictions by different simulation codes

1. Klys4.5 (1-D): Efficiency **77%.** Original company code used to optimise the tube.
2. KlypWin (1-D, A. Baikov): Efficiency **69.9%**. The code used by HEIKA study for the basic design and optimisation of high efficiency klystrons.
3. KLYS2D (2-D, Thales): Efficiency **65.74%**.

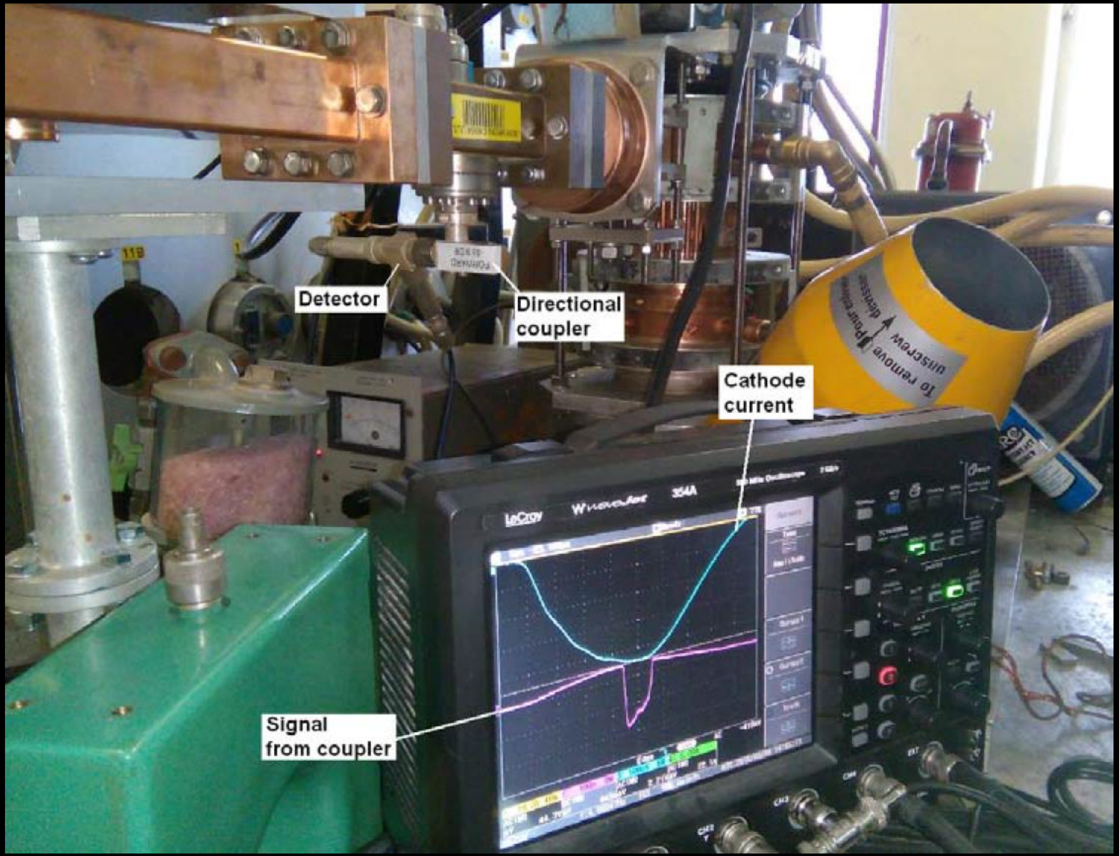




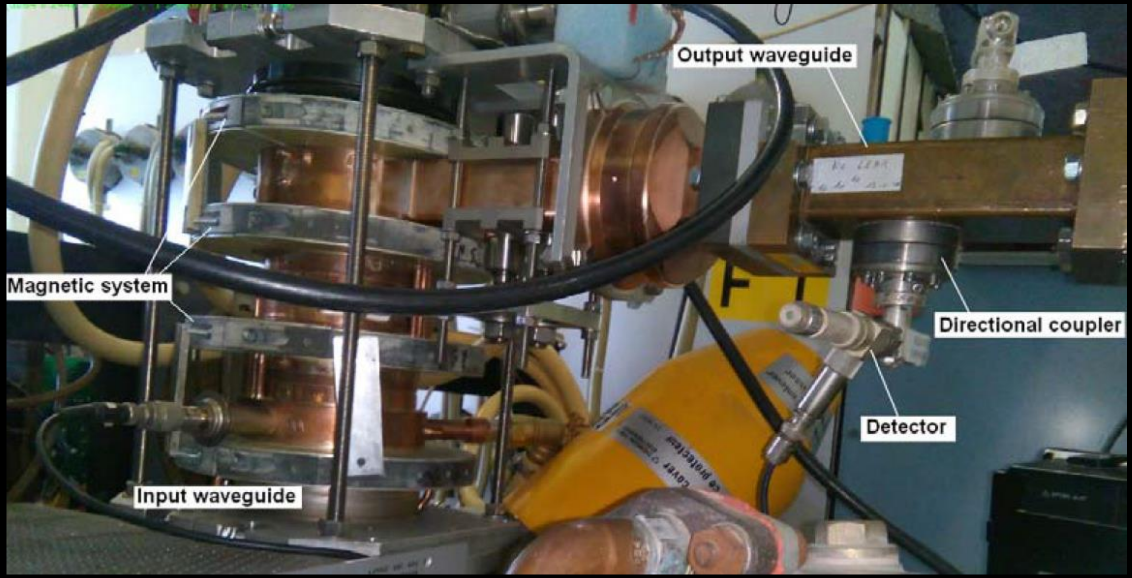


I. Guzilov (VDBT)

VDBT Prototype – status Mar 2016



Test set-up – first RF pulses

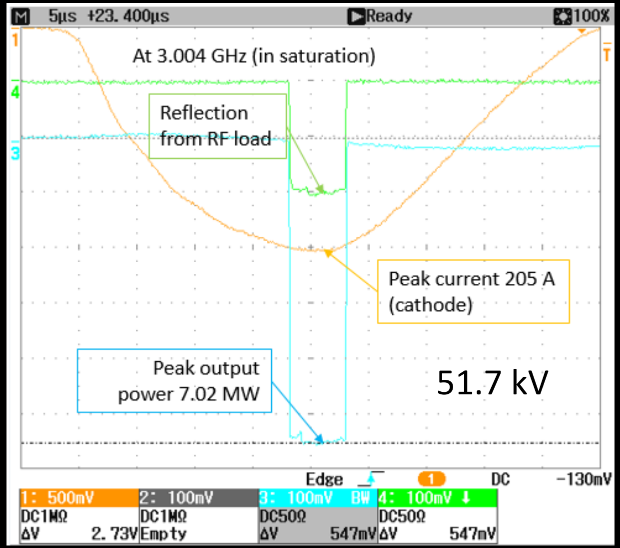


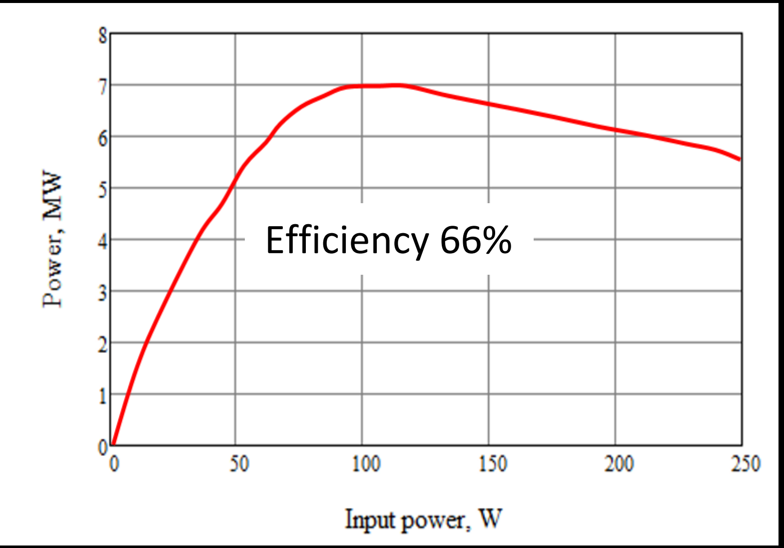
The rear view of the test set-up

I. Guzilov (VDBT)

VDBT prototype – factory test

In the lab - ready to go





I. Guzilov (VDBT)

VDBT prototype factory test – results

- Initial tests of the transmission through the 40 beams (230 A) was 96%!
- Initial RF power tests resulted in 7 MW peak with 100 W drive (48 dB gain)

Parameter	specification	1st prototype measurement (preliminary)
RF frequency	2.99855 GHz	3.004 GHz
Peak power	> 6 MW	7.02 MW
RF gain	> 45 dB	48 dB
Efficiency	> 60% (aiming at > 70%)	66%
Voltage	≤ 60 kV (aiming at 52 kV)	51.7 kV
pulse length × rep rate	$\geq 7.5\ \mu s \times 300\ \text{Hz} = 2.25 \cdot 10^{-3}$	$7.5\ \mu s \times 300\ \text{Hz}$

- This result is remarkable for a 1st prototype!
- This is a beautiful confirmation of the concept!
- The measured efficiency is remarkably close to the Klys2D prediction!

This is just meant to water your mouth for tomorrow afternoon's session "RF Efficiency Optimization" – Giulio & Tiberio, 15:30

Closing remarks

- The FCC RF parameters have converged towards a baseline design.
- FCC-hh is naturally integrated with the more challenging FCC-ee designs.
- Energy efficiency is a major concern that is addressed
- A recent major breakthrough in klystron technology has made significant, impressive progress, both theoretically and experimentally!
- Find out more in tomorrow's RF sessions in Giulio & Tiberio

Thank you for your interest and attention!