Recent developments towards very high efficiency klystrons

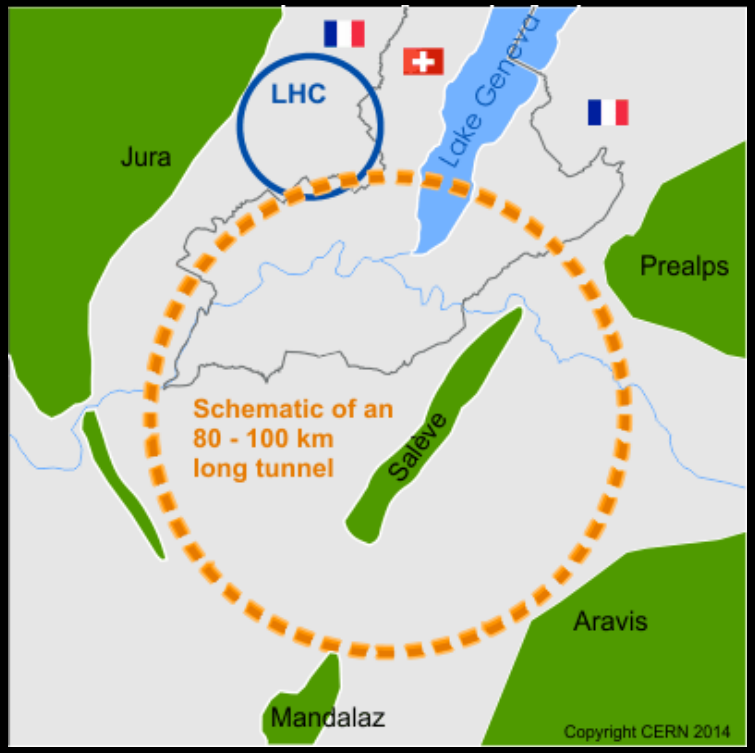
Erk Jensen/CERN presenting for the HEIKA Collaboration *)

HEIKA: "High Efficiency International Klystron Activity"

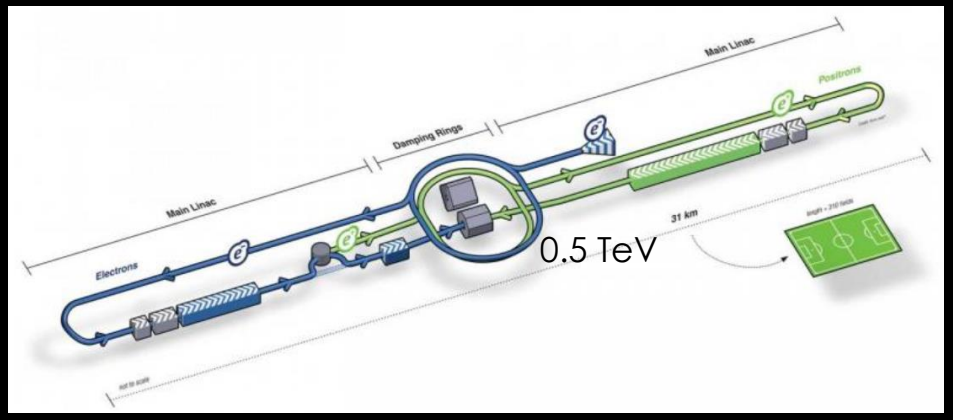
I. Syratchev/CERN, A. Baikov/MFUA, I. Guzilov/VDBT, C. Lingwood, D. Constable, V. Hill/U Lancaster, R. Marchesin, Q. Vuillemin/TED, C. Marrelli/ESS, R. Kowalczyk/L-3, T. Habermann/CPI, A. Jensen/SLAC

Motivation

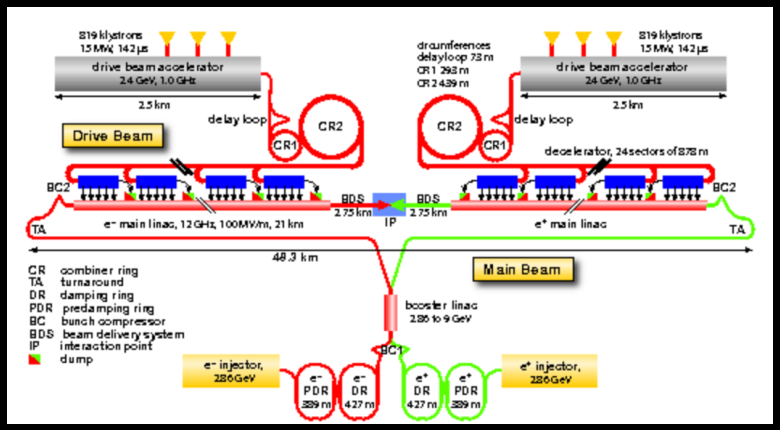
Future large scale accelerators



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



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



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

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}]		207	89.4	19.1	5.1	1.3
SR power (total) ≈ total RF power [MW]				**100**		
Electric power for RF [MW]				**≈ 165**		
Total cryogenic power [MW]	**0.4**	**2**	**2**	**5**	**23**	**39**

The significance of efficiency

Let us assume 70% efficiency for RF power generation – now what happens if we get 1% less?

- 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!

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

The idea

- 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 "HEIKA" has started – prototypes are being designed. (SLAC plans to convert an existing 5045 klystron – simulations are encouraging)

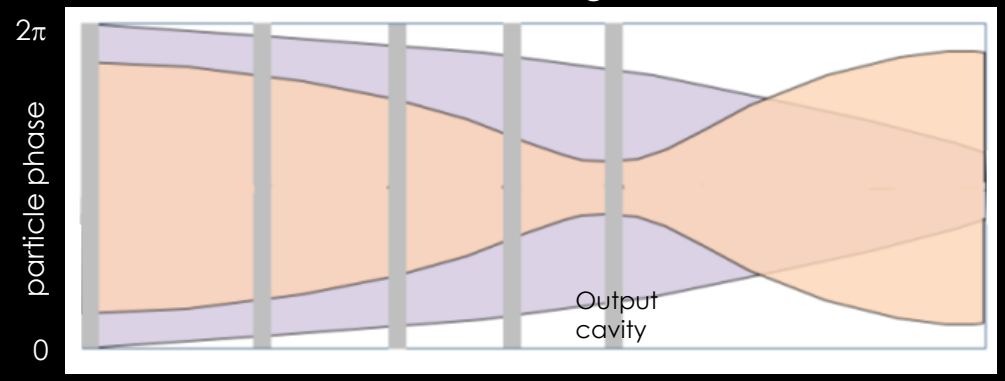
HEIKA collaboration

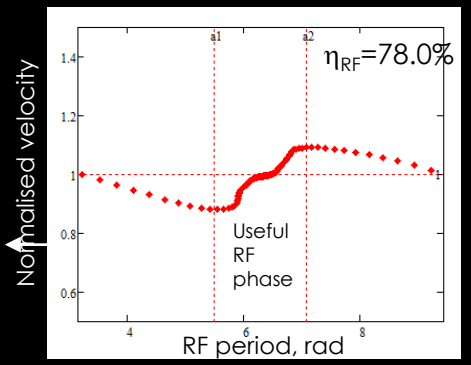
- HEIKA – "High Efficiency International Klystron Activity" is evaluating and implementing this "breakthrough".
- HEIKA Members: Labs (CERN, ESS, SLAC, CEA), Universities (MFUA, Lancaster), Industry (Thales, L3, CPI, VDBT)
- It studies theoretically and experimentally high efficiency klystrons for both 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, C. Lingwood, D. Constable, V. Hill/U Lancaster, R. Marchesin, Q. Vuillemin/TED, C. Marrelli/ESS, R. Kowalczyk/L-3, T. Habermann/CPI, A. Jensen/SLAC

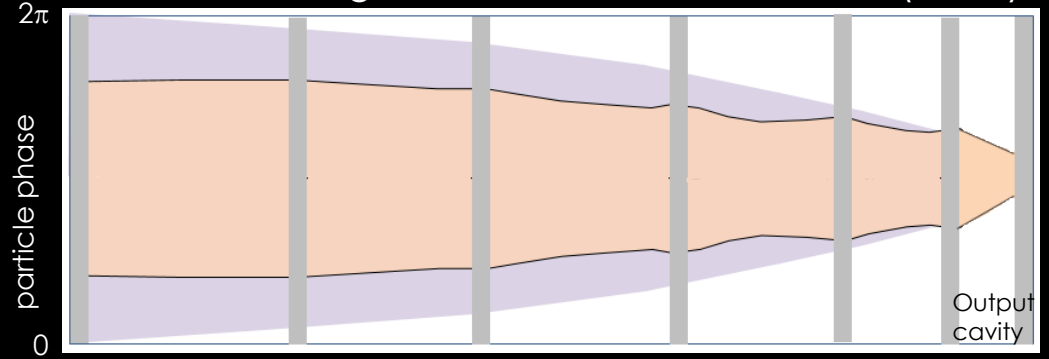
"Bunch core oscillations" explained

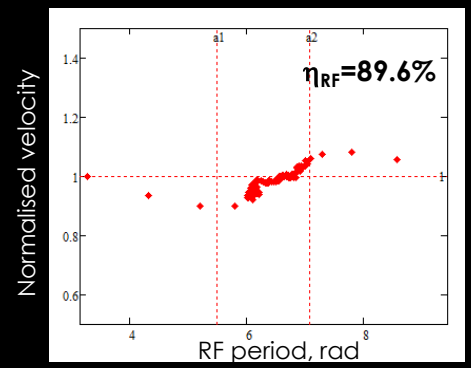
"Classical" bunching





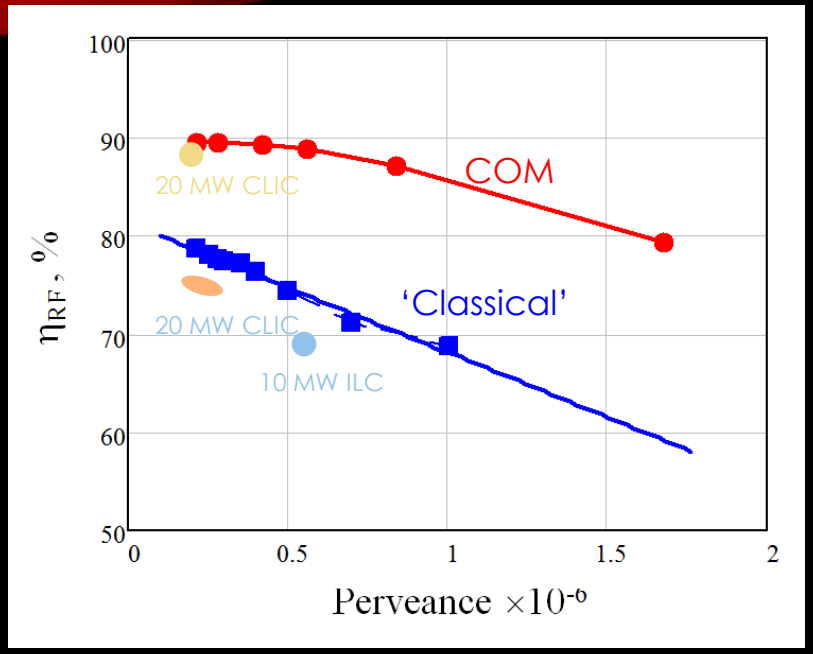
New bunching method with core oscillations (COM)

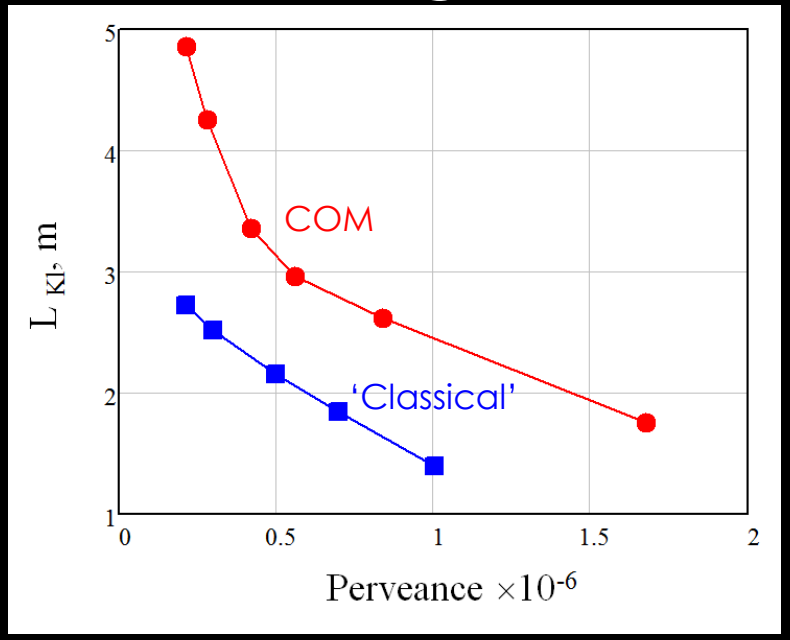


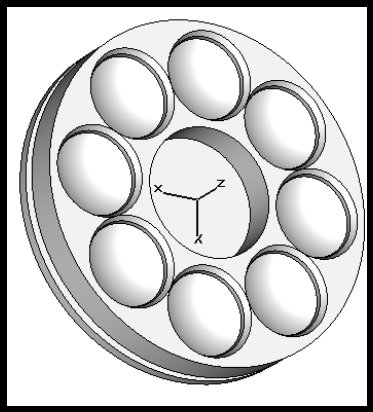


Link: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7194781

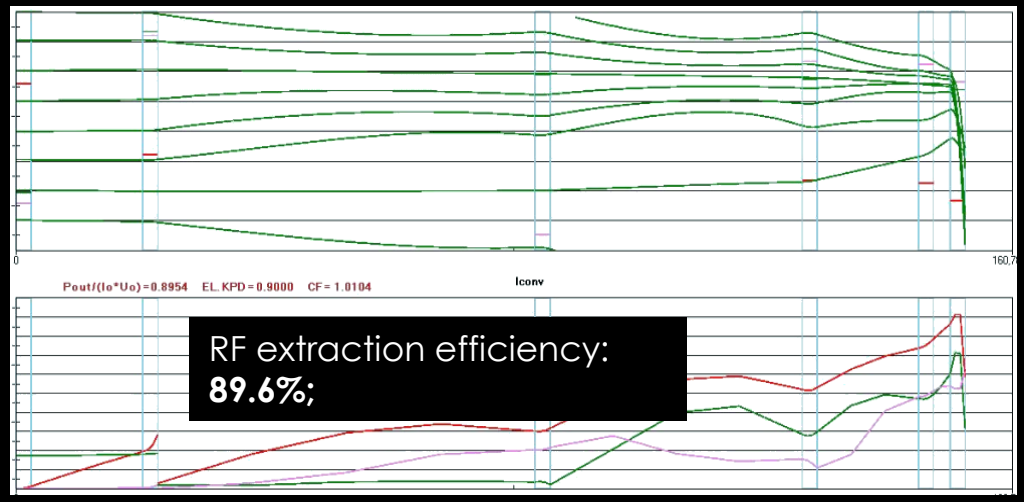
Comparison of the bunching methods







N beams = 8
V = 180 kV
I total = 128 A



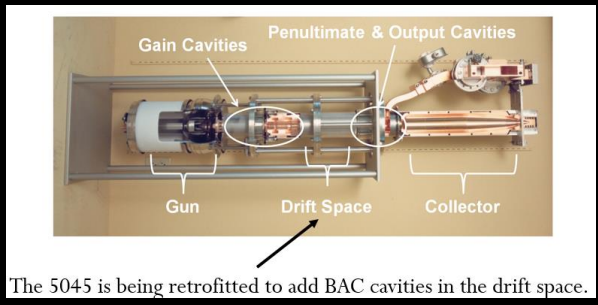
RF extraction efficiency:
89.6%;

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!



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

Aaron Jensen et al., IVEC2015

- … design a klystron for FCC!

FCC klystron – initial target parameters

Operating frequency	$800\ \mathrm{MHz}$ initially
Target RF Output power	$1.5\ \mathrm{MW}$ (CW)
Voltage	$40\ \mathrm{kV}$
N-beams×Current	$16 \times 2.6\ \mathrm{A} = 42\ \mathrm{A}$
Target Efficiency	$\mathbf{90}\%$
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	$2.3\ \mathrm{m}$

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

Evolution of the HEIKA CW klystron (PIC simulations)

Original 8_01 design. Saturated bunch.

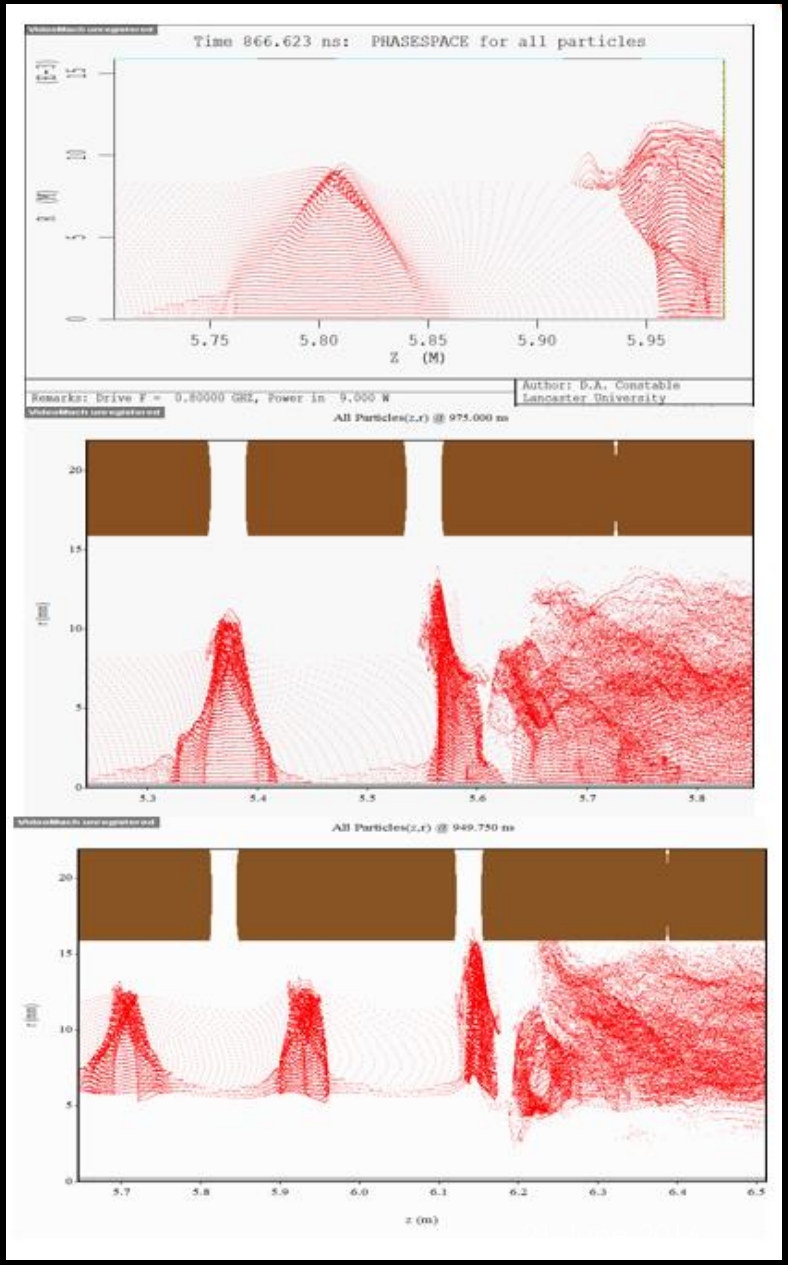
79.8%

8_04. The new design of 'gentle' buncher reduced significantly radial bunch stratification.

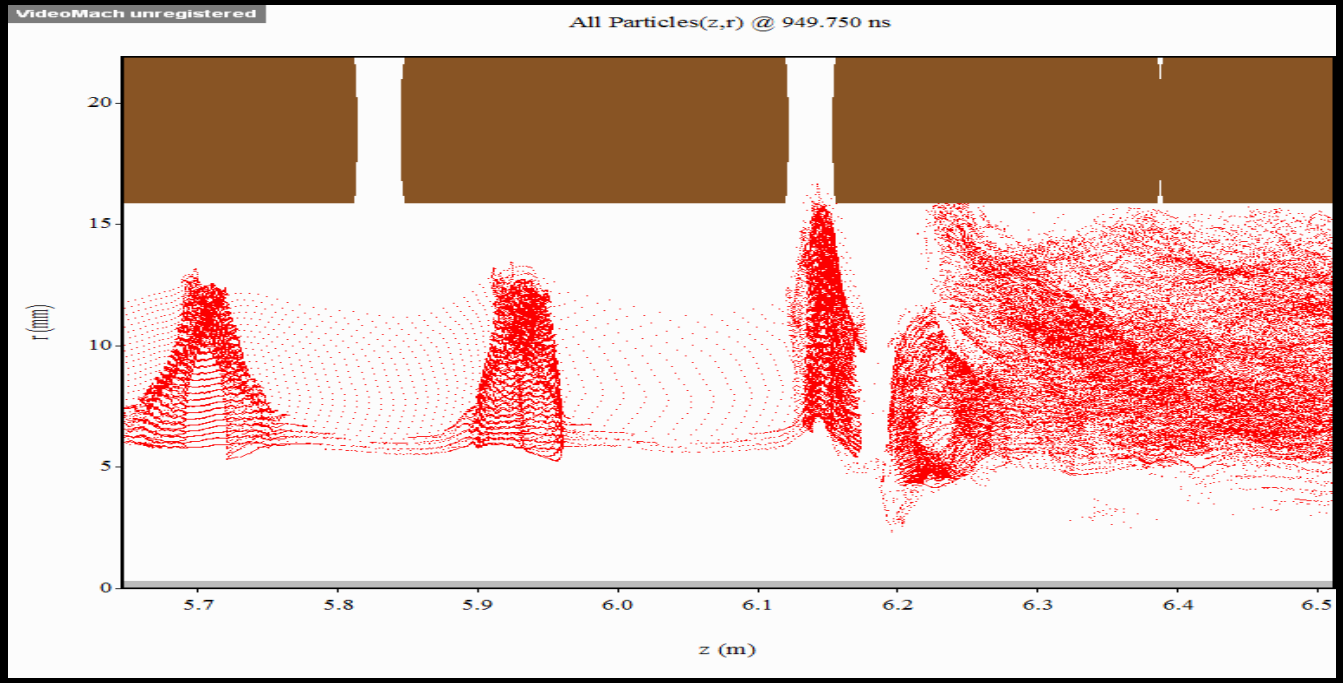
83.3%

8_H02. Hollow beam configuration with optimal geometry made bunch nearly perfect.

86%



The way out: hollow beams!



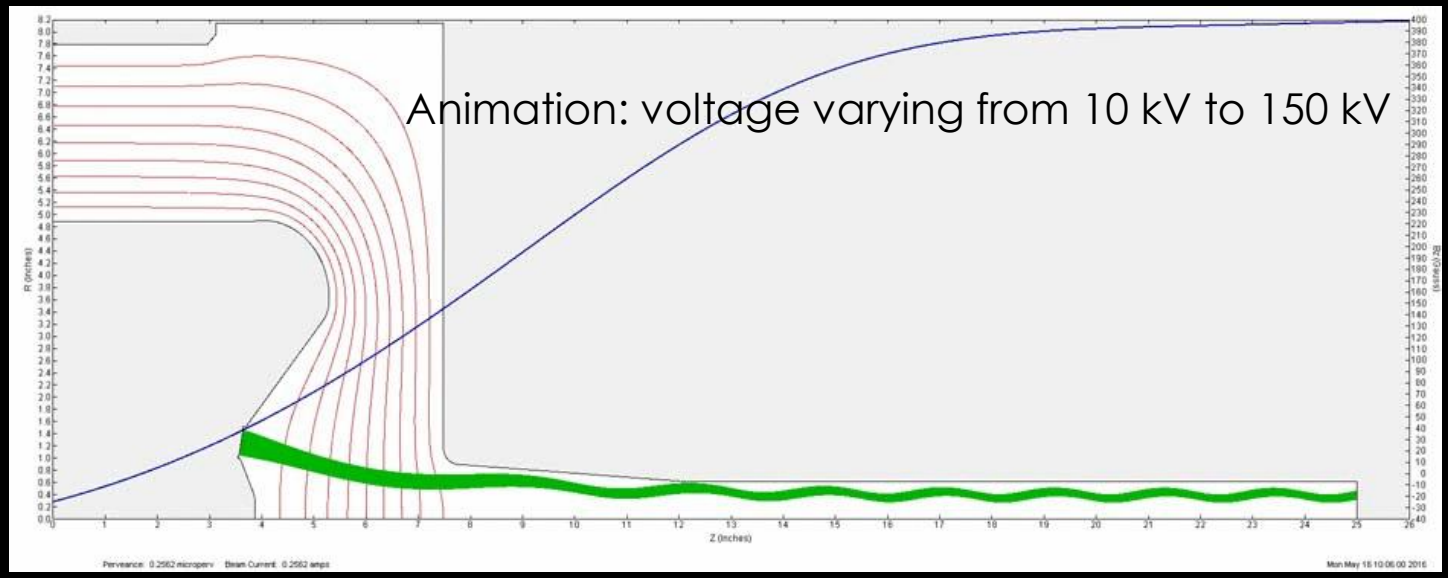
86%

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

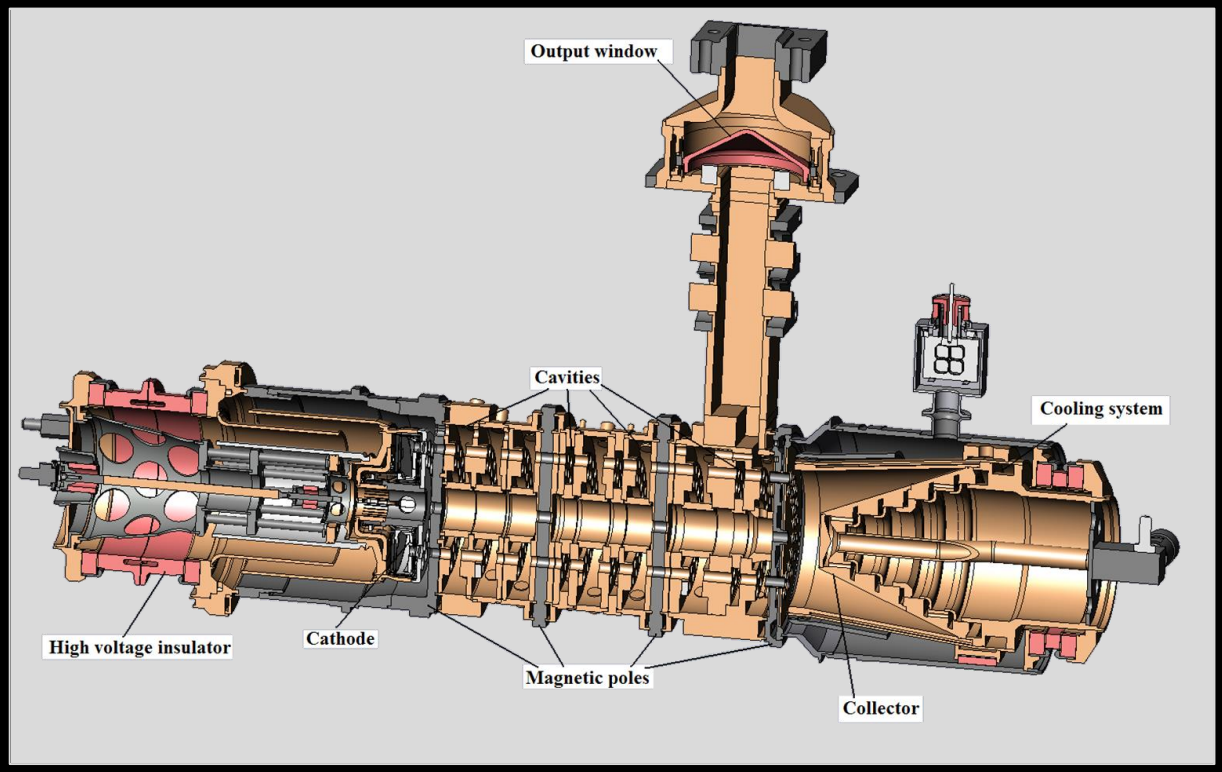
How to make a hollow beam?

- Initial simulations validating the design of a hollow-beam tube.

Bmax=400G
Router(avg)=0.464"
Rinner(avg)=0.323"
Jc <= 0.63 A/cm2
Scallop (outer) = 1.4%
Scallop (inner) = 12.4%



Progress with the VDBT prototype

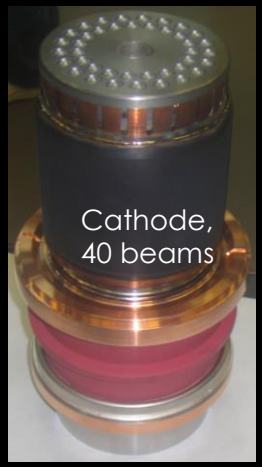


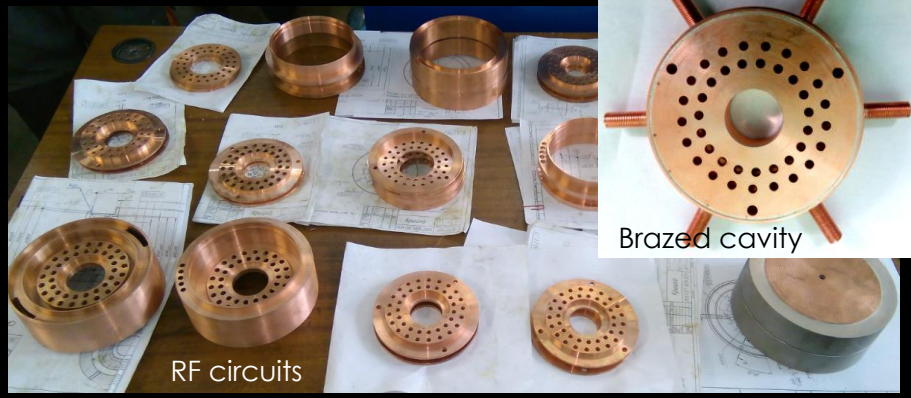
The engineering design and fabrication of parts started in 2015

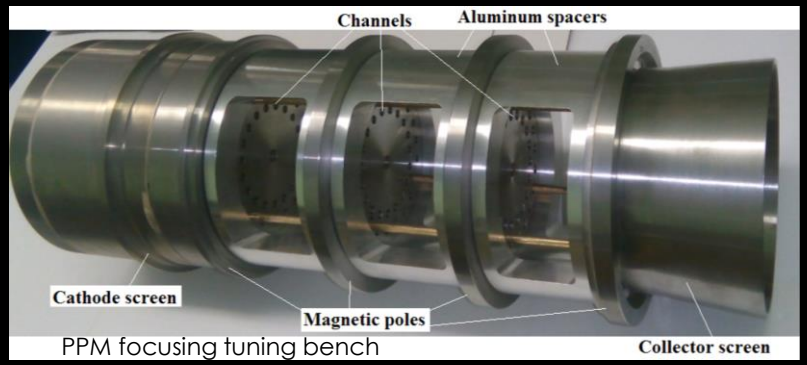
I. Guzilov (VDBT)

Based on an old tube that reached $\eta = 42\%$

VDBT Prototype – status Aug 2015



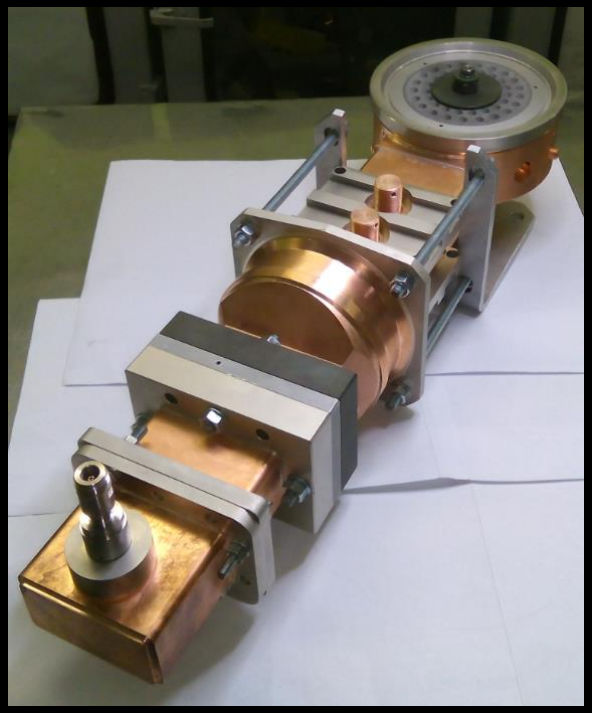




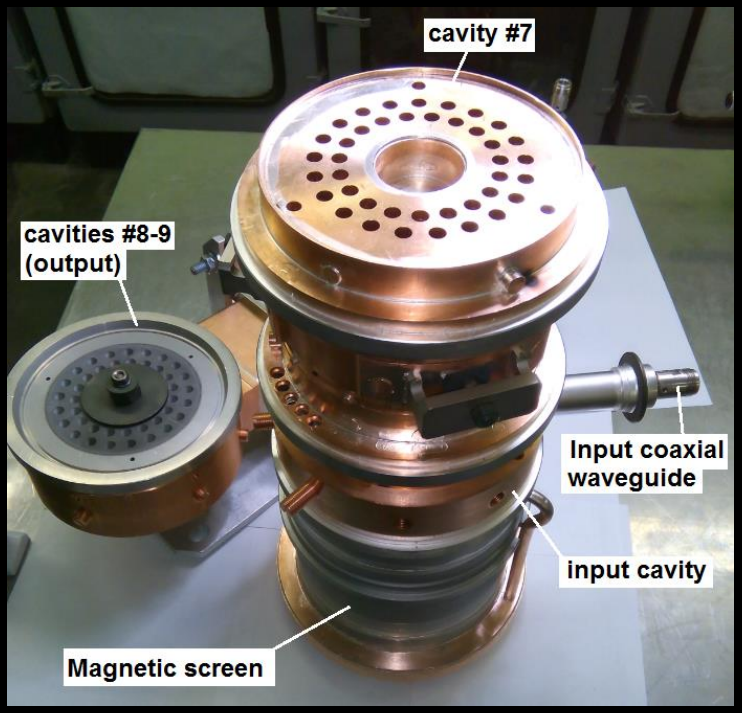
PPM focusing tuning bench

I. Guzilov (VDBT)

VDBT Prototype – status Dec 2015



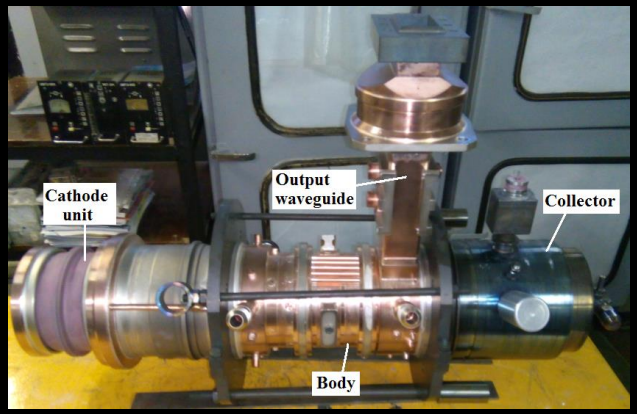
Cavities 8 and 9 and output waveguide



Cavities during assembly

I. Guzilov (VDBT)

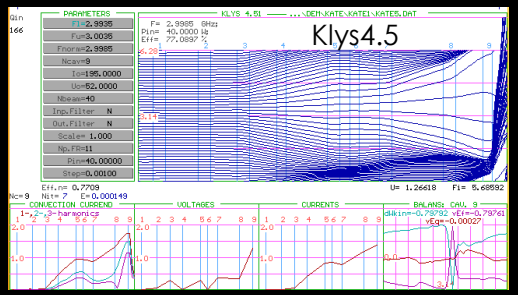
Progress with the VDBT prototype

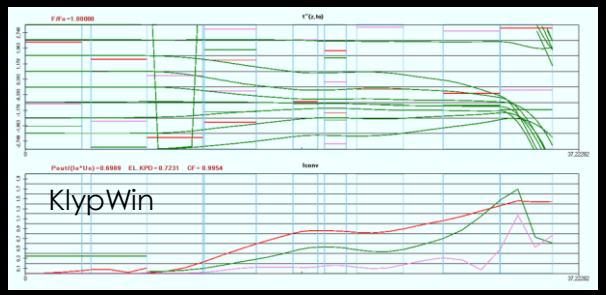


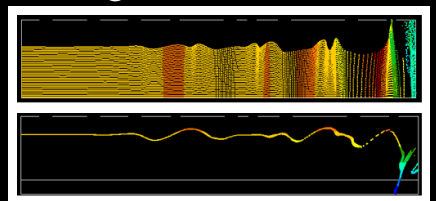
Assembled prototype ready for testing

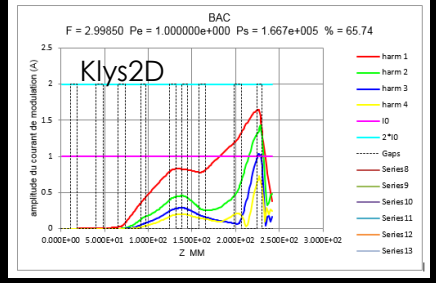
- Predictions by different simulation codes

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%**.



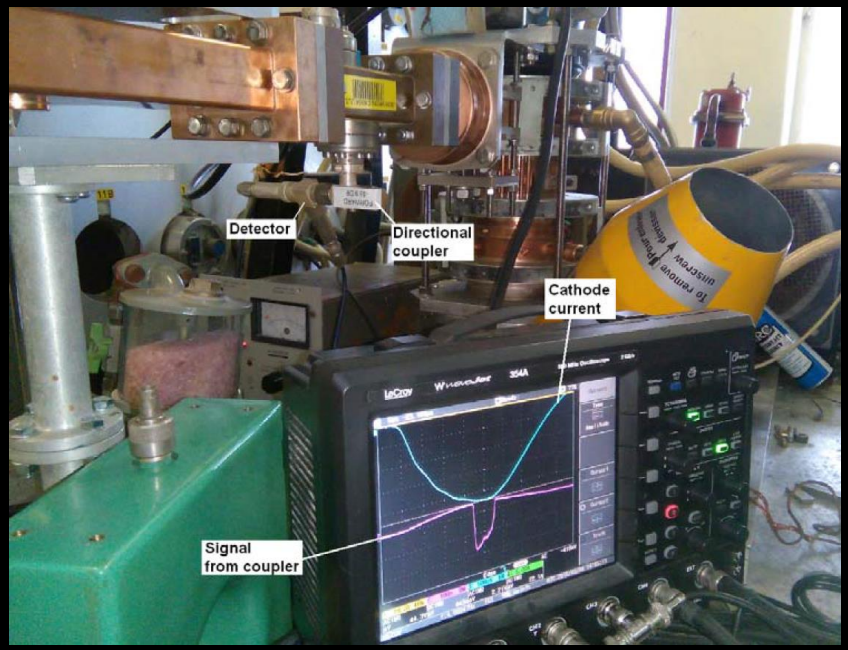




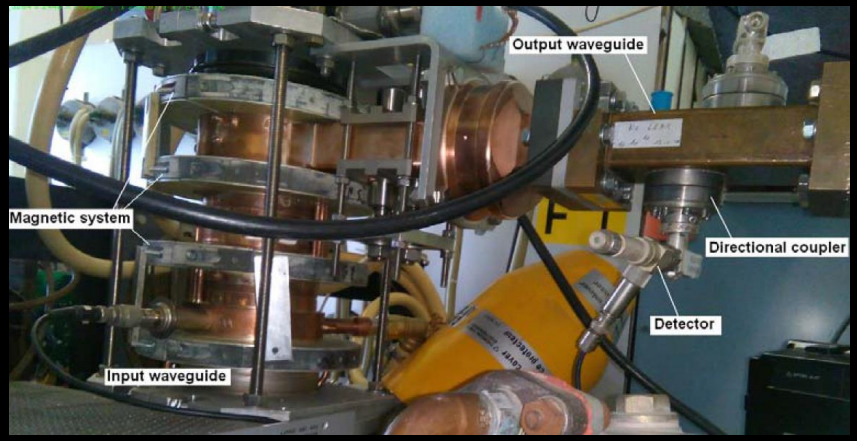


I. Guzilov (VDBT)

VDBT Prototype – status Mar 2016



Test set-up – first RF pulses

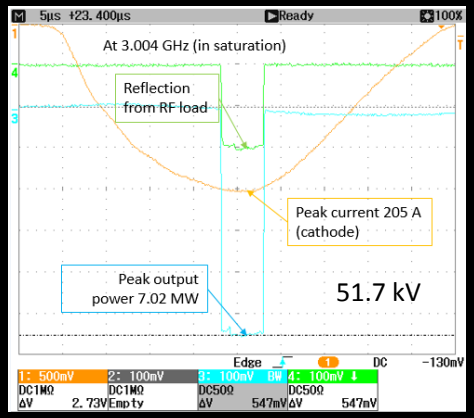


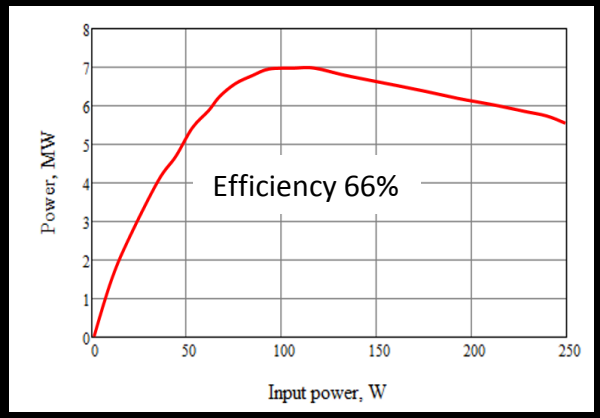
The rear view of the test set-up

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	$\geq 7.5\ \mu s \times 300\ Hz = 2.25 \cdot 10^{-3}$	$7.5\ \mu s \times 300\ Hz$

- 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!

Full scale tests at CERN to start on June 20 (**now!**).

Closing remarks

- At an age of 60 years, the klystron seems to be learning new tricks.
- An efficiency of well in excess of 80% seems in reach.
- A prototype 40-beam MBK allowed to validate the approach. An old tube ($\eta = 42\%$) was refurbished, implementing the new methods, and reached 66% with 52 kV.
- This is a very exciting development with huge potential!

Thank you for your interest and attention!