RF sources, discussion items

Frank Gerigk, CERN, GARD-SRF Roadmap Workshop
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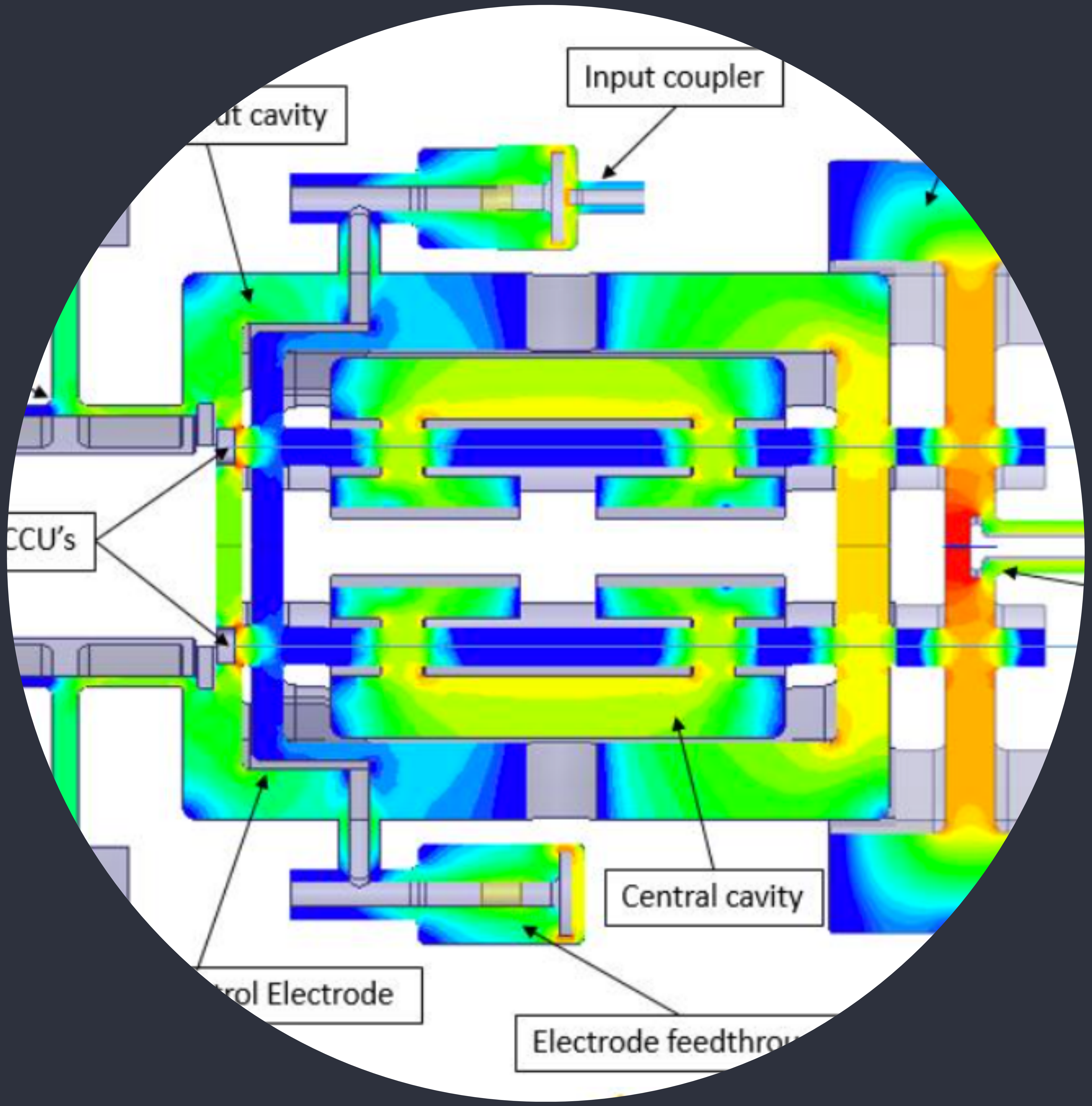
Material from:

Andrey Baikov, Brian Chase (FNAL), David Constable (Lancaster U), Marcos Gaspar (PSI), Igor Guzilov, Chris Lingwood (Lancaster U), Carlos Martins (ESS), Eric Montesinos (CERN), Igor Syratchev (CERN), Proton driver efficiency workshop 2016 (PSI),

Content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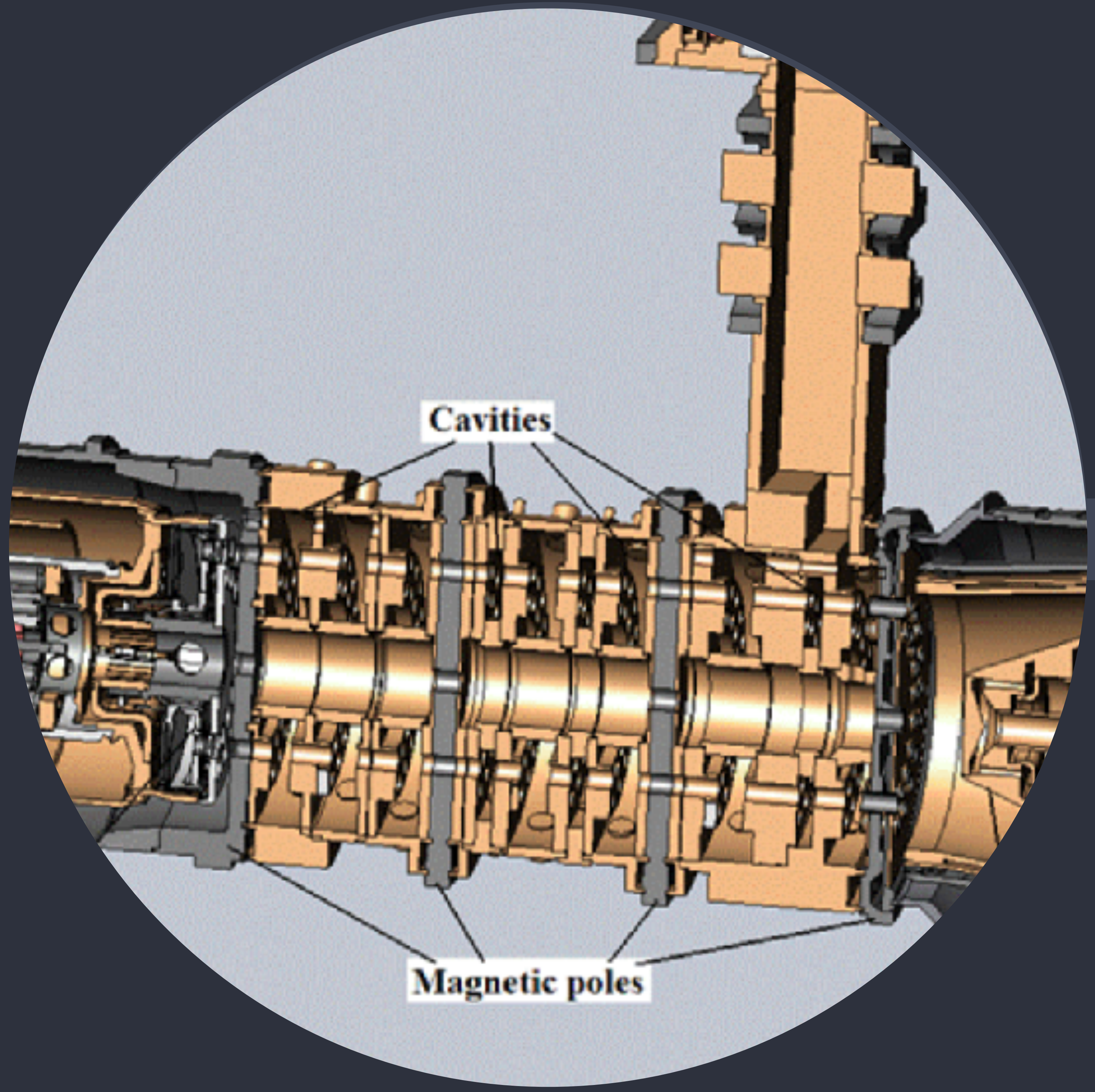


Klystrons

Efforts towards higher efficiency

HEIKA collaboration

- High Efficiency International Klystron Activity (HEIKA)
- CERN, SLAC (USA), Lancaster University (UK), Cockroft Institute (UK), Thales Group, L3, ESS (SE), Moscow University of Finance & Law (RU), VDBT (RU), …
- Close collaboration between institutes and industry.
- Use of modern beam dynamics tools to optimise efficiency rather than peak power.
- Goal is to push state of the art efficiency to > 65%

RF source type	Gain [db]	Op. output power pulsed [kW]	Rise /Fall time [us]	Pulse length range [us]	Rep rate range [Hz]	Op. output power CW [kW]	Efficiency at working point [%]	High voltage needs [kV]	Frequency range [MHz]
Single Beam	40-5	1000-3000	300 ns	4 ms		<1200 kW	55 (65 max)	~90-120kV	0.3GHz-1.5GHz
MB	40-5	10,000-15,000 kW (up to 1.5 ms at least	300 ns	4 ms		< 1200 kW (no point)	60 (70 max)	~90-120kV	0.3GHz-1.5GHz
Future Single Beam			-		-		70	40-60 kV	0.3GHz-1.5GHz
Future MB							80	40-60 kV	0.3GHz-1.5GHz

Some numbers

LHC

- 5 MW, 400 MHz, CW

ILC, 0.5 TeV

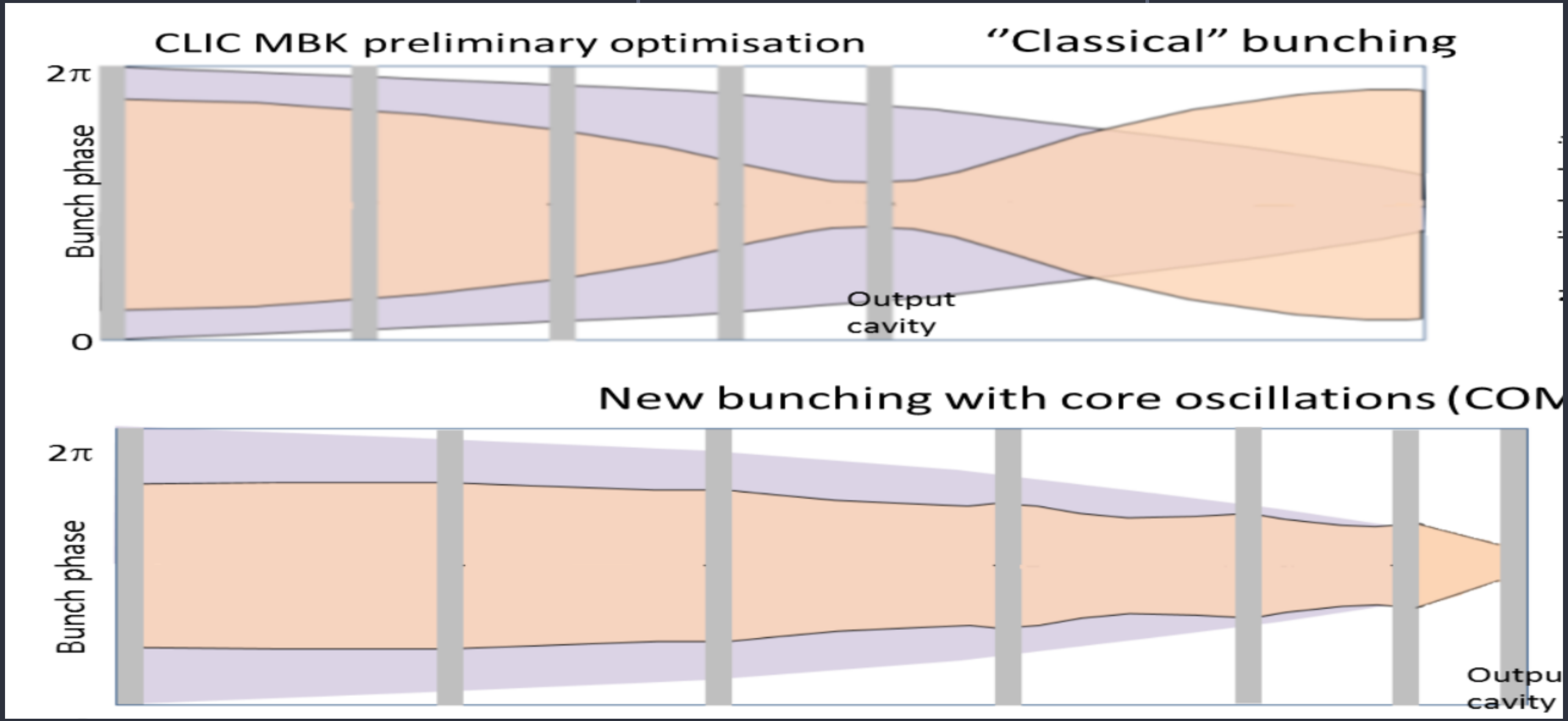
- RF power: 88 MW, 1.3 GHz, pulsed

FCCee, 45-175 GeV

- 100 MW, 400/800 MHz, CW

CLIC, 3 TeV

- Drive beam accelerator:
- 180 MW, 1 GHz, pulsed



particles outside of the core are focused towards the output cavity:

simulations predict efficiencies above 80%

Example Target: Proposed FCC-ee HEKCW Tube

HEIKA working team:

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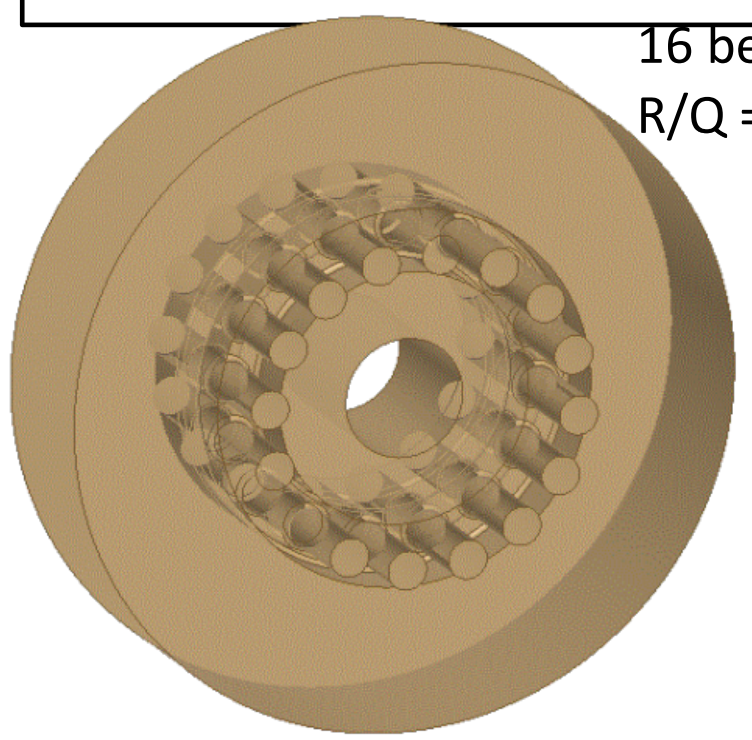
II. G. Burt (Lancaster)
III. C. Lingwood (Lancaster)
IV. D. Constable (Lancaster)
V. V. Hill (Lancaster)
VI. R. Marchesin (Thales)
VII. Q. Vuillemin (Thales/CERN)
VIII. A. Baikov (MUFA)
IX. I. Guzilov (VDBT)
X. C. Marrelli (ESS)
XI. R. Kowalczyk (L-3com)
XII. T. Habermann (CPI)
XIII. A. Jensen (SLAC)

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



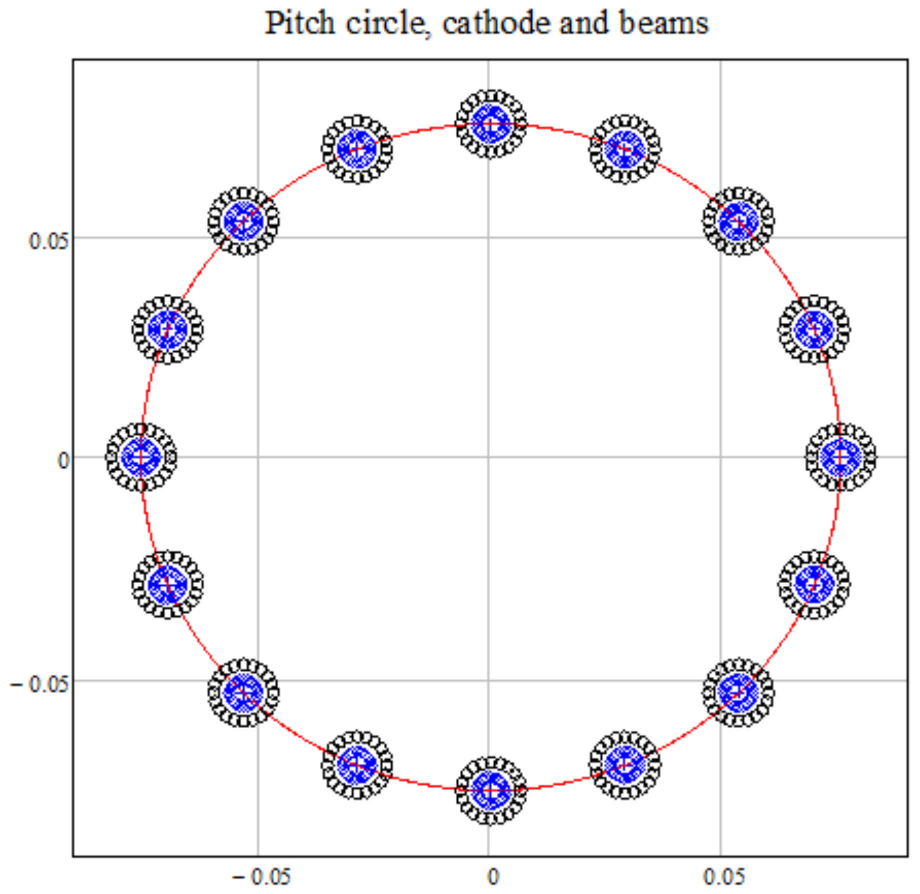
Tube parameters:

- 1.5MW
- Voltage: 40 kV
- Total current: 42A
- **Target efficiency: 90%**
- N beams: 16
- µK/beamx10^6 : 0.23
- N cavities: 8
- Frequency: 800 MHz

- 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

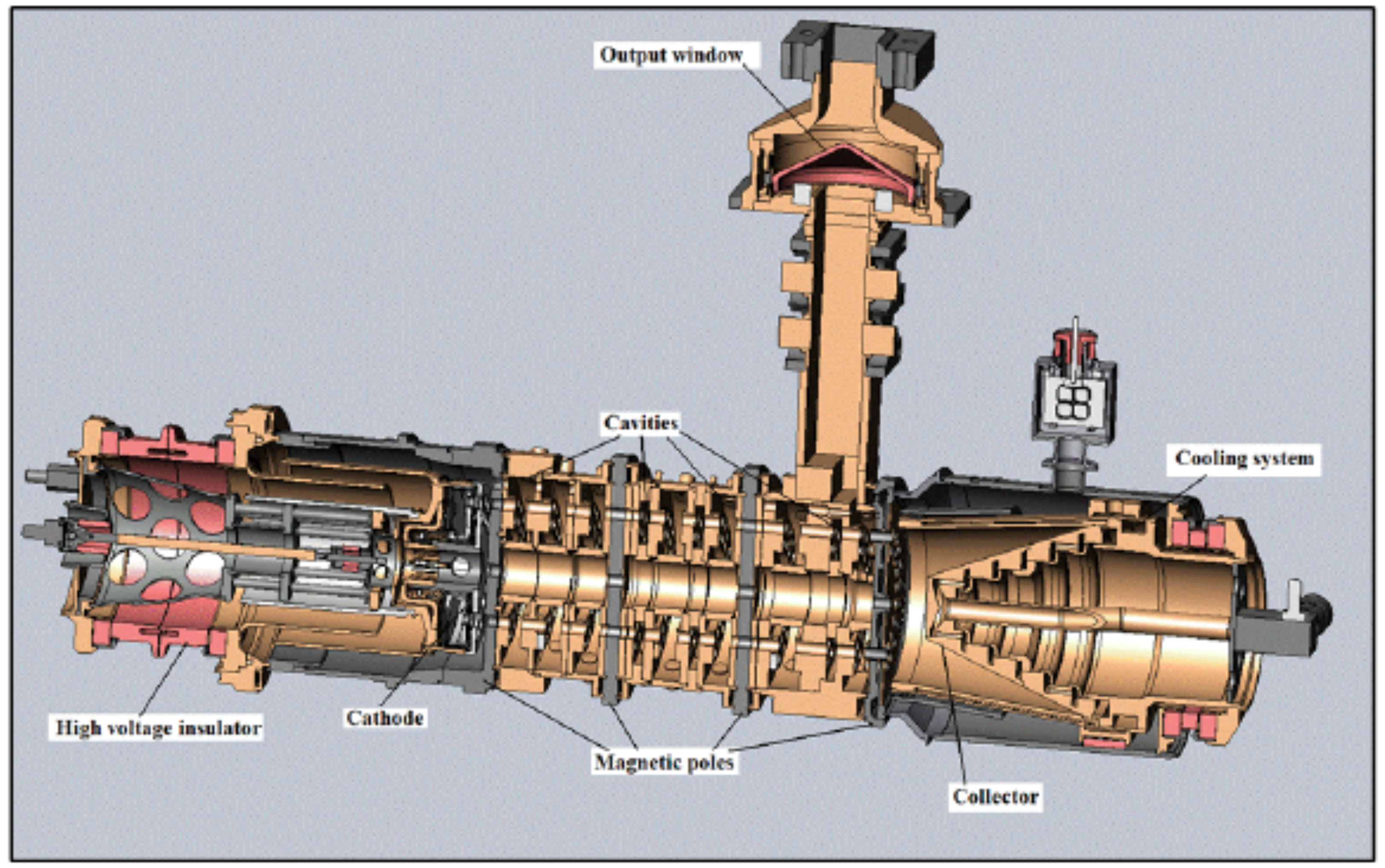
HEIKA

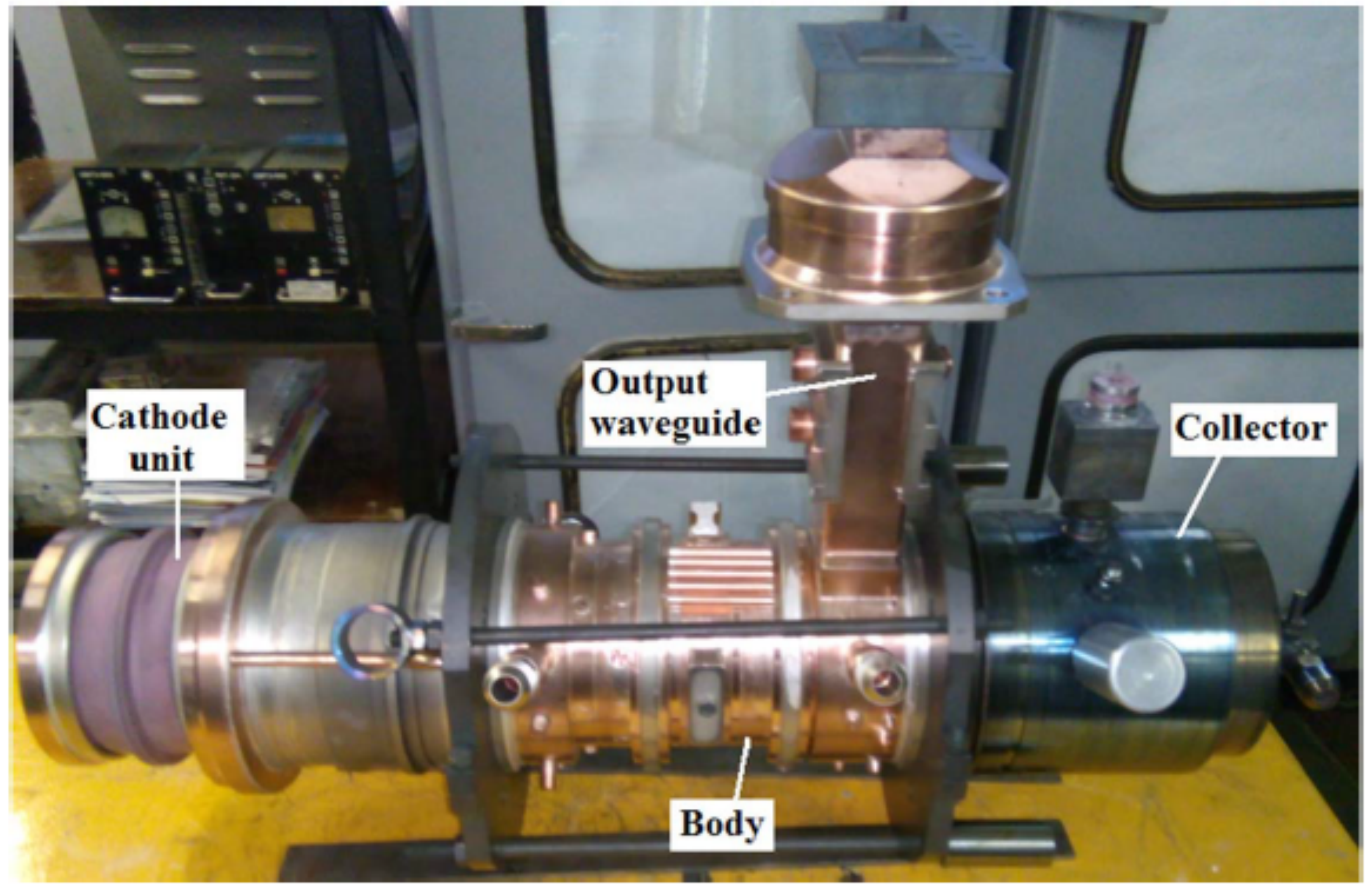
HEKCW



VDBT S-Band BAC Klystron

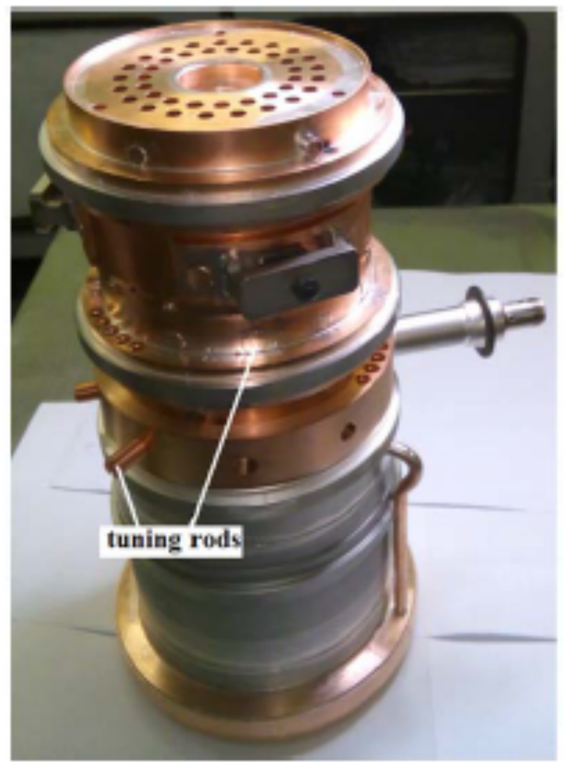
(I. Guzilov)

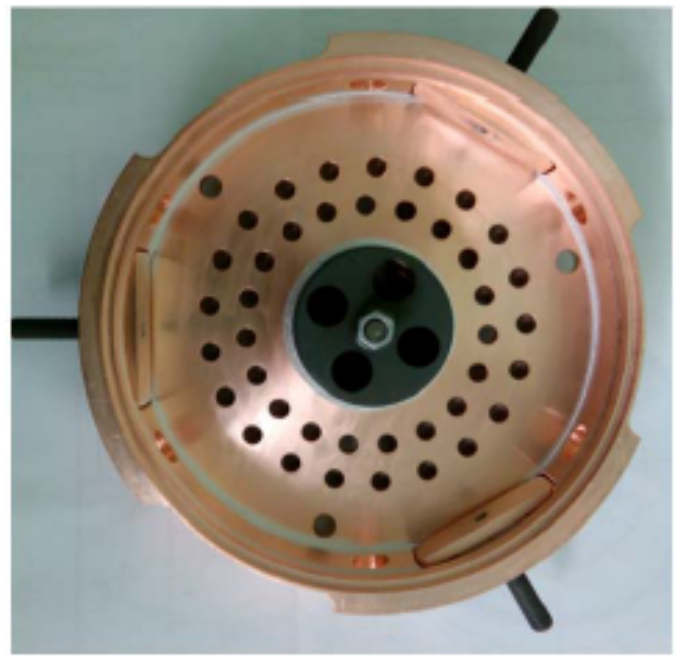




The first commercial S-band MB tube prototype which employs the new bunching technology (BAC). Contractual technical specification:

- 40 beams
- Permanent Magnets focusing system
- Voltage: <60 kV
- Peak power: >6.0 MW
- Efficiency: >60%
- Pulse length: 5 microsecond
- Repetition rate: 300 Hz
- Average power: 30 kW

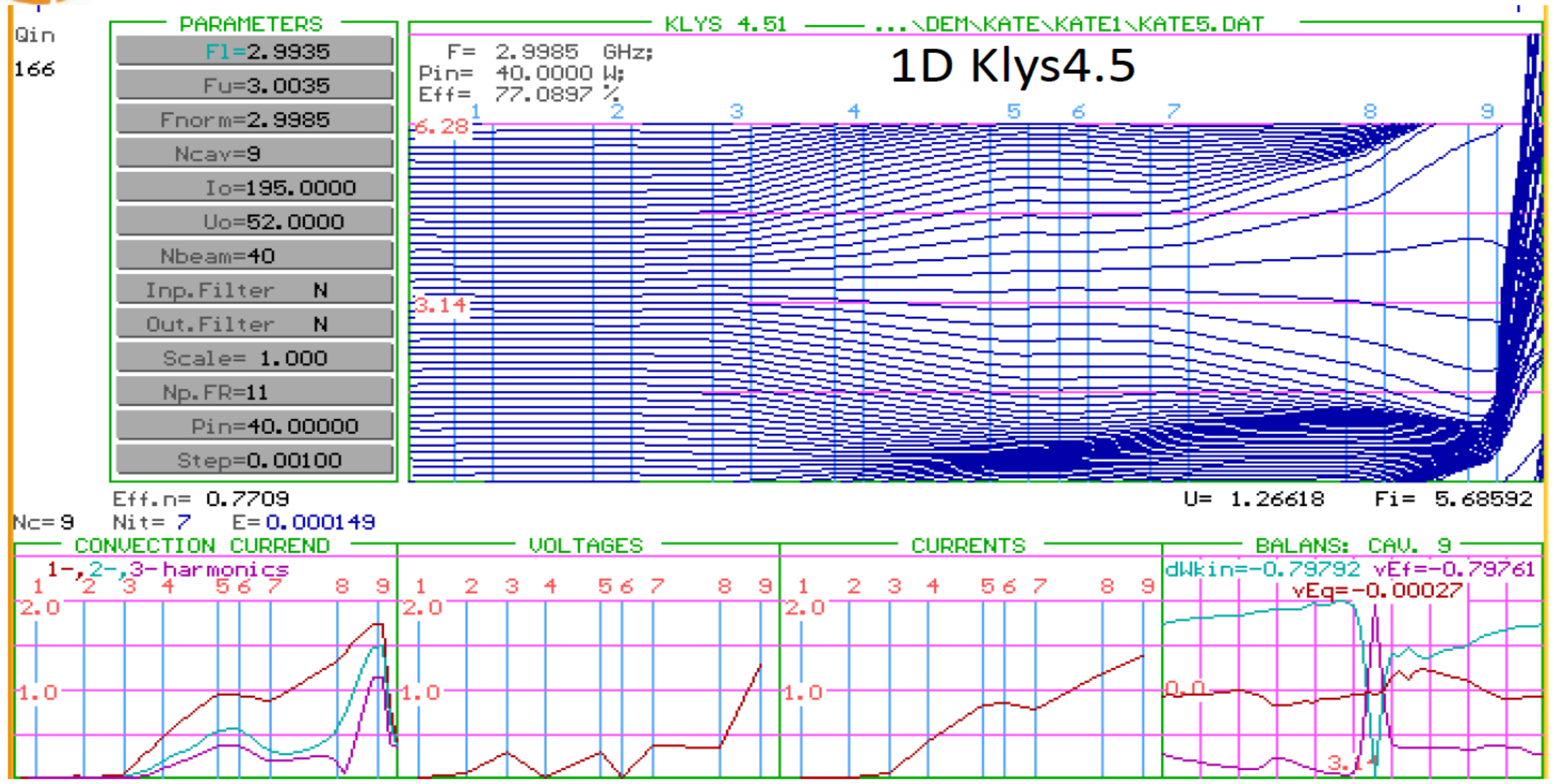




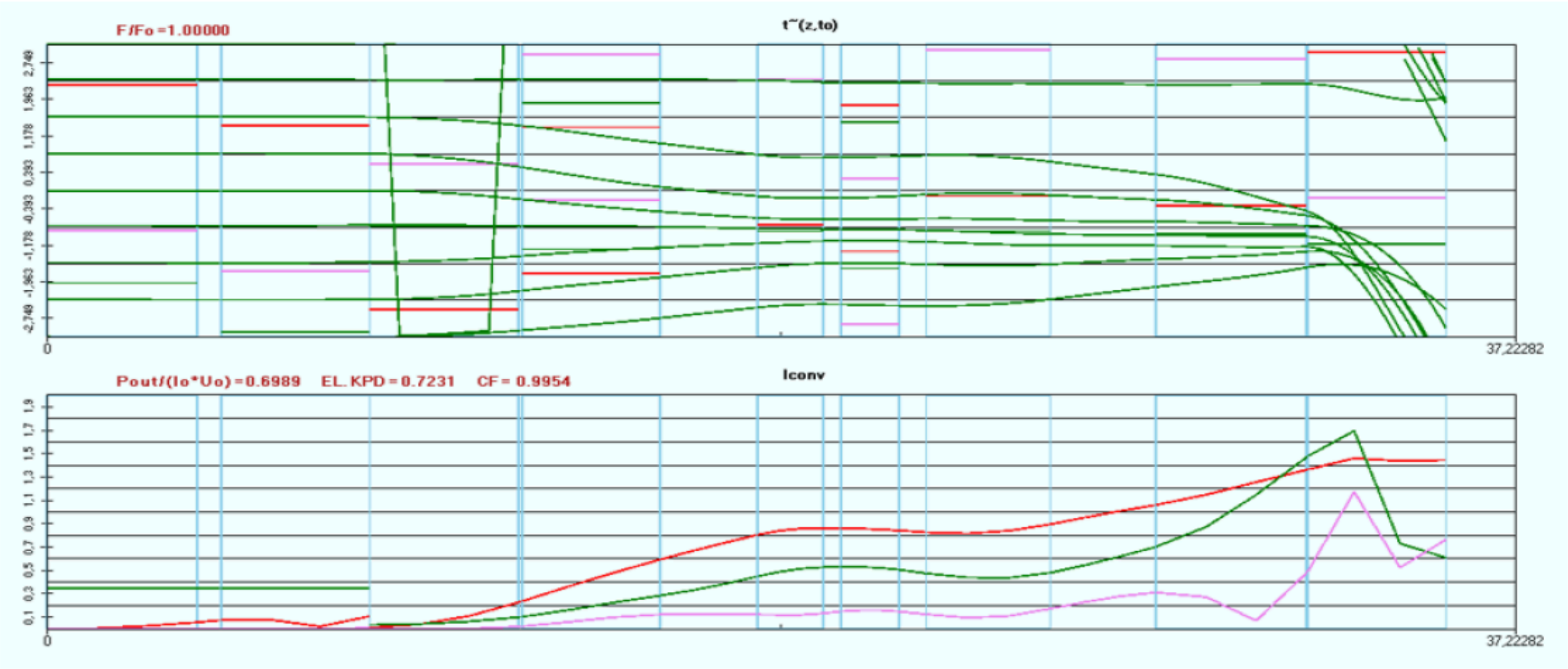
VDBT S-Band BAC Klystron

Numerical Results (I. Guzilov)

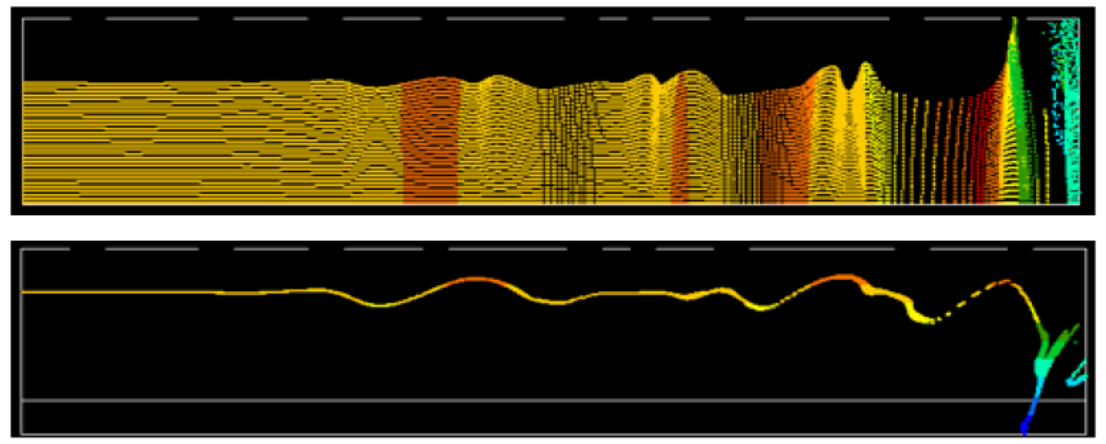
Expected efficiency (in simulations)

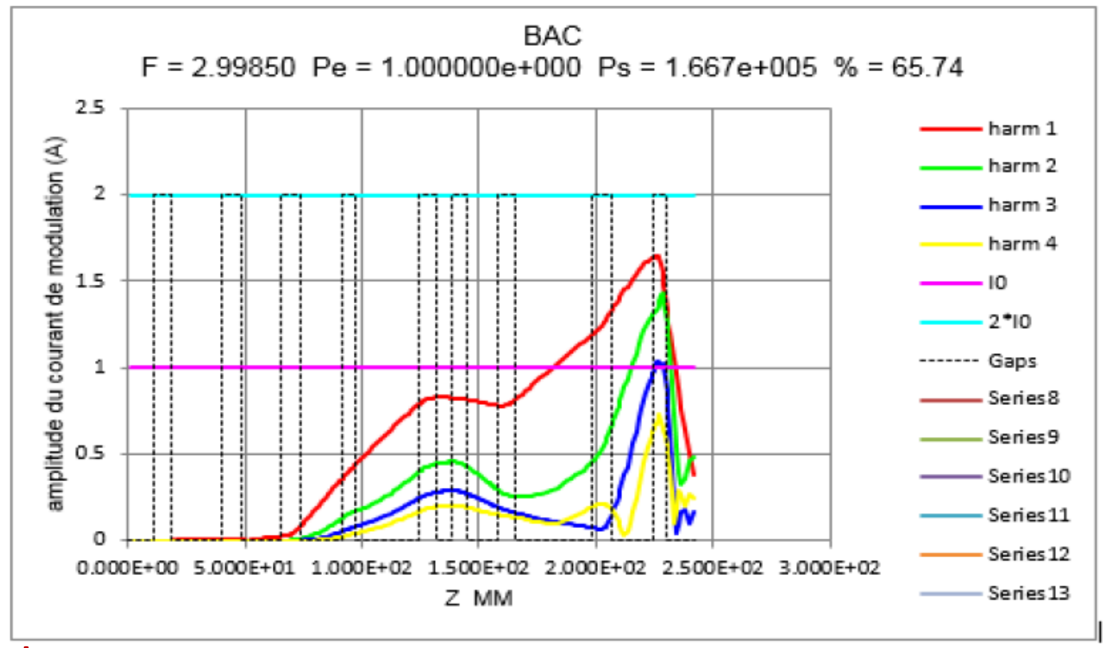


1D KlypWin



2D KLYS2D



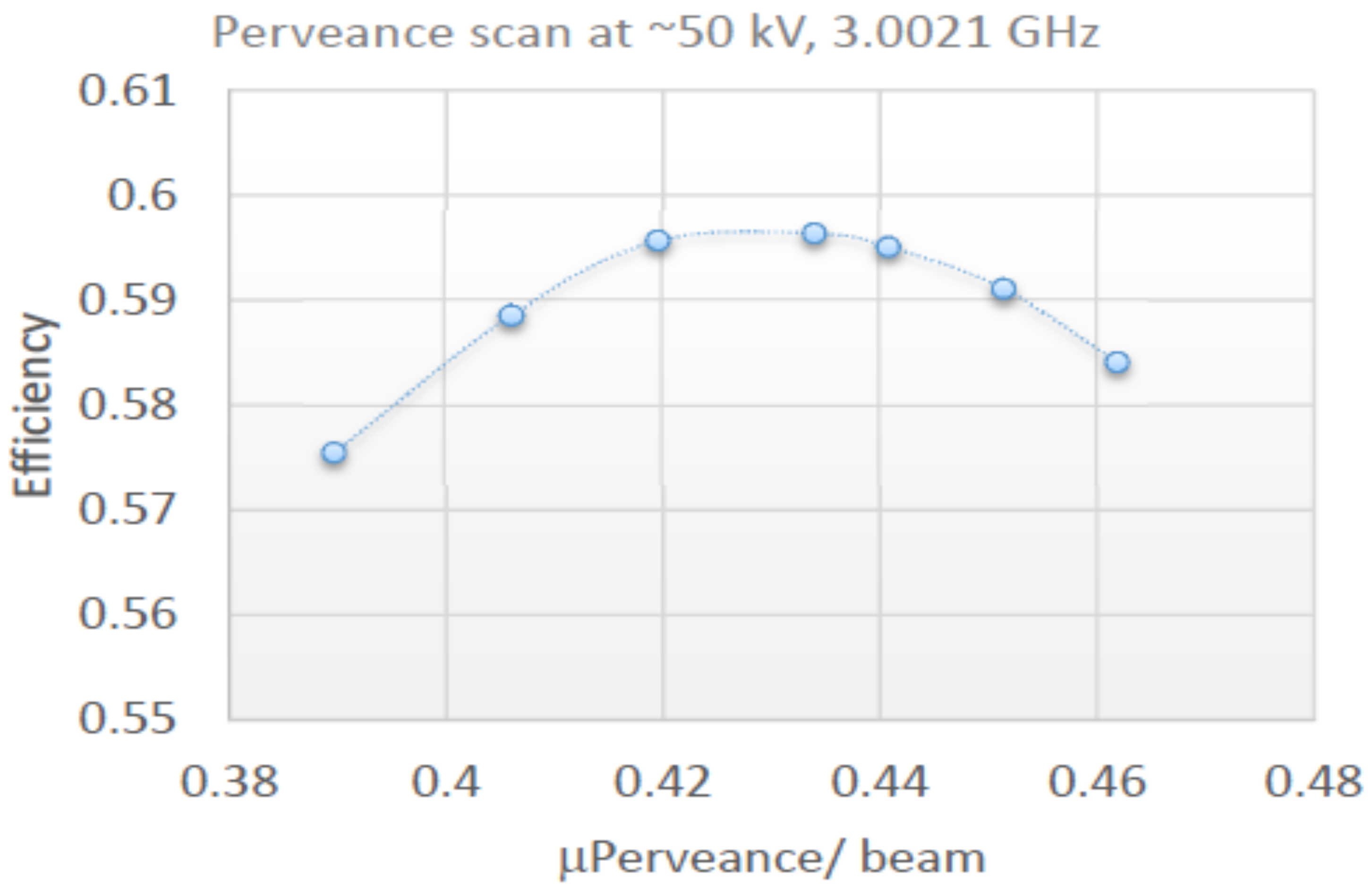


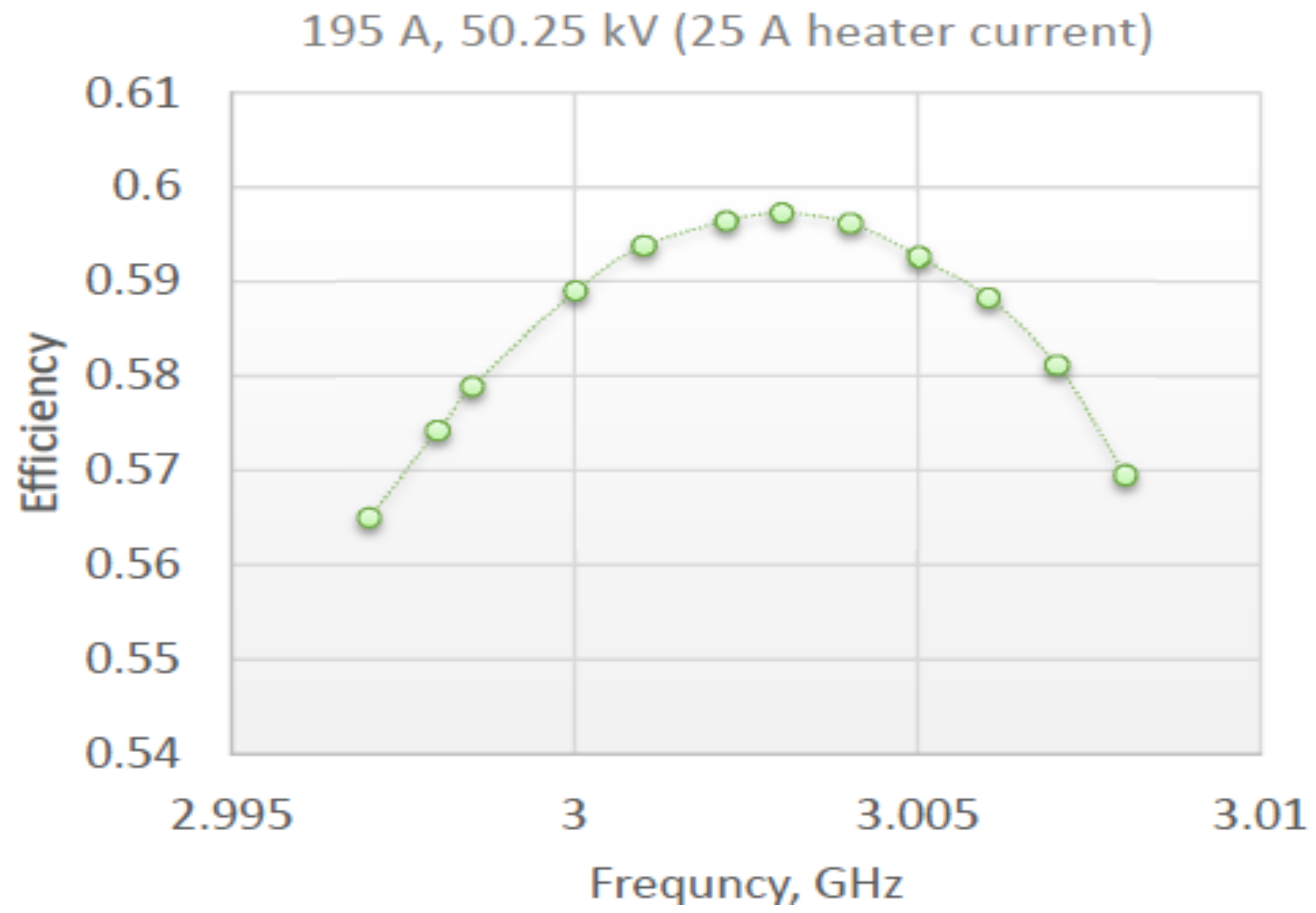
1. Efficiency **77%**. (1D) Klys4.5. Company code used to optimise the tube.
2. Efficiency **69.9%**. (1D) KlypWin (A. Baikov). The code used by HEIKA study for the basic design and optimisation of high efficiency klystrons.
3. Efficiency **65.74%**. (2D) KLYS2D is the code used at Thales.

The tube is a retrofit modification (only RF circuit is replaced) of original KIU-147 MBK klystron which has an efficiency of 42%. All the used codes predicted efficiency above 60%.

VDBT S-Band BAC Klystron

Experimental Results



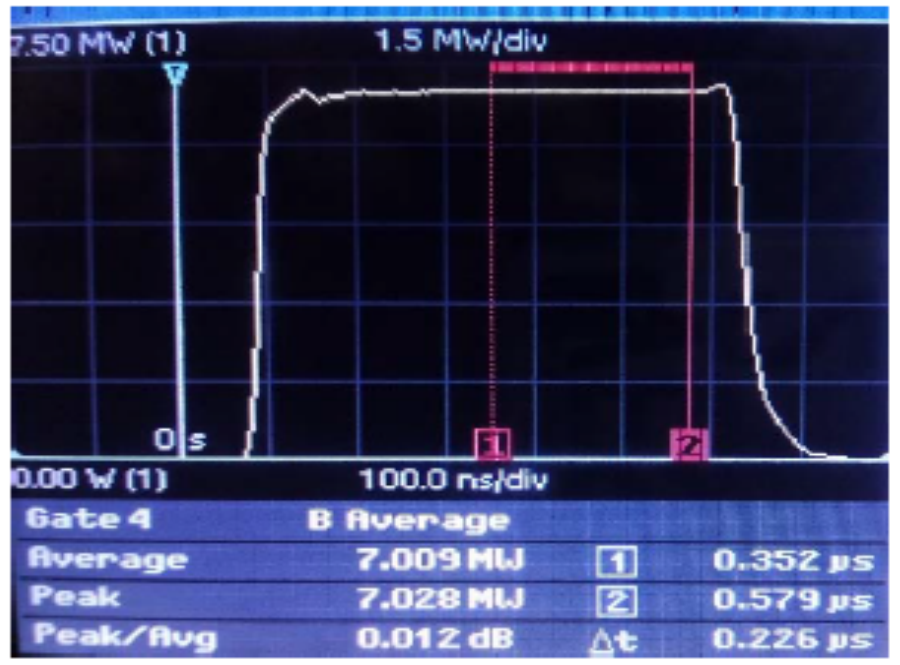


The best klystron performance was measured at 3.003 GHz:

- Efficiency: 59.7%
- Total current: 195 A
- Voltage: 50.25 kV
- μK/beam =0.432
- Beam power: 9.8 MW
- RF power: 5.84 MW
- Power gain: 46.7 dB

Pushing harder. By increasing the heater current to almost saturation and restricting the voltage to be below 57 kV max:

- Current: 246.3 A
- Voltage: 56.88 kV
- Perveance /b: 0.454
- RF power: 7.01 MW
- Efficiency: 50.0%
- Reliable operation



Gridded tubes

200 MHz tetrode combination in operation at the CERN SPS since 1976 (Eric Montesinos)

Tetrodes/Diacrodes

RF source type	Gain [db]	Op. output power pulsed [kW]	Rise /Fall time [us]	Pulse length range [us]	Rep rate range [Hz]	Op. output power CW [kW]	Efficiency at working point [%]	High voltage needs [kV]	Frequency range [MHz]	Comment
Tetrode: state of the art	14-16	4000	ns	any	any	1500	70	10-25	30-400	
Diacrode: state of the art	14-16	3000	ns	any	any	2000	70	20-30	30-400	

- Tetrodes typically < 500 MHz, up to MW-range for low frequencies, DC - RF 70%
- Diacrodes: higher power and higher frequencies possible at same efficiency, DC-RF up to 70%
- Only moderate drop in efficiency for lower output power.
- Gridded tubes are very tolerant to HV changes (10-20%), very short rise time as compared to klystrons (—> increase in efficiency), no RF no current..
- Can be overdriven in pulsed operation to get higher output power, (not possible with saturated klystrons, or solid state).

IOTs

RF source type	Gain [db]	Op. output power pulsed [kW]	Rise /Fall time [us]	Pulse length range [us]	Rep rate range [Hz]	Op. output power CW [kW]	Efficiency at working point [%]	High voltage needs [kV]	Frequency range [MHz]	Comment
IOT: state of the art	20-23	130	ns	any	any	85	70	36-38	?-1300	
MB-IOT: performance potential	20-23	1300	ns	any	any	150	70	50	704	first prototype tested

- same points as for tetrodes/diacrodes…
- ESS has ordered 2 704 MHz MB IOTs from industry (MW level).
- One tube has seen first successful tests at the supplier.
- Both tubes will see a soak test at CERN in 2017, so that ESS can decide whether to use these tubes for the high-energy part of the ESS linac.
- new ideas for 3-cavity IOTs, resotrode explored within HEIKA

Magnetrons

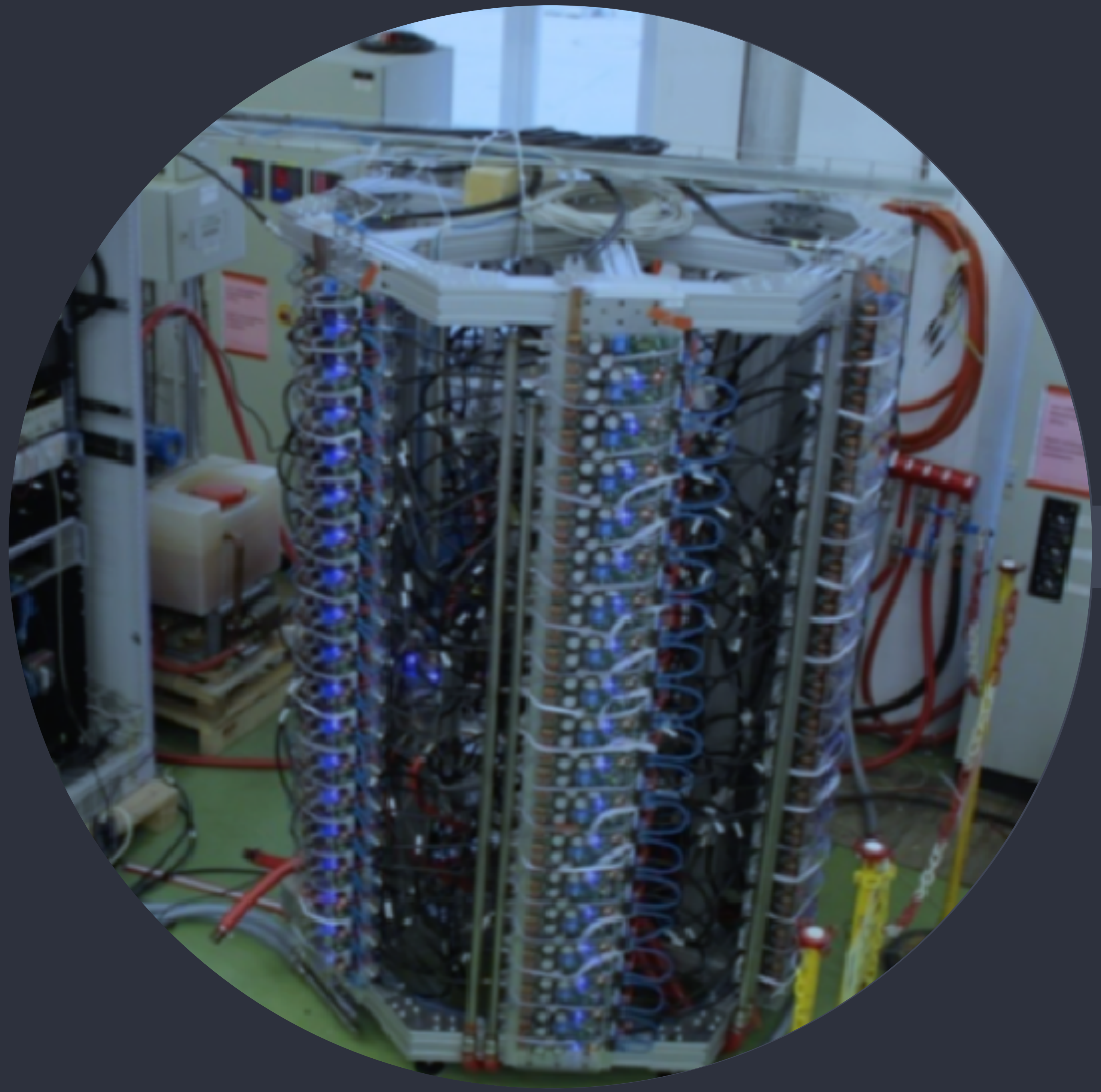
Cross section of a typical microwave cooker magnetron (courtesy: Brian Chase, FNAL)

Magnetrons

RF source type	Gain [db]	Op. output power pulsed [kW]	Rise /Fall time [us]	Pulse length range [us]	Rep rate range [Hz]	Op. output power CW [kW]	Efficiency at working point [%]	High voltage needs [kV]	Frequency range [MHz]	Comment
State of the art: CPI ECONCO	**25**	**?**	**?**	**-**	**-**	**100**	**80**	**20**	**826 - 929**	**tube only**
CCR/CPI	**25**	**100**	**?**	**10 ms**	**10**	**10**	**80**	**22**	**1300**	**tube only**
Performance potential?	**25**	**100**				**100**	**60**		**400**	**AC-RF**

- Proof of principle at Lancaster University
- Phase control of 1 magnetron, using 2 magnetrons with phase control gives amplitude control.
- Constant output power devices; fast phase modulation can move power into sidebands, which will be reflected back from the cavities —> amplitude control with a single device.
- Proof of principle with u-wave oven type magnetron at FNAL. 1.3 GHz, 100 kW peak power (10 kW average). Current status?
- High potential for high efficiency (85%) at moderate price. Maybe not for all operational scenarios.

Solid state



: 65 kW, 500 MHz solid state amplifier at PSI (Marcos Gaspar, PSI)

Solid state

RF source type	Gain [db]	Op. output power pulsed	Rise /Fall time [us]	Pulse length range [us]	Rep rate range [Hz]	Op. output power CW	Efficiency at working point [%]	High voltage needs [kV]	Frequency range [MHz]	Comment
ELBE		16 kW	0.02/0.06	0.001 - 100	0-CW	16 kW	47%	-	1300	
R&K		16 kW	0.01/0.01	any	0-CW	16 kW	36%	-	1300	forced air/water
Tomcod		-		-	CW	10 kW	45%	-	700	up to 80 kW
R&K		-		-	CW	20 kW	?	-	509	forced air/water
PSI		~70 kW	0.045	any	0-CW	~70 kW	~50%	-	500	grid to RF
Cryoelectra		-		-	CW	45 kW	51%	-	500	
LNLS		-		-	CW	25 kW	57%	-	472	
ESRF		70 kW		any	1 - CW	70 kW	55%	-	352	DC-RF
Soleil		30 kW		any	0-CW	30 kW	50%	-	352	DC-RF, 180 kW
Tomco		-		-	CW	10 kW	55%	-	350	up to 110 kW
Cryoelectra		-		-	CW	16 kW	46%	-	118	
Siemens		-		-	CW	18 kW	75%	-	72.5	
Cryoelectra		-		-	CW	115 kW	57%	-	72.8	
R&K		60 kW		any	0-CW	60 kW	56%	-	1.8	
State of the art		**10 - 100 kW**	**10-60 ns**	**any**	**any**	**10-100 kW**	**45-55%**	**-**	**0-1300**	
potential?										
R&D: Siemens/ESS		48 kW		3000	14 Hz	-	60%	-	352	up to 400 kW
Thales		135 kW		-	CW	135 kW			200	test at CERN

Solid state

- Frequency range 0 - 2.5 GHz but with lower efficiency and power output/transistor for frequencies > 700 MHz,
- Can be operated at lower output power without loosing too much efficiency.
- At present maximum power < 200 kW.
- Overall DC to RF efficiency ~55%.
- Modular systems, hot swapping of faulty modules possible.
- Newer systems make use of combining cavities instead of 2x2x2… combiners (200 MHz 135 kW Thales tower under soak test at CERN, intention is to have a 2 MW system for the SPS)

Conclusions I

from Proton Driver Efficiency Workshop, Feb 2016, PSI

- Tetrodes, diacrodes: < 500 MHz (up to several MW, better for lower frequencies); IOTs: 500 MHz to 1.3 GHz (presently < 100 kW); klystrons: 300 MHz - 10 GHz (100's kW to multi-MW), Solid state: 0 - 2.5 GHz (presently up to ~200 kW, lower efficiency > 700 MHz), magnetrons: > 300 MHz (to be explored)
- AC - DC: Power supplies 85 - 92% for all systems (solid state to klystrons).
- DC - RF: Magnetrons claim up to 85% efficiency (to be proven in a complete system); gridded tubes: 70%, klystrons: 55%, solid state: 55%.
- Adding cooling systems, reduces total efficiency by a factor of ~0.73 compared to DC-RF.
- Modulator rise times have an impact on efficiency (e.g. HV klystron modulators).

Conclusions II

adapted from Proton Driver Efficiency Workshop, Feb 2016, PSI

- R&D on klystron efficiency improvement is very active continues. Higher efficiency not only means electrical savings, but also simpler lower-voltage modulators and no need for oil tanks.
- MB-IOTs reach the MW class and may become an alternative to klystrons. (First tests are promising). To be continued.
- Solid state is developing and has the same efficiency at lower power (100 kW range) than what can be done with klystrons today at high power (MW range). Unlikely that higher power transistors will be developed soon (not needed for broadcasting, telephone networks, …). Future lies with combining cavities.
- Work on magnetrons just started; needs a lot of work, which is presently done only at 2 labs: FNAL and Lancaster University. High potential for lower prices and higher efficiency (85%). More labs should join!