Summary: RF Systems Workshop on Energy Efficiency of Proton Drivers, 29 Feb - 2 March 2016 F. Gerigk, CERN



Introduction: RF Systems

Grid to DC: Modulators, Carlos Martins, ESS

DC to RF:

Established technologies:

Tetrodes (diacrodes), Eric Montesinos, CERN

Established technologies with newly discovered potential:

- Klystrons, Chris Lingwood, Lancaster University (Cockroft Inst.)
- Solid state, Marcos Gaspar, PSI
- IOTs, Eric Montesinos, CERN

Technologies not yet (or hardly) used for accelerators

Magnetrons, Brian Chase, FNAL

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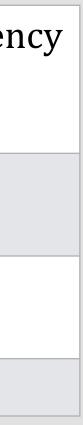
Goal of session on RF sources

Establish a list of comparable numbers, assuming DC to RF power conversion:

RF source type	Gain [db]	Op. output power pulsed [kW]	_	Pulse length range [ms]	Rep rate range [Hz]	Op. output power CW [kW]	Efficiency at working point [%]	High voltage needs [kV]	Frequen range [MHz]
Typical performance today A									
Typical performance today B									
Performance potential									

- Which systems need more air cooling (and therefore AC) than others? lacksquare
- Where is the "reasonable" balance between efficiency investment cost (\$/W)? \bullet
- Do we reduce reliability, when we try to increase efficiency?
- Which R&D directions have the highest promise?
- Magnetrons claim up to 85% efficiency?? power supplies? cooling?

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Modulators

- Main choice for MW class modulators is between i) pulse transformer based and ii) HF transformer based devices.
- Pulse transformer based: ~85 90% efficiency, multi-MW rise times: ~300 us (for a reasonably sized transformer)
- HF transformer based (Stacked Multi-Level): 90 92%, up to 5 MW output power for klystrons, tetrodes or IOTs, low rise time (110 us) In general 85 % - 92 % efficiency seems to apply to all types of transformers (solid state power supplies to klystron modulators)



Klystrons

RF source type	Gain [db]	Op. output power pulsed [kW]	Rise /Fall time [us]	Pulse length range [us]		Op. output power CW [kW]	Efficiency at working point [%]	High voltage needs [kV]	Frequency range [MHz]
Single Bea	40-5	1000-3000	300 ns	4 ms		<1200 kW	55 (65 max)	~90-120kV	0.3GHz-1.5G
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-1.5G
Future Single Beam			-		-		70	40-60 kV	0.3GHz-1.5G
Future MB							80	40-60 kV	0.3GHz-1.5G

- ms-range klystrons achieve MW-range output power. •
- Supplying power values below the max. operational power reduces the efficiency, using a ulletmodulating anode helps but may reduce reliability.
- Rise time determined by the modulator: 100 300 us.
- Long life time: 40 kh, high-gain (< kW pre-amplifier). ullet
- Efficiency in operation limited by saturation curve. At working point ~55%. ullet
- or 80% (multi beam).
- Lower HV requirements (no oil tanks). \bullet

Vigorous R&D program promises to increase efficiency at working point up to 70% (single beam),

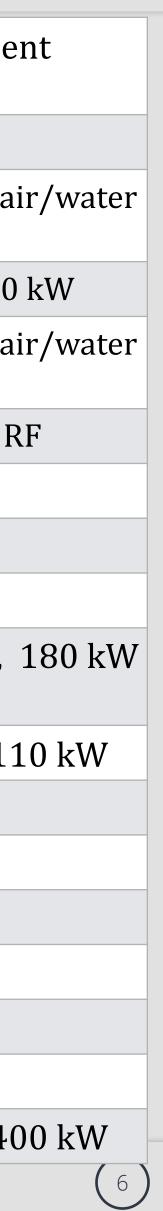




Solid state

RF source type	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]	Commer
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
Tomcod	-		-	CW	10 kW	45%	-	700	up to 80
R&K	-		-	CW	20 kW	?	-	509	forced air
PSI	~70 kW	0.045	any	0-CW	~70 kW	~50%	-	500	grid to R
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, 1
Tomco	-		-	CW	10 kW	55%	-	350	up to 11
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 40

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Solid state

- Frequency range 0 2.5 GHz but with lower efficiency and power output/ transistor for frequencies > 700 MHz,
- At present maximum power < 200 kW.
- Overall DC to RF efficiency ~55%.
- Modular systems, hot swapping of faulty modules possible.

Can be operated at lower output power without loosing too much efficiency.



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]	Comme
State of the art: CPI ECONCO	25	?	?	-	-	100	80	20	826 - 929	tube on
CCR/CPI	25	100	?	10 ms	10	10	80	22	1300	tube on
Performance potential?	25	100				100	60		400	AC-RF

- Proof of principle at Lancaster University
- control.
- power (10 kW average) under development.
- scenarios.

Phase control of 1 magnetron, using 2 magnetrons with phase control gives amplitude

 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

High potential for high efficiency (85%) at moderate price. Maybe not for all operational



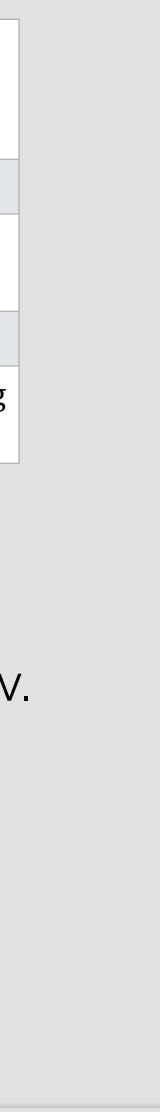


Tetrodes/Diacrodes

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RF source type	Gain [db]	Op. output power pulsed [kW]	-	Pulse length range [us]	Rep rate range [Hz]			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	
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	prototype testing in 2016

- 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% • IOTs: used for accelerators since ~2000 (light sources), up to ~100 kW, MB MW tubes under dev. • 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).



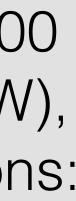
Observations:

- much choice: dialogue between accelerator designers and users necessary!
- ADS: breakeven point at 2% accelerator efficiency, 20% makes it reasonable, 40% is desirable.
- > 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). ullet

 So far no machine has been designed with the goal of maximum efficiency. Operational parameters (energy, duty cycle, pulse length, CW, beam power level) have a strong impact on the final efficiency and very often the accelerator designers (and RF engineers) have not

• 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 \sim 200 kW, lower efficiency > 700 MHz), magnetrons:







Conclusions:

R&D recommendations:

- and no need for oil tanks.
- tests this year ESS/CERN). To be continued.
- development of new high-power low-loss transistors.
- (85%). More labs should join!

• R&D on klystron efficiency improvement is very active and should continue. Higher efficiency not only means electrical savings, but also simpler lower-voltage modulators

• MB-IOTs may reach the MW class and may become an alternative to klystrons. (First

• 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). Dependent on

• 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

