Summary: RF Systems

Workshop on Energy Efficiency of Proton Drivers, 29 Feb - 2 March 2016

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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

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]	Rise time [us]	Pulse length range [ms]	Rep rate range [Hz]	Op. output power CW [kW]	Efficiency at working point [%]	High voltage needs [kV]	Frequency range [MHz]
Typical performance today A									
Typical performance today B									
Performance potential									

- Which systems need more air cooling (and therefore AC) than others?
- Where is the “reasonable” balance between efficiency investment cost ($/W)?
- 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?

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]	Rep rate range [Hz]	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-1.5GHz
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

- ms-range klystrons achieve MW-range output power.
- Supplying power values below the max. operational power reduces the efficiency, using a modulating 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).
- Efficiency in operation limited by saturation curve. At working point ~55%.
- Vigorous R&D program promises to increase efficiency at working point up to 70% (single beam), or 80% (multi beam).
- Lower HV requirements (no oil tanks).

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

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.

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

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	
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:

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

R&D recommendations:

- 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 and no need for oil tanks.
- MB-IOTs may reach the MW class and may become an alternative to klystrons. (First tests this year ESS/CERN). 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). Dependent on development of new high-power low-loss transistors.
- 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!