Preliminary Technology Option Data Capture

D.A. Constable

Introduction

- Collate parameters of available RTT technology options:
  - Create table of key parameters, e.g. frequency, peak output power, dimensions, weight, cooling, etc…
  - Identify suitability of specific sources in different frequency regimes.
  - Identify configurations/solutions which could reduce system complexity and improve system robustness.

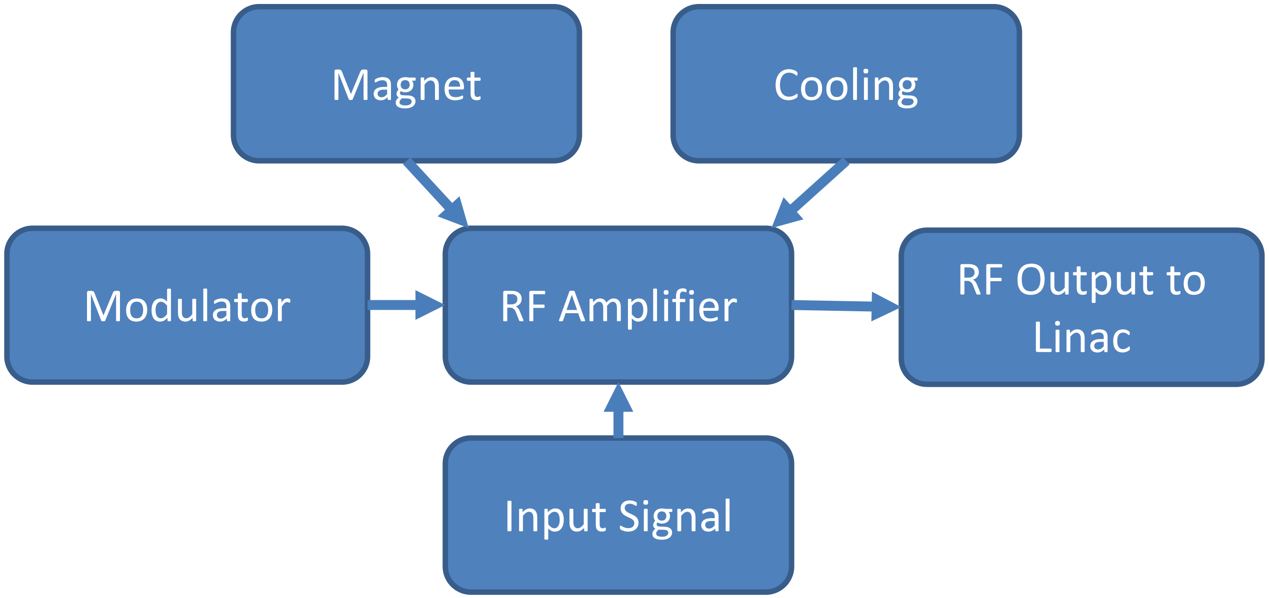
		Frequency Range			Cost Comparison	Operability
		<1GHz	1-3 GHz	>3GHz		
Amplifiers	Klystron					
	Magnetron					
	Solid State					
Linac	Standing Wave					
	Travelling Wave					
Magnet	Electro					
	Permanent					
Configurations	All RF in RTT gantry					
	Linac only in RTT gantry					
	No RF in RTT gantry					
Simplification	Removal of key components					
	Modular systems					

RF System Considerations

- Several additional components required depending on choice of RF source:
  - Electron beams require magnets.
  - High powers require cooling.
  - Input signal may be required for amplifier.
  - Modulator required for high voltage pulse to RF amplifier.

- Such components add complexity to RF system.

- Typical failures:
  - Electron source in RF amplifier.



RF Source Summary

- Data collection of sources identified:
  - Target frequency range 10 MHz – 18 GHz.
  - Not all parameters could be found, e.g. weight, dimensions, cost.
  - ~360 devices identified thus far - non-exhaustive list.
  - Focused on devices which are available commercially.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Device	Manufacturer	RF Device Type	Centre Frequency (GHz)	Bandwidth (MHz)	Peak Output Power (MW)	Normalised Power (MW)	Average Output Power (kW)	Peak Beam Voltage (kV)	Peak Beam Current (A)	Gain (dB)	Efficiency (%)	Pulse rate (pps)	Duty (%)	RF pulse width (us)	Height (m)	Length (m)	Depth (m)	Volume (m^3)	Physical Weight (kg)
2	L4153	L-3	Crossed-Field Amplifier	1.33	70	20	13.2916014				10			0.0003	2				0	
3	L4253	L-3	Crossed-Field Amplifier	1.58	100	17.5	12.6799547				10			0.0003	2				0	
4	L4717	L-3	Crossed-Field Amplifier	3.00	200	0.06	0.06				16			0.028	35				0	
5	L4719	L-3	Crossed-Field Amplifier	3.00	200	0.525	0.525				10			0.025	28				0	
6	L4756	L-3	Crossed-Field Amplifier	3.30	420	1.2	1.25857062				10			0.025	110				0	
7	L4764	L-3	Crossed-Field Amplifier	9.75	500	0.5	0.90138782				12			0.011	2				0	
8	L4806	L-3	Crossed-Field Amplifier	1.30	100	0.1	0.06582806				13.5			0.032	40				0	
9	L4822	L-3	Crossed-Field Amplifier	5.65	500	0.63	0.86457793				10.2			0.01	37				0	
10	L4939/4940	L-3	Crossed-Field Amplifier	1.30	100	0.55	0.36205432							0.0124	3				0	
11	L4953	L-3	Crossed-Field Amplifier	1.33	70	5.3	3.52227436				11.2			0.001	2				0	
12	SFD233G	CPI	Crossed-Field Amplifier	9.30	600	0.9	1.58461352		38	60		39.4737		0.01	0.83	0.33	0.11		0	
13	SFD251H	CPI	Crossed-Field Amplifier	9.75	500	0.5	0.90138782		34					0.001	0.5	0.31	0.22		0	
14	VXC1606	CPI	Crossed-Field Amplifier	5.65	500	0.5	0.68617296		27					0.0025	3.5	0.2	0.32		0	
15	VXC1659	CPI	Crossed-Field Amplifier	5.65	500	0.9	1.23511133		30					0.005	50	0.22	0.25		0	
16	VXL1169	CPI	Crossed-Field Amplifier	1.30	100	0.09	0.05924525		11	25		32.7273		0.032	40				0	
17	VXS....	CPI	Crossed-Field Amplifier	3.30	400	0.22	0.23073795		16	36		38.1944		0.02	50				0	
18	1AV65/E3775	Toshiba	Klystron	1.30	100	5.7	3.75219936		130	94	53	47	400	0	3	1.6	1.6		0	100
19	3AV85	Toshiba	Klystron	2.80	200	1.6	1.54574685		79	44	53	46	360	0	8	1.4			0	60
20	E37100	Toshiba	Klystron	9.50		0.1	0.1779513		4.5	8.5	53	28	1000	0	4	0.3			0	16
21	E3712	Toshiba	Klystron	2.86		80	78.0563899		400	488	53	42	50	0	4	1.9			0	380
22	E3712	Toshiba	Klystron	2.86		100	97.5704873		422	522	56	46	50	0	1	1.9			0	380
23	E37122	Toshiba	Klystron	11.42		0.05	0.09757049		28	5.1	39	35	100	0	2	0.4			0	6
24	E37201	Toshiba	Klystron	5.35	40	0.2	0.26708301		50	12	53	42	1000	0	2	0.6			0	35
25	E37202	Toshiba	Klystron	5.71		50	68.9927532	6.5	354	315	52	47	60	0.013	2.5	1.4			0	300
26	E3729	Toshiba	Klystron	2.86		24	23.416917		284	280	50	31	10	0	24	1.9			0	380
27	E3729	Toshiba	Klystron	2.86		34	33.1739657		304	316	52	34	50	0	12.5	1.9			0	380
28	E3729	Toshiba	Klystron	2.86		70	68.2993411		378	451	55	42	50	0	4	1.9			0	380
29	E37302	Toshiba	Klystron	2.86		45	43.9067193		325	400	51	43	50	0	3	1.4			0	140
30	E37306	Toshiba	Klystron	2.86		50	48.7852437		354	315	52	47	60	0	2.5	1.7			0	170
31	E37307	Toshiba	Klystron	2.86		5	4.87852437		135	95	46	39	667	0	18	1.5			0	110
32	E37308	Toshiba	Klystron	2.86		25	24.3926218		245	255	50	40	200	0	4	15			0	160
33	E3730A	Toshiba	Klystron	2.86		50	48.7852437	10	312	362	51	45	50	0.02	4	1.4			0	140
34	E3734	Toshiba	Klystron	5.30	100	0.2	0.26583203		50	12	53	42	1000	0	2	0.6			0	35
35	E3735A	Toshiba	Klystron	2.86		5	4.87852437		132	86	48	44	600	0	15	1.3			0	80
36	E3740A	Toshiba	Klystron	0.32		3	0.9859006		110	50	50	55	50	0	620	4.5	4.5		0	730
37	E3746A	Toshiba	Klystron	5.71		50	68.9927532		354	315	52	47	50	0	2.5	1.4			0	300
38	E3748	Toshiba	Klystron	5.71		50	68.9927532		354	315	52	47	60	0	2.5	1.4			0	300
39	E37501	Toshiba	Klystron	1.30		0.75	0.49371044		66	50	43	55	5	0	1500	1.2			0	70
40	E3754	Toshiba	Klystron	2.86		40	39.0281949		284	320	51	43	50	0	4	1.4			0	140
41	E3758	Toshiba	Klystron	5.71		50	68.9927532		315	300	52	47	50	0	2.5	1.4			0	300
42	E37612	Toshiba	Klystron	1.43		30	20.697826		295	260	48	40	60	0	6	2			0	450
43	E3765A	Toshiba	Klystron	2.86		5	4.87852437	36	135	89	48	44	550	0.72	13	1.3			0	80
44	E3766A	Toshiba	Klystron	0.97		3	1.70762994		110	50	50	55	50	0	620	3	3		0	500
45	E3768I	Toshiba	Klystron	11.42		50	97.5704873		500	270	60	55	25	0	0.4	1.9			0	190
46	E3772A	Toshiba	Klystron	2.86		7.5	7.31778655		150	110	51	45	200	0	4	1			0	40

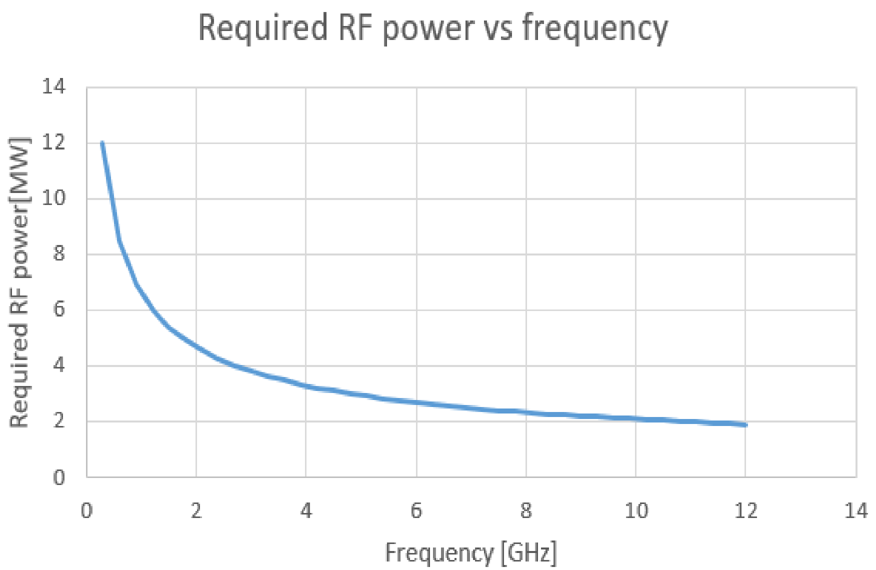
Required RF Output Power for a Linac

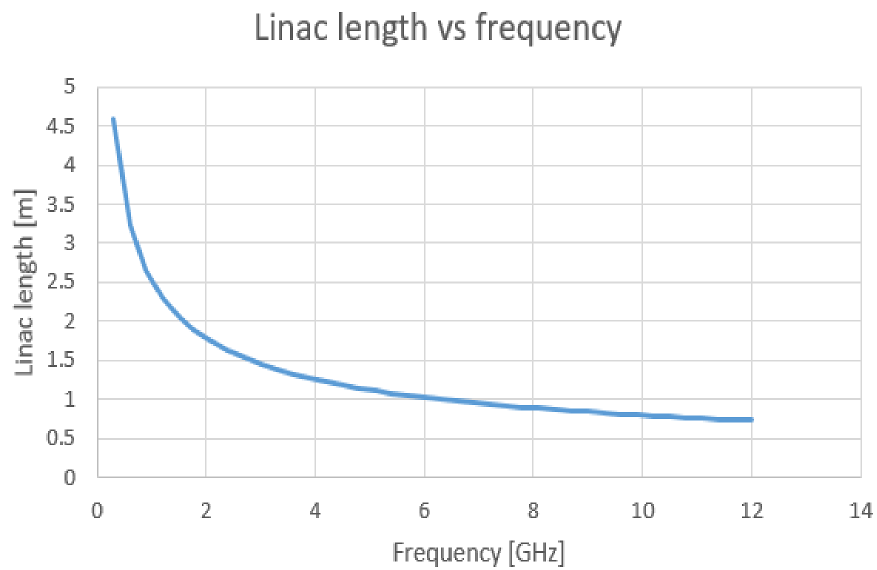
R. Apsimon - RTT Platform Specification Assessment

- To allow comparison of RF source performance:

$$P_{RF}^{linac} \propto \frac{1}{\sqrt{\omega} L_{linac}}$$

  - For a 1.45 m linac, a (minimum) RF power of 3.88 MW is required at 3 GHz.
  - Will use this as benchmark.

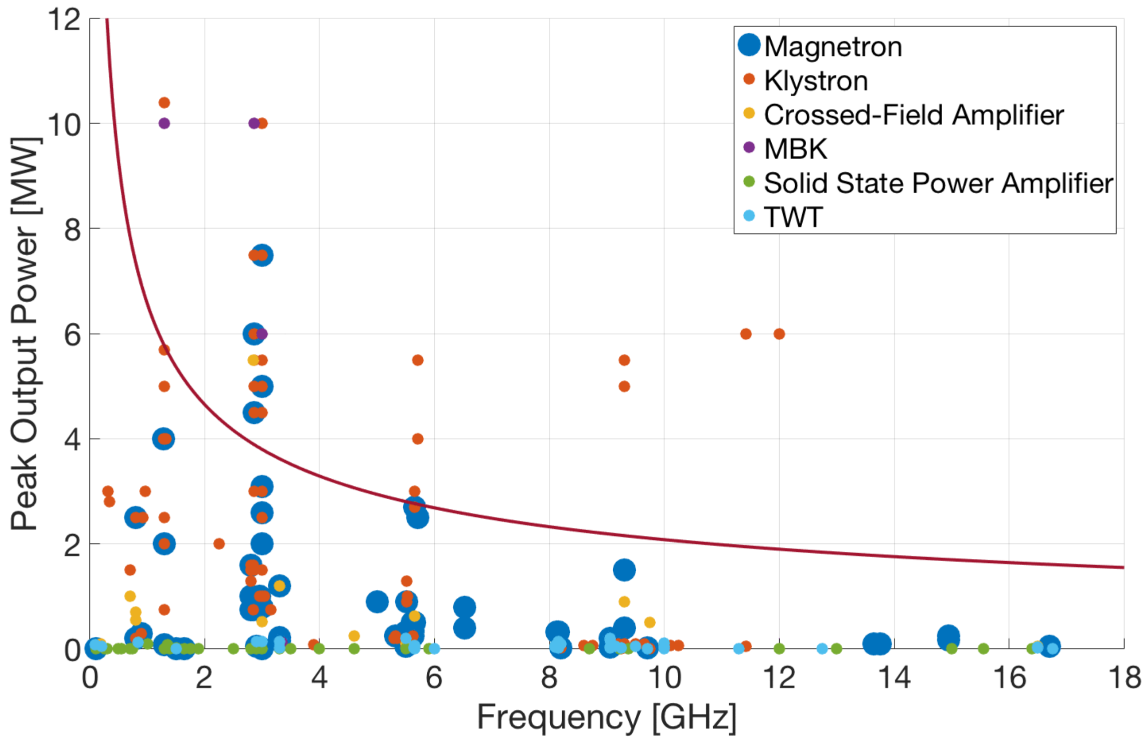




Peak Output Power Comparison

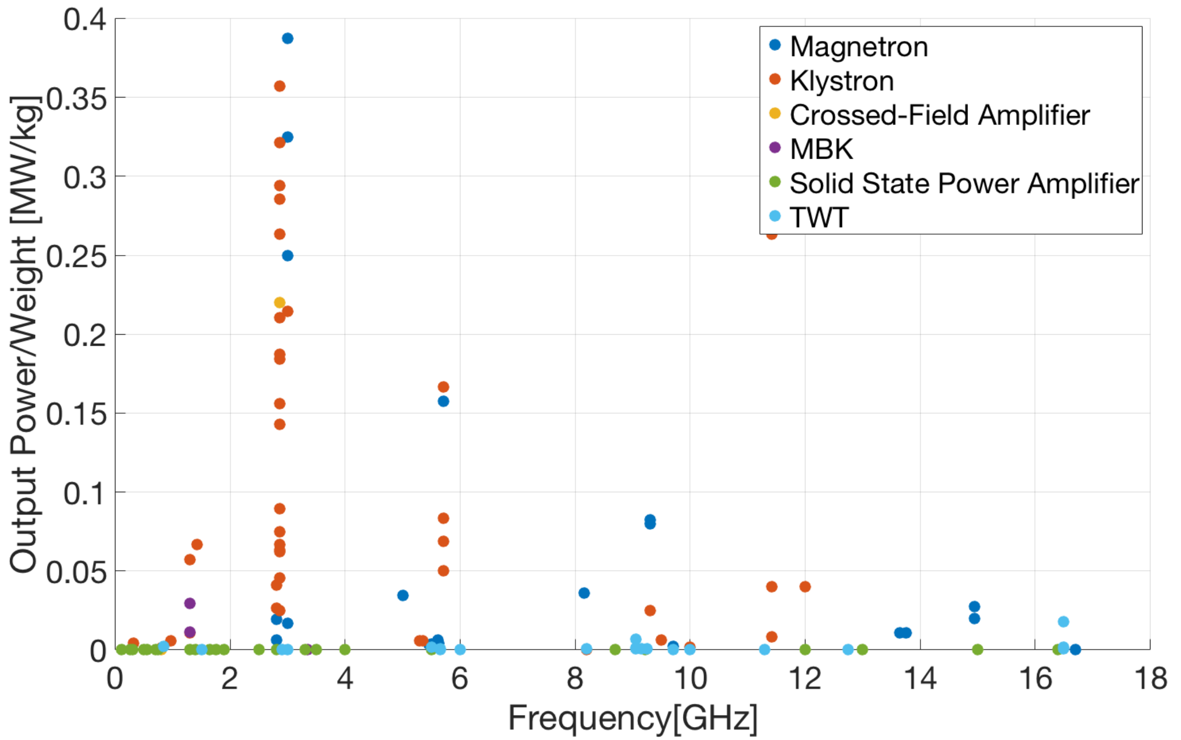
$$P_{RF}^{linac} \propto \frac{1}{\sqrt{\omega} L_{linac}}$$

- Comparison of single devices:
  - Larger RF power required for lower frequency.
  - Magnetrons & klystrons offer largest peak power across all frequencies.
  - TWTs and SSPAs would require multiple devices to meet example specification.
  - Few single devices meet required specification.



Output Power per Unit Weight

- Comparison of single devices:
  - View of output power per unit weight.
  - Magnetrons and klystrons offer best performance.
  - Very high power klystrons ~3 GHz (~100 MW).

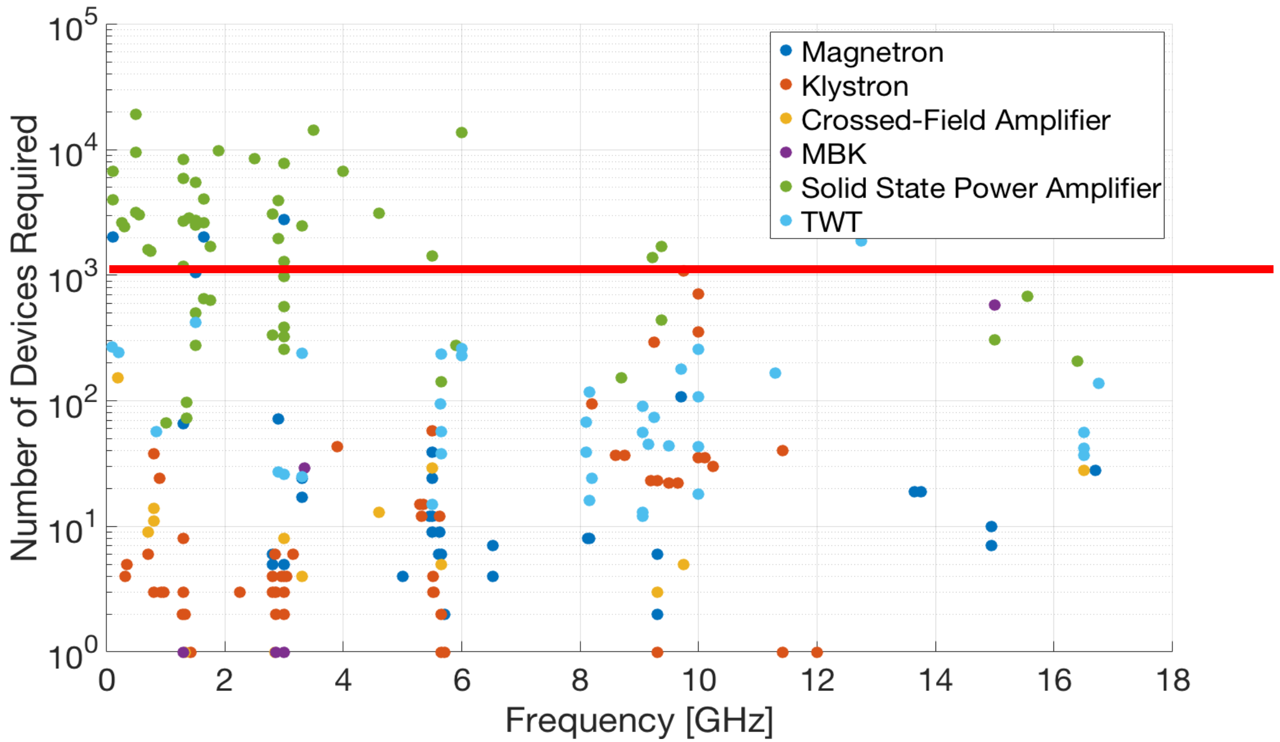


Number of Devices to Meet Benchmark

$$P_{RF,norm} = P_{RF,0}\sqrt{\frac{f}{f_0}}$$

- Calculate the number of devices required to meet a normalised benchmark:
  - Normalised output power of 3.88 MW at f_0 = 3 GHz (RTT specification report).
  - SSPA require least number (~hundreds) at hundreds of MHz.
  - Klystrons, MBKs, CFAs and magnetrons require least number, over <10 GHz.
  - Power combining could become challenging with many sources.
  - Conservative max. limit of 1,000 units might be imposed.

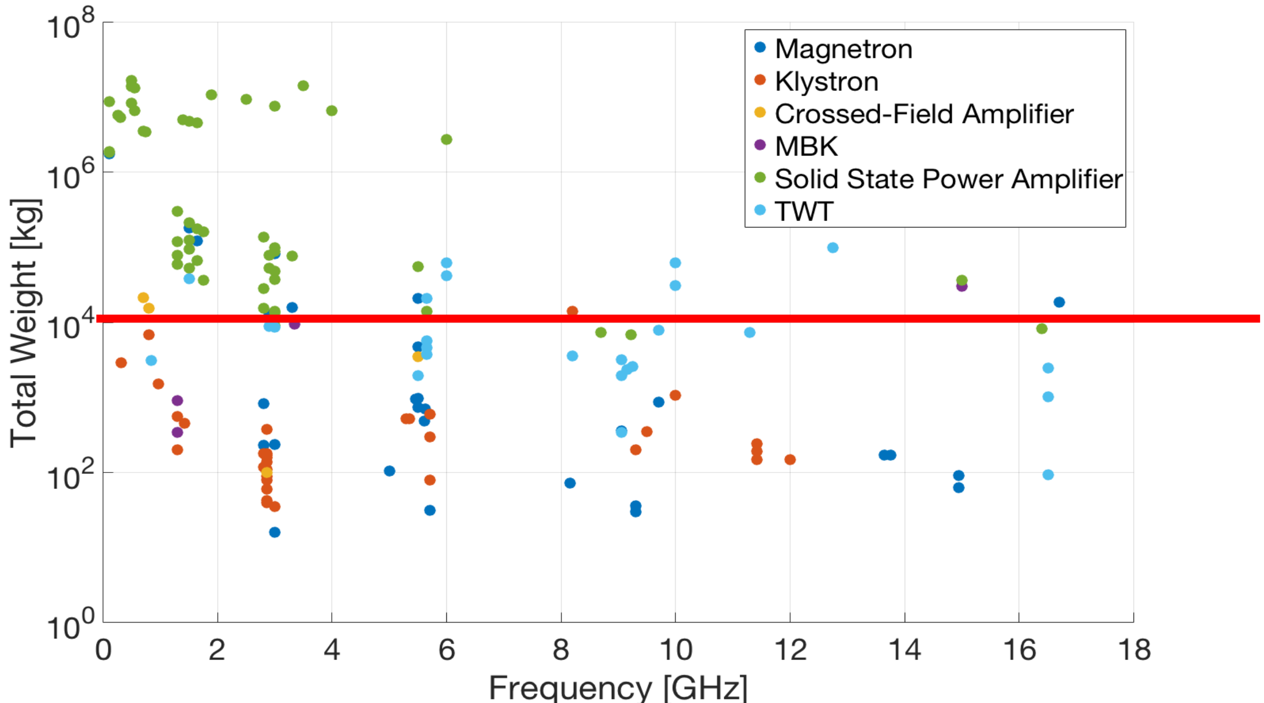
$$N_{device} = \frac{3.88MW}{P_{RF,norm}}$$



Total Weight of RF Sources to Meet Benchmark

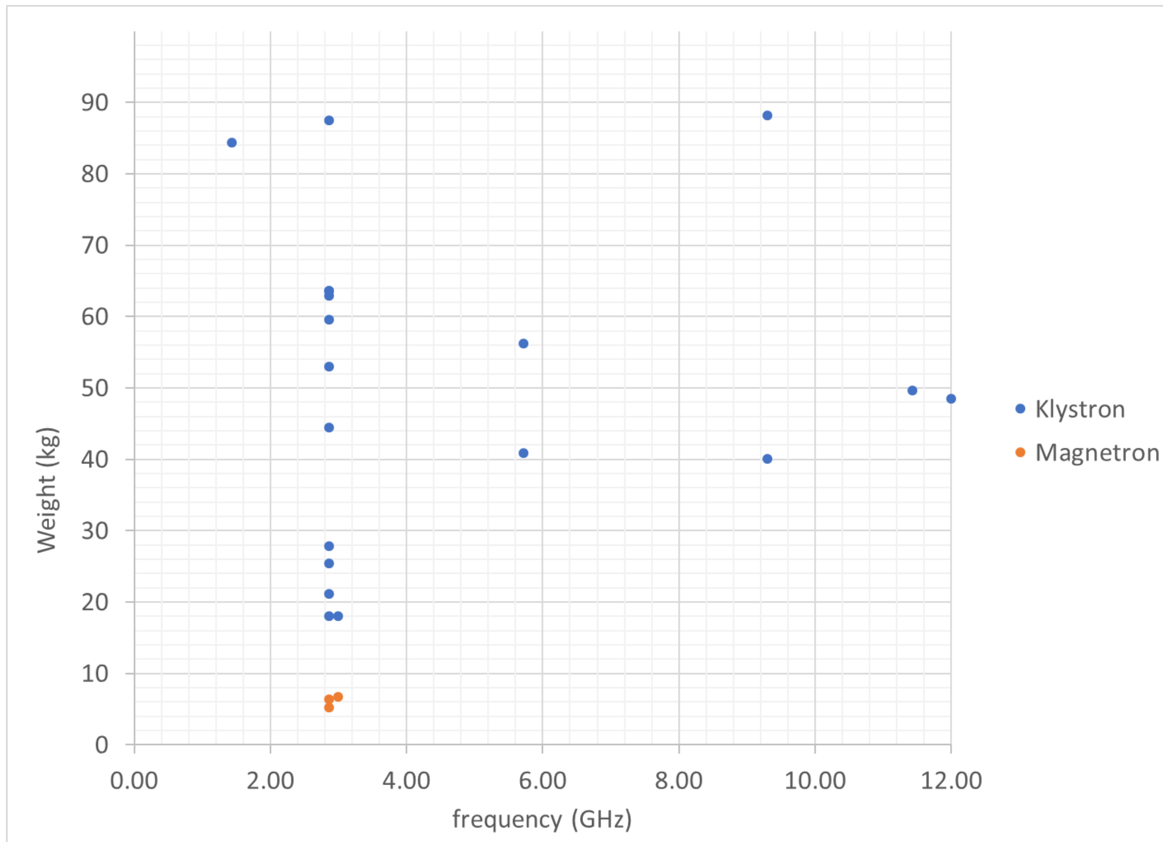
$$Total\ Weight = N_{device} * Weight$$

- Significant spread in data:
  - Magnetrons and klystrons present lowest weight across frequency range.
  - SSPA are largest weight.
- Data represents weight of the source only:
  - Does not account for cooling, magnets, power supply, waveguide, power combiners, etc…
  - Total installation weight could be much larger.



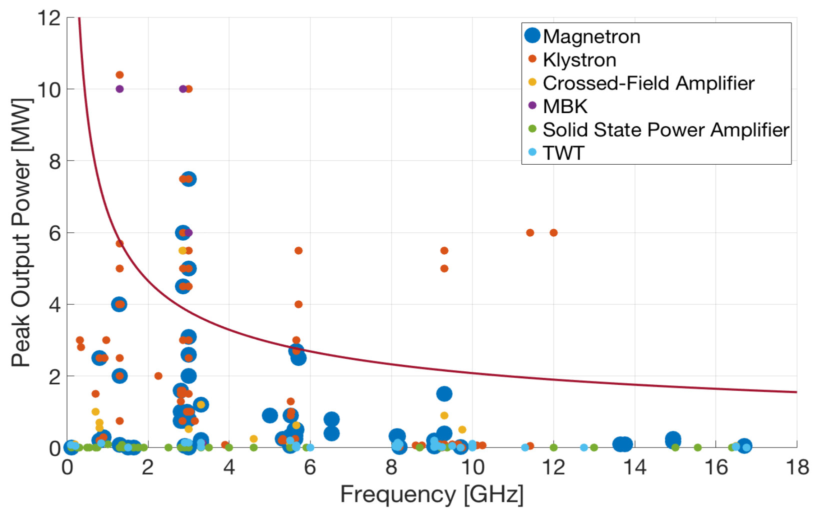
Klystrons and Magnetrons

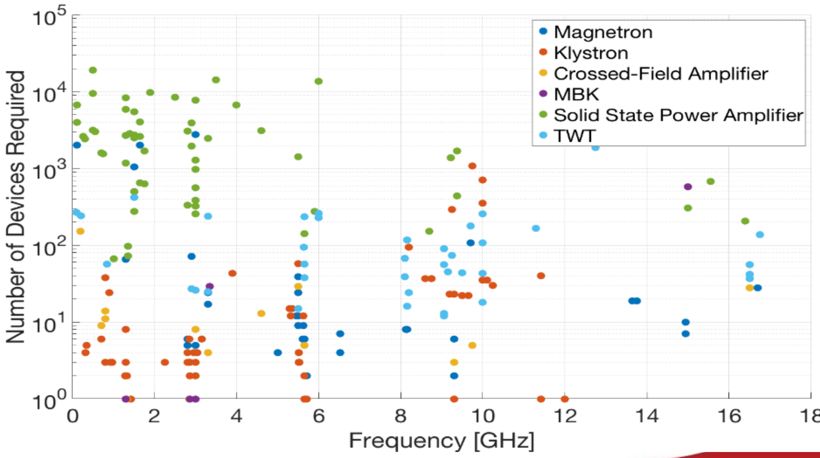
- If we exclude using multiple sources combined and remove highly over-specified sources (50 MW klystrons) we get the following
- Magnetrons are far lighter but need a 15 kg magnet as well so in reality they have similar weight
- 3 GHz is far smaller and lighter but doubling the weight isn't likely an issue.



Initial Conclusions from Data

- Across entire frequency range, klystrons deliver desired output power in single device:
  - Other devices can be put into specific frequency categories.
  - Based on number of devices required.
- Low frequency (< 1.3 GHz):
  - SSPAs.
  - Crossed Field Amplifiers.
- Between 2-4 GHz:
  - Magnetrons.
  - Klystrons.
- Above 4 GHz:
  - Klystrons.
  - Magnetrons
  - TWTs.
  - Crossed Field Amplifiers.





Example RF Source Configurations

Solid State Power Amplifier Example

Suggested frequency: ~400 MHz

- Rhode & Schwarz THU9:
  - Peak output power, 100 kW.
  - Centre frequency, 200 MHz.
  - Bandwidth, ~200 MHz
  - Dimensions, 2m x 2.4m x 1.1m
  - Weight (estimate), 150 kg per unit.
  - Forced air cooling.
  - No magnet or modulator required.

- Power required at 400 MHz for benchmark linac, 10.4 MW:
  - Minimum number required, 140.
  - Total weight (estimate), 21,000 kg.
  - Total size, 739 m^3.
  - Would need to be separate from linac.

Data sheet:

https://cdn.rohde-schwarz.com/pws/dl_downloads/dl_common_library/dl_brochures_and_datasheets/pdf_1/service_support_30/THU9-THV9_bro_en_5214-5990-12_v0503.pdf

Magnetron Example

Suggested frequency: 2.86 GHz

- e2v MG6028:
  - Peak output power, 5 MW.
  - Centre frequency, 2.86 GHz.
  - Bandwidth, 3 MHz.
  - Dimensions, 0.477m x 0.147m x 0.147m
  - Weight (estimate), 8 kg.
  - Liquid cooled.
  - Pulse width, 3 us.
  - Electromagnet required, 50 kg.
  - DC power supply required.
- Power required at 2.86 GHz for benchmark linac, 3.9 MW:
  - Minimum number required, 1.
  - Total weight, 58 kg.
  - Total size, 0.477m x 0.147m x 0.147m.
  - Could easily be implemented on linac gantry.

Data sheet:
https://www.e2v.com/shared/content/resources/A1A-MG6028_5_v1.pdf

Klystron Example

Suggested frequency: ~2.86 GHz

- Toshiba E3765A:
  - Peak output power, 5 MW.
  - Centre frequency, 2.856 GHz.
  - Bandwidth, ~2 MHz
  - Dimensions, 1.3m x 0.468m x 0.468m
  - Weight (estimate), 100 kg.
  - Liquid cooling.
  - Pulse width, 11.5 us.
  - Electromagnet and modulator required.

- Power required at 2.86 GHz for benchmark linac, 3.9 MW:
  - Minimum number required, 1.
  - Total weight, >100 kg (no data for magnet).
  - Total size, 1.3m x 0.468m x 0.468m

Data sheet:
https://etd.canon/eng/product/read_binary.php?cid=400000100200&pid=20140730_4021&fn=E3765,A_PI(E)_rev1.pdf

Travelling Wave Tube Example

Suggested frequency: 5.5 GHz

- CPI VTC-5764C:
  - Peak output power, 200 kW.
  - Centre frequency, 5.5 GHz.
  - Bandwidth, ~500 MHz
  - Dimensions, 0.21m x 0.21m x 1.11m
  - Weight (estimate), 132 kg.
  - Water cooled.
  - PPM focussed
  - Pulse width, 1-100 us.

- Power required at 5.5 GHz for benchmark linac, 2.8 MW:
  - Minimum number required, 14.
  - Total weight, ~1,850 kg.
  - Total size, 0.65 m^3

Data sheet:
http://www.cpii.com/docs/datasheets/110/VTC5764C.pdf

Multiple-Beam Klystron (MBK) Example

I. Syratchev, “Personal overview of special issues of the robust/reliable medical accelerator,” CERN-ICEC-STFC Workshop on Innovative, Robust and Affordable Medical Linear Accelerators for Challenging Environments, 2017.

JSC “Vacuum device’s basic technologies”
Moscow, 117342, Vvedenskogo str., 3, k.1,
Russian Federation, tel. +7 (495) 578-05-46
www.vdbtc.com

VDBT

Sales Agent:
NELSON Created AB
www.nelsoncreated.com
NELSON

0.72m long
92 kg (incl. PPM solenoid)
No oil tank.
Positioning: arbitrary (rotation possible)
Modulator required.

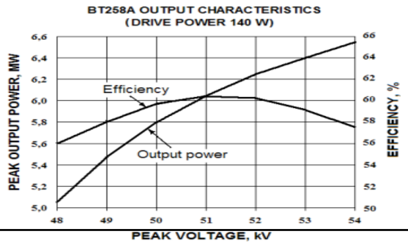
TECHNICAL SPECIFICATION
#10258-01
Multi-beam S-band Klystron type BT258A

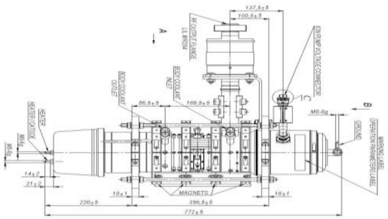
VDBT
The company was created for the development and manufacture of precision microwave vacuum-electron-tube devices (VETD).
The main product areas being manufactured are:
- Linear electron accelerators.
- Vacuum-tube radar devices.
- Multi-beam high power klystrons (MBK).

BT258A Data sheet --

TYPICAL OPERATION
(Example)

		Units
Frequency	2998.5	MHz
Heater Voltage	21	V
Heater Current	25	A
Peak Beam Voltage	50	kV
Peak Cathode Current	200	A
Peak RF Drive Power	150	W
Peak RF Output Power	6	MW
Efficiency	60	%
Gain	46	dB
Pulse Width (Beam Voltage)	7	µs
Pulse Width (RF Output Power)	5	µs
Pulse Repetition Rate	200	pps





Data sheet: https://nelsoncreateddotcom.files.wordpress.com/2017/05/vdbt-bt258a-b.pdf

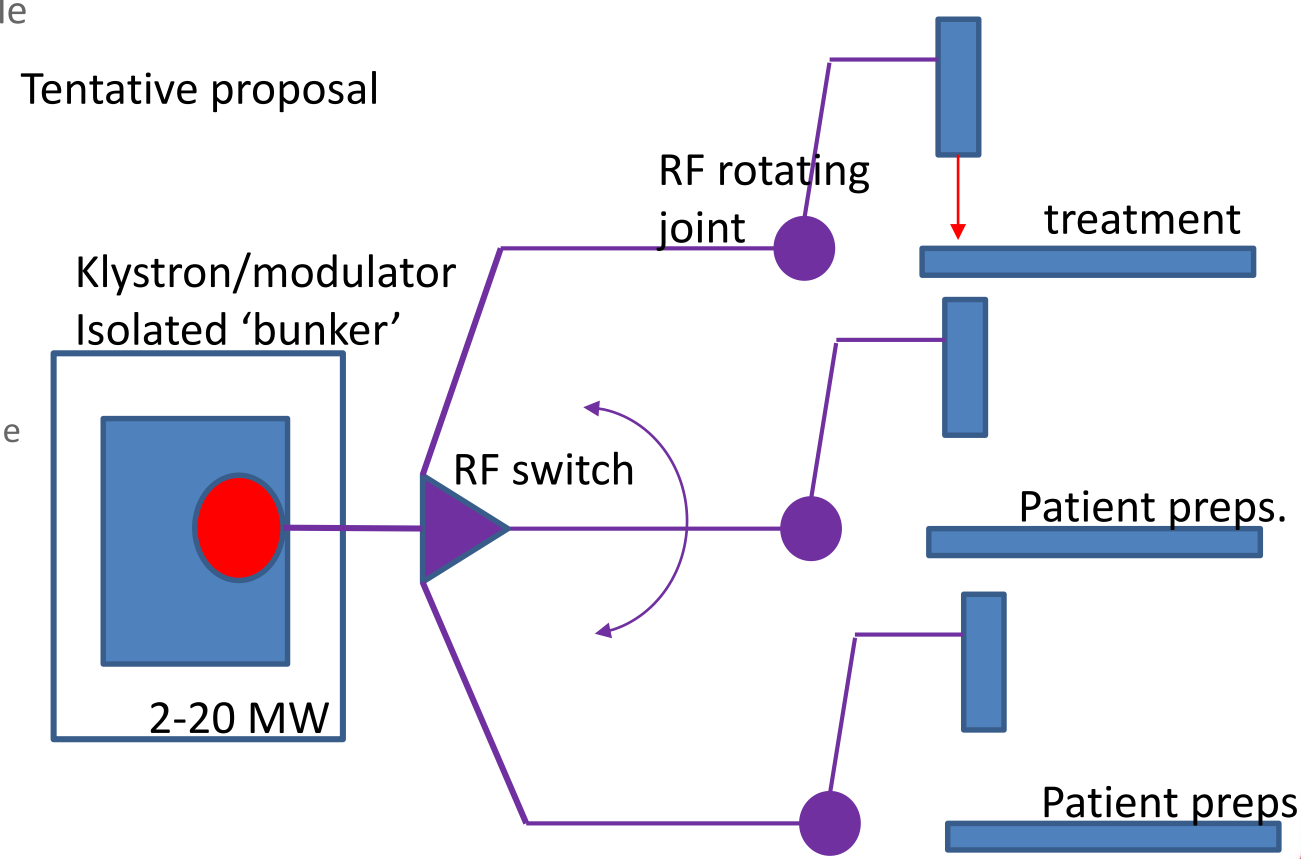
RF Source Examples Summary

Device Type	Magnetron	Klystron	Crossed-Field Amplifier	Solid State Power Amplifier	Travelling Wave Tube	Multiple-Beam Klystron
Individual Unit Peak Output Power (MW)	5	5	0.5	0.1	0.2	6
Frequency (GHz)	2.86	2.86	9.75	0.4	5.5	2.998
Efficiency (%)	60	50	~50	No data	~25	60
Required RF power (MW)	3.9	3.9	2.68	10.4	2. 8	3.88
Units Required for ~5 MW at 3 GHz	1	1	6	140	14	1
Total Volume (m^3)	0.0103	0.2847	0.3	739	0.65	~0.2
Cooling	Forced air or water	Water	Forced air	Forced air	Water	Water
Magnet Required	Yes, electromagnet	Yes, PPM	Yes, electromagnet	No	Yes, PPM	Yes, PPM
Total Weight (kg) (incl. magnets)	58	150	150 (estimate)	21,000	1,850	95
Modulator Required	Yes	Yes	Yes	No	Yes	Yes

Example Implementation

I. Syratchev, “Personal overview of special issues of the robust/reliable medical accelerator,” CERN-ICEC-STFC Workshop on Innovative, Robust and Affordable Medical Linear Accelerators for Challenging Environments, 2017.

- Multiple MBKs driving multiple linacs:
  - Over-pressurised bunker to isolate RF sources.
- Control over RF sources:
  - Single klystron feeds single linac.
  - Single klystron feeds multiple linacs.
  - Achieved with mechanical switches.
- Extension in lifetime of RF source:
  - Not all devices active at all times.
  - Should minimize downtime if one source fails.



Maximize facility put through in the most economic way.

Summary

- Data collection of potential RF sources conducted:
  - Available data suggests klystrons, MBKs or magnetrons are best options for RTT source.
  - <10 units can easily meet RF power demands.
  - Additional components (magnets, cooling, modulators) increase complexity of RF installations.
  - SSPAs will be a very large/massive solution at present.

- Possible implementation:
  - Multiple RF units feeding multiple linacs.
  - Use of existing technologies to improve robustness.
  - Remove sources from linac assembly.
  - Ease of access, improved lifetime.