Progress with the RTT specifications report

Dr Rob Apsimon
(Lancaster University/Cockcroft Institute)

Remit for the implementation specification report

- Research existing x-ray/ electron beam RTT
  - Tabulate key parameters
  - Identify differences and similarities between systems
- Identify and understand the needs and expected input from ODA recipient countries RTT operators
  - Hubert Foy will talk about this in his talk
- Define agreed RTT specifications

Research existing x-ray/ electron beam RTT

- > 30 RT systems researched
  - Vast majority of systems employ isocentric gantries (~90%)
    - Varian, Siemens[*], Elekta, NCBJ
    - [*] Siemens no longer selling RTT
  - Remaining systems opt for less conventional designs
    - Accuray, Mitsubishi[*]
    - [*] Mitsubishi no longer selling RTT
- Available information is patchy and inconsistent
  - Mostly from secondary owners
    - Primary owners bound by NDAs with manufacturers
    - Information possibly unreliable/outdated
  - Most information only publically available for systems > 10 years old

Selection of RTT devices

Isocentric gantries

 Varian Edge	 Varian TrueBeam	 Varian Trilogy	 Varian Clinac*
 Varian Unique	 Siemens Artiste	 Siemens Oncor	 Siemens Primus
 Elekta Versa HD	 Elekta Infinity	 Elekta Synergy	 Elekta Precise
 Elekta Compact	 Neptune10 (NCBJ)	 Coline4/6 (NCBJ)	

Table 1: images of a selection of isocentric RT systems by Varian, Siemens, Elekta and NCBJ [1, 3-14].
* Varian Clinac covers a range of variants, such as 2100C/CD, 21EX, 6EX, iX.

"Unconventional" RTT

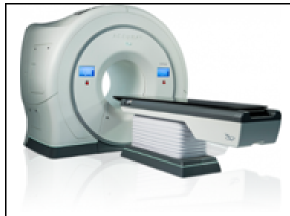
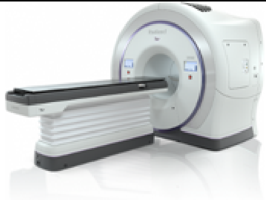
 Accuray TomoTherapy	 Accuray Radixact	 Accuray CyberKnife	 Mitsubishi Vero
- Integrated imaging with CT scanner - Helical treatment delivery system allows treatment of a wider range of tumours.	- Rapid imaging - Fully integrated system - Allows good flexibility on treatment options (image-guided, gantry rotation and intensity modulation can all be toggled)	- Robotic system allows more precise treatment - Precise tracking and adjustment of moving targets - Dynamic motion compensation	- Real time tumour tracking

Table 2: Images of Accuray and Mitsubishi RT systems and their unique features [15-18].

Table of RTT data

Device	Manufacture	manufacture dates	energy	RF source	RF power (MW)	Linac type	device size LxWxH (m)	min. room size needed LxWxH (m)	Linac length (m)	RF frequency (GHz)	Max. Dose rate (rad/min) (e): electron (x): X-ray
600C/D	Varian	1989 +	4/6 MeV	magnetron	2.5	SW	2.72 x 1.27 x 2.69	6.7 x 6.1 x 3.2	0.3	2.856	250-400 (x)
6EX	Varian	1999 +	4/6 MeV	magnetron	3	SW	2.72 x 1.27 x 2.69	6.7 x 6.1 x 3.2	0.3	2.856	400-600 (x)
Unique	Varian	2012 +	6 MeV	magnetron							100-600 (e)
2100/2300 C/CD	Varian	1988-2007	6-20 MeV	klystron	5.5	SW	2.59 x 1.24 x 3.71	6.1 x 7.1 x 3.1	1.3 - 1.45	2.856	400 (e) 250-600 (x)
21/23 series	Varian	1998-2006	6-20 MeV	klystron	5.5	SW	2.59 x 1.24 x 3.71	6.1 x 7.1 x 3.1	1.3	2.856	250-600 (x) 1000 (e)
Trilogy	Varian	2005 +	6-25 MeV	klystron	5.5	SW	3.71 x 1.24 x 2.64	7.8 x 6.1 x 3.1	1.3		600 (x) 1000 (e)
iX	Varian	2004 +	6-25 MeV	klystron	5.5	SW	3.71 x 1.24 x 2.64	7.8 x 6.1 x 3.1	1.3	2.856	300-600 (x) 1000 (e)
TrueBeam	Varian	2010 +	6-22 MeV	klystron							
Edge	Varian	2013 +		klystron							
Clinac 4	Varian		4 MeV	Magnetron	2	SW			0.3	2.856	
Clinac 6X	Varian		6 MeV	Magnetron	2	SW			0.3	2.856	
Clinac 12	Varian		6-12 MeV	Magnetron	2	SW			1.0	2.856	
Clinac 18	Varian		6-18 MeV	Klystron	5	SW			1.4	2.856	
Clinac 35	Varian		7-28 MeV	Klystron	20	TW			2.25	2.856	
Precise Systems	Elekta	1997-2005	4-22 MeV	magnetron	5	TW	3.51 x 3.90 x 2.48	6.5 x 6.0 x 3.2	2.5		400(e) 600(x)
Synergy Platforms	Elekta	2002 +	4-20 MeV	magnetron	5	TW	3.51 x 3.90 x 2.48	6.5 x 6.0 x 3.2	2.5		400(e) 600(x)
Axesse/Infinity	Elekta	2009 +	4-18 MeV	magnetron	5	TW	3.51 x 3.90 x 2.48	6.5 x 6.0 x 3.2	2.5		400(e) 600(x)
MRLinac/Unity	Elekta										
Versa HD	Elekta	2013 +		magnetron							
Primus	Siemens	1998-2005	6-21 MeV	klystron	7.5	SW	3.09 x 1.43 x 2.60	6.1 x 5.8 x 3.0			300/900 (e)
Oncor mid-energy	Siemens	2004-2011	5-14 MeV	magnetron	2.6	SW	2.83 x 1.31 x 2.64	6.1 x 5.8 x 3.0			300/900 (e) 200-300 (x)
Oncor high energy	Siemens	2004-2011	6-21 MeV	klystron	7.5	SW	3.09 x 1.43 x 2.60	6.1 x 5.8 x 3.0			300/900 (e)* 200-300 (x)*
Artiste	Siemens	2009-2011	6-23 MeV	klystron	7.5	SW	3.14 x 1.43 x 2.60	6.25 x 6.1 x 2.95	1.2		300/900 (e)* 300-500 (x)*
Mevatron 6	Siemens		6 MeV	Magnetron	2	SW			0.95	2.9985	
Mevatron 12	Siemens		3-11 MeV	Magnetron	2	SW			1.35	2.9985	
Mevatron 20	Siemens		3-18 MeV	Klystron	7	SW			1.38	2.9985	
TomoHD	Accuray	2012 +	6 MeV	magnetron	2.5	SW	4.63 x 2.81 x 2.52	6.0 x 4.6 x 2.7	0.3		850 (x)
Hi-Art II	Accuray	2004 +	6 MeV	magnetron	2.6	SW	0.62 x 1.07 x 0.97	6.7 x 5.2 x 2.7	0.3		850 (x)
Radixact	Accuray	2016 +	6 MeV	magnetron							
Cyberknife	Accuray	2003 + (6 generations)	6 MeV	magnetron							
Vero	Mitsubishi	2011									
Coline4	NCBJ		4 MeV	magnetron	2.6						
Coline6	NCBJ		6 MeV	magnetron	3.1						
Neptune10	NCBJ		≤26 MeV	magnetron							

Table 3: Summary of RTT design parameters [1, 19-46]. SW stands for standing wave and TW stands for traveling wave.
* Other dose rates possible with optional extras

All systems believed to operate at 3 GHz, but difficult to find information publicly available

Almost all systems are standing wave (except for Elekta), which is more efficient for shorter structures (< ~1.5 m)

Travelling wave structures more efficient in longer structures (>~2 m)

Isocentric gantries

- All isocentric gantries are remarkably similar
  - Almost all RTT require a treatment room size of ~6 x 7 x 3 m^3
    - Varian Trilogy and Clinac iX require a slightly larger room (7.8 x 6.1 x 3.1 m^3)
    - Allows hospitals to change RT supplier without significant civil engineering
      - More competition between manufacturers
  - Provide electron energies of ~4-20 MeV (or 4-18 MV for x-rays)
    - Exact available energies depends on specific make + model, optional extras etc
  - RF technology has changed very little in c. 70 years
    - Main advancement is in beam quality and imaging
      - Field flatteners, spoilers, multi-leaf collimators etc
      - This falls outside the remit of this study

Unconventional RTT

- Avoid competing with larger companies by targeting more specific customer base
  - Addressing one or more specific issues
    - Accuray Cyberknife: robotic system reduces human error, automatic compensation of moving target
    - Accuray Radixact: high treatment flexibility
    - Accuray TomoTherapy: CT scanner allows for 4D scanning, helical treatment delivery allows for treatment of wider range of tumours
    - Mitsubishi Vero: real time tumour tracking
      - Competed with Accuray target tracking
  - All these systems are 6 MeV fixed energy machines

NCBJ experience

- Studied NCBJ RT experience as they developed systems for former Soviet states
  - Some key similarities with RTT for ODA recipient countries
    - Limited availability of replacement parts + technical support
    - Need for high-reliability/low-maintenance
  - Gun + Linac integrated together
    - Simplifies system, gun and linac don't need to be designed separately
  - Cavity geometry optimised to allow for easy brazing
    - Reduces machining costs
  - No Multi-leaf collimators / electronic portal imaging devices
    - Reduces overall system cost by removing non-essential sub-systems

Typical RTT: Varian Clinac 2300 C/D

- Linac
  - π/2 mode side-coupled standing wave S-band structure
    - High gradient like π-mode, but much more stable
    - Used in almost all medical accelerators
  - Linac split into bunching and accelerating sections
    - “energy switch” used to alter coupling from RF input coupler to accelerating section
      - Allows accelerating gradient to vary without affecting field in the bunching section

Typical RTT: Varian Clinac 2300 C/D

Structure	Side-coupled standing-wave	
RF source	5.5 MW klystron	
Accelerator length	1.45 m	
Frequency	2.856 GHz	
Effective shunt impedance	102 MΩ/m	
Q_0	$1.5x10^4$	
Energy [MeV]	6	20
RF power [MW]	1.2	3.8
Maximum accelerating gradient [MV/m]	15.6	27.8
Maximum dose rate (electrons) [rad/min]	400	
Maximum dose rate (x-rays) [rad/min]	250	600
Device size (LxWxH) [m]	2.6 x 3.7 x 1.2	
Minimum room size needed (LxWxH) [m]	6.1 x 7.1 x 3.1	

Sources:

- http://www.medwow.com/med/linear-accelerator/varian/clinac-2100c/25927.model-spec
- http://www.medwow.com/med/linear-accelerator/varian/clinac-2100cd/35317.model-spec
- http://accelconf.web.cern.ch/AccelConf/l76/papers/d08.pdf

Component lifetime: Varian Unique

Component	Lifetime [years]
Machine	10
Thyratron	3
Ion chamber	15
Accelerator structure	10
Magnetron	5
Field light	1
aSi portal imager	7

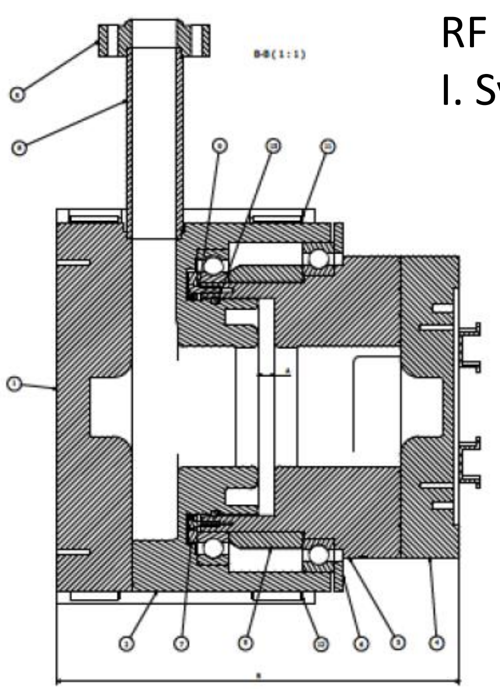
Source:

- http://www.medwow.com/med/linear-accelerator/varian/unique/51445.model-spec

We have been informed (anonymously) that the main problems with the linac resulting in downtime are with the vacuum, and IT (treatment planning) system. The main RF failures relate to the gun and magnetron, but are rare and mostly fairly minor repairs. The main failures relate to moving parts (MLC, gantry bearings etc).

Note: this may not be true for ODA recipient countries as they have different needs and environmental conditions (Hubert to give more information in the next talk)

New ideas to improve RTT manufacture:

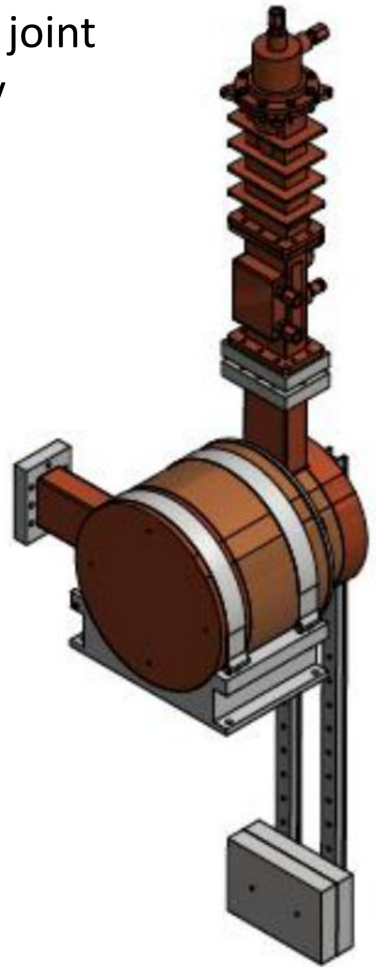


Mechanical design by

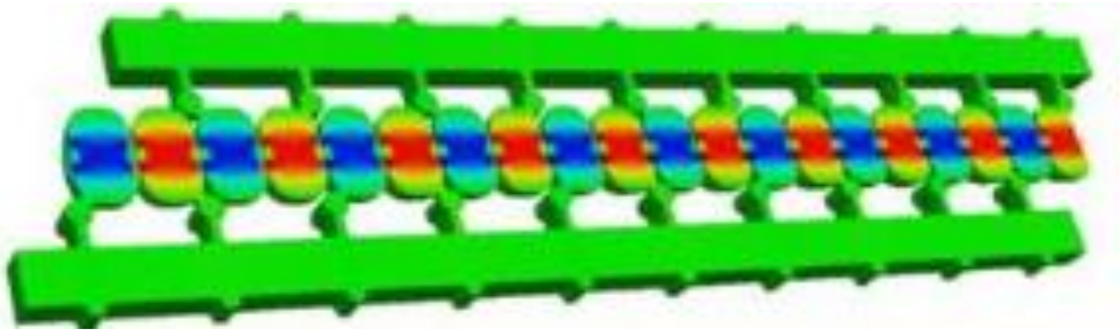
Paolo Magagnin - TERA

NOTE:
- For production steps refer to TLPRJ_001;
- (final gap after spacer remachining A=11.24± 0.04 mm)

RF rotating joint
I. Syratchev

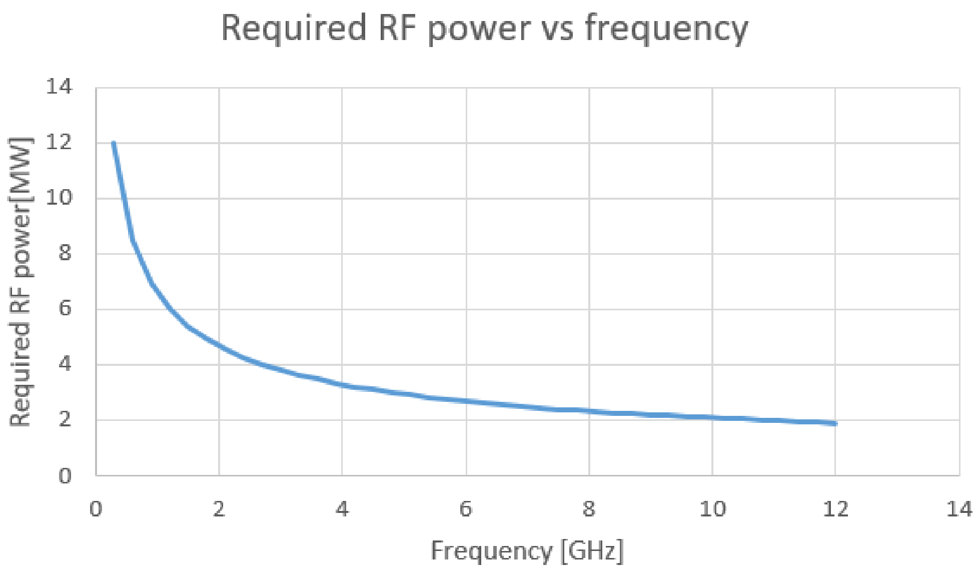


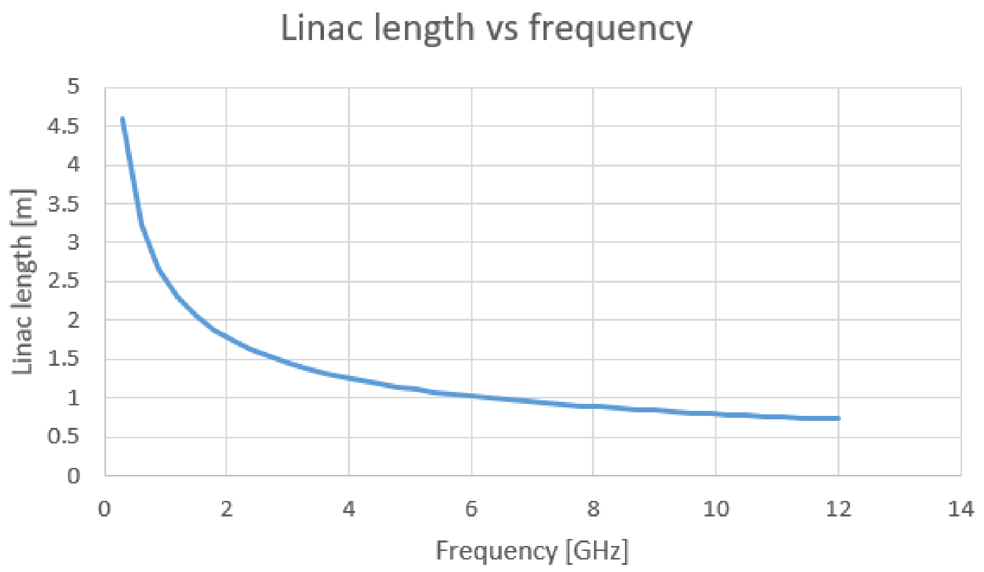
Distributed coupling structures
S. Tantawi et al.



Design considerations: frequency

- RF power: $P_{RF} \propto \frac{V_{linac}^2}{\cos^2(\phi_s)\sqrt{\omega_{RF}}L_{linac}}$
- Effective shunt impedance: $R/L_{linac} \propto \sqrt{\omega_{RF}}$





* Based on Varian Clinac 2300 C/D specifications

Design considerations: Industrial perspective

Criteria	Achieved value (1994)	'Future' value (1994)	Achieved <2018	System affected
Energy range	6-20 MeV	2-25 MeV	6-25 MeV	**Linac input coupler + klystron + linac**
Dose rate [rad/min]	400 (electrons) 600 (x-rays)	1000	1000	**RF gun + RF power source*** ** Beam loading ~1%*
Beam spot size		1 mm	<3 mm	**RF gun** + beam line optics
Spatial precision		0.1 mm	0.1	Imaging + control systems
Field size		1x1mm-40x40cm	1x1mm-40x40cm	Beam optics + collimator
Flatness & Symmetry		1%	2.5% flatness 2.0% symmetry	Flatteners + spoilers

Sources:

- http://accelconf.web.cern.ch/AccelConf/l76/papers/d08.pdf
- http://www.medwow.com/med/linear-accelerator/varian/clinac-2100c/25927.model-spec
- http://www.medwow.com/med/linear-accelerator/varian/trilogy/9937.model-spec
- https://varian.force.com/servlet/servlet.FileDownload?retURL=%2Fapex%2FCpEventPresList%3Fid%3Da0OE000000pZaMdMAK&file=00PE000000VdYq9MAF
- http://www.medwow.com/med/linear-accelerator/varian/clinac-ix/9935.model-spec
- https://varian.force.com/servlet/servlet.FileDownload?retURL=%2Fapex%2FCpEventPresList%3Fid%3Da0OE000000pZaMdMAK&file=00PE000000VdYOPMA3

Design considerations: Industrial perspective

- Some design criteria highlighted by Varian relate to linac and RF system
- Increased energy range
  - Improve energy switch for greater range of energies
  - Improve cavity design and/or RF power source for higher energies
- Dose rate
  - Improve gun cathode design for higher current
    - Beam loading too small to affect RF power requirements
- Spot size
  - Can reduce spot size by changing design of gun cathode
    - Photocathode has lower emittance than thermionic cathode
    - Photocathodes require lasers: not appropriate for ODA recipient countries
    - More likely focus on beam optics
- Are these improvements important/necessary for ODA recipient countries?

RTT specifications

- Frequency
  - > 1 GHz seems to be only solution
    - 3 GHz seems to be the preferred value for Western RTT (W-RTT)
    - What about for ODA recipient countries? Is this still be best option?
- Linac
  - Standing wave
    - Better choice for linac lengths < ~1.5 m
    - Preferred choice for W-RTT
  - Travelling wave
    - Better choice for longer structures
      - Might be good for ODA countries if we go for longer linac + lower power??
  - Most RTT devices are a standard size
    - Reducing linac length (higher shunt impedance) does not reduce device size
    - Increasing linac length will increase device size
- RF power source
  - Depends on choice of RT energy range
    - Low-energy (4-6 MeV): Magnetron c. 2 MW
    - High-energy (6-25+ MeV): Klystron c. 5-7.5 MW