# Electron Gun for Radiotherapy Treatment (RTT) System

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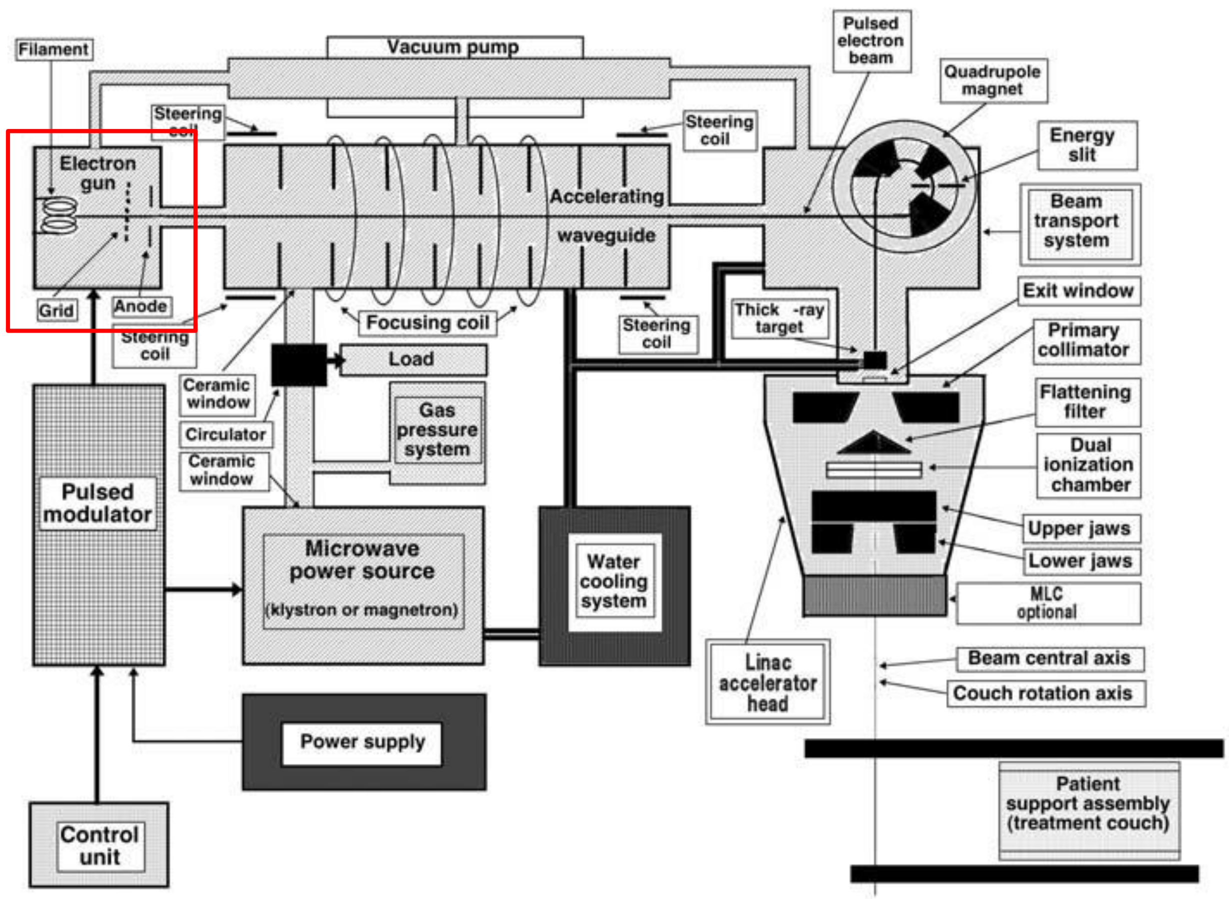
# Outline

- Medical and beam specifications of RTT accelerator
  - Derived electron gun specifications
- Operation modes of the electron source
- Design of a modular electron gun
- Beam dynamics in the electron gun
- Required future work
- Conclusions

# Typical Linear Accelerator for Radiotherapy Treatment (RTT)




**TREATMENT MACHINES FOR EXTERNAL BEAM RADIOTHERAPY**

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# Specifications for the RTT Accelerator

- Medical parameters
  - Radiation dose – 600-800 cGy/min (TBC)
  - Average X-ray energy – 3 MeV
- To achieve these medical specifications the accelerator should provide following beam parameters:
  - Average current – 75 µA on the X-ray target (TBC)
  - Electron beam energy – 6-8 MeV (TBC)
  - Beam spot diameter on the target (FWHM) – 1-3 mm
  - Beam time structure – pulsed
- Robust and highly reliable
- Need considerations for
  - Cost, procurement, infrastructure, operation and maintenance

# Basic Specifications of the Electron Gun

- RF accelerator cannot operate in Constant Wave (CW) regime due to high thermal load of the RF power in the accelerating structure, it operates in pulsed mode.
  - Pulse repetition frequency typically varies up to 300 Hz and is used as a knob to change required radiation dose.
    - For 75 µA on X-ray target this translates to pulse charge of 0.25 µC
  - Pulse duration is typically defined by heat load on the X-ray target and RF structure, but typically does not exceed 5 µs.
    - Thus average pulse current on the X-ray target could be possibly reduced up to 50 mA (TBC with further studies).
- Electron gun of the RTT accelerator is typically based on grid-modulated thermionic cathode and should provide electron pulses with the current and duration enough to meet general RTT accelerator specifications

# Operation Modes of Electron Gun

- Electron gun can operate in two possible modes:
  - **Pulsed mode** – convenient scheme when gun generates electron pulse with the length equal to the duration of the linac RF pulse which is captured by the linac with a typical efficiency of 50% or less.
    - So gun average pulse current needs to be more than **100 mA**
  - **Train-pulsed mode** – more advance technology widely used in scientific linear accelerators. In this scheme the gun delivers a train of short electron pulses with a repetition rate of the main linac frequency or its subharmonic. Capture efficiency of these trains is close to 100%
    - So gun average pulse current could be reduced between **50 mA – 100 mA** (need further studies to confirm this number).
- Electron gun voltage is defined by available low cost high voltage technology and rarely exceeds 25 kV.

# Disadvantages of Pulsed Operation Mode

- Large energy spread of the beam at the exit of the linac
  - Difficult to obtain small beam size
  - Difficult to transport the beam to the X-ray target
  - Relative Low efficiency of X-ray generation
- Low capture efficiency at the linac
  - Significant loss of electrons at injection to the linac
  - Loss of electrons during acceleration leading to parasitic X-rays increasing shielding requirements
  - Requires higher average pulse current from the cathode and HV power supply

# Challenges of Train-Pulsed Mode

- Maximum grid modulation frequency – now up to 3 GHz
- High cathode peak current
  - Material with higher emissivity
  - High temperature of the cathode
  - Higher requirements for the vacuum in the accelerator
- Synchronisation of the linac RF and grid modulation RF
- Some additional R&D are required
  - Optimisation of the micropulse length to obtain higher beam quality on the X-ray target
  - Simulation of the micropulse lengthening/deformation in the gun on the way to the linac
  - Optimisation of the modulation pulse length and cathode diameter to obtain beam with required parameters

# Example of Train-Pulsed Gun Specifications

Typical grid modulated 8 mm dispenser thermionic cathode used in scientific accelerators:
$I_{max}$= 3 A

| S-band linac | | |
|---|---|---|
| | | |
| *Target average current, μA* | | 75 |
| *Macropulse repetition rate, Hz* | | 300 |
| *Macropulse duration, μs* | | 5 |
| *Grid modulation frequency, GHz* | | 3 |
| *Micropulse charge, pC* | | 16.5 |
| | | |
| *Micropulse duration, ° of S-band linac RF* | *Micropulse duration, ps* | *Micropulse current, A* |
| | | |
| 10 | 9.26 | 1.80 |
| 20 | 18.52 | 0.90 |
| 30 | 27.78 | 0.60 |
| 40 | 37.04 | 0.45 |
| 60 | 55.56 | 0.30 |
| No modulation at caption efficiency 50% | | 0.10 |
| | | |



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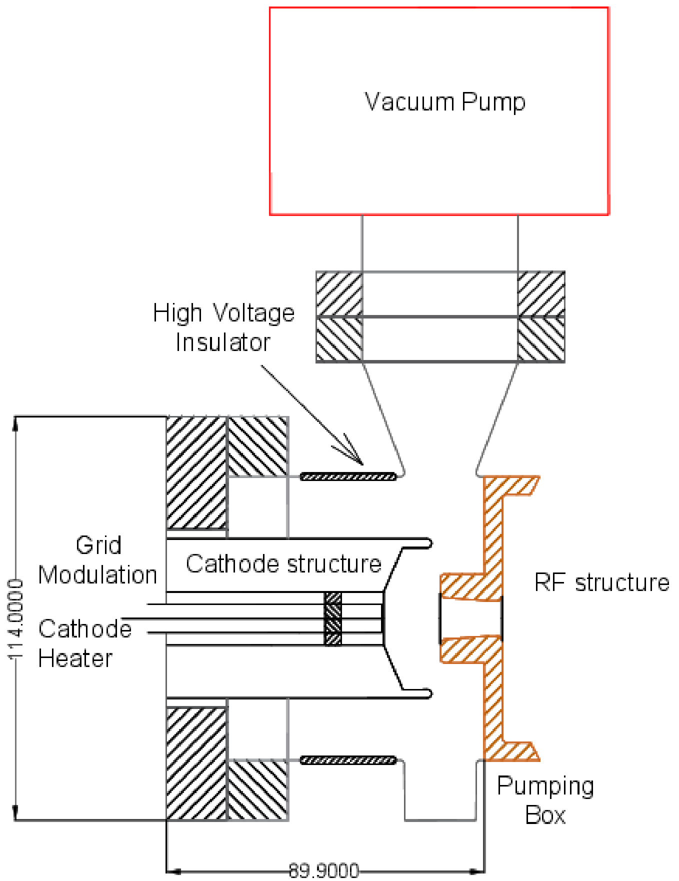
# Modular Approach to the RTT Accelerator

- For operation in challenging environment, the accelerator should have high reliability
- Repair of the failed accelerator components should be cheaper and faster
- Consider modular design of the accelerator from simple and relative cheap components available from more than one manufacturer
- Least reliable components in the gun are cathode and vacuum pump
- We propose to implement two flange gun design based on standard cathode and vacuum pump.

# Modular Design of the RTT Electron Gun




Grid modulated 8 mm Ir coated cathode JRC NJK2221.

$J_{max}$=10 A/cm$^2$

$I_{max}$= 5 A

# Vacuum Design of the Electron Gun

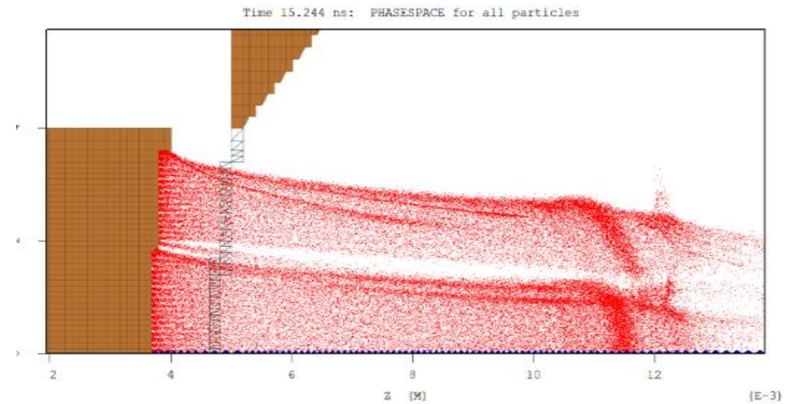
- Assumptions
  - Pre-pumped using mobile pump cart to **~ $1 \cdot 10^{-6}$ mbar.** All surfaces exhibit typical UHV characteristics (copper, stainless steel, aluminium etc.)
    **Q ~ $1 \cdot 10^{-9}$ mbar·l/s/cm$^{-2}$**
  - Satisfactory outgassing can be achieved through bakeout AND/OR pre-bake of components and 'clean' assembly along with sufficient pumping time
  - Fast response over-pressure trips can be set reliably to protect main pumps
- Outline Design
  - Pump connected through 70mm (knife edge) flange with conductance **C~ 150 l/s**
  - Therefore the Max effective pumping speed possible is **$S_{eff}$ ~ 150 l/s**
  - Selection of **Sputter Ion Pump** – Star Cell or Noble Diode due to likely presence of non-getterable gases (vacuum interventions and leaks). Generic Pump e.g. Agilent VacIon Plus (Star Cell) OR Gamma Vacuum TiTan (Triode)

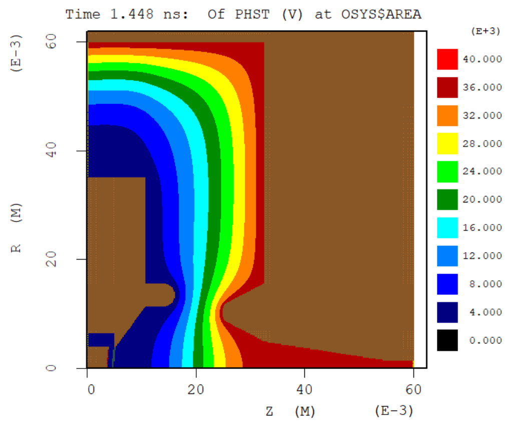
| Generic Pump Size, l/s | $S_{eff}$ l/s | Pressure, mbar | Area, cm$^2$ |
|---|---|---|---|
| 150 | 75 | $1 \cdot 10^{-8}$ | 750 |
| 100 | 60 | $1 \cdot 10^{-8}$ | 600 |
| 75 | 50 | $1 \cdot 10^{-8}$ | 500 |
| 40 | 40 | $1 \cdot 10^{-8}$ | 400 |

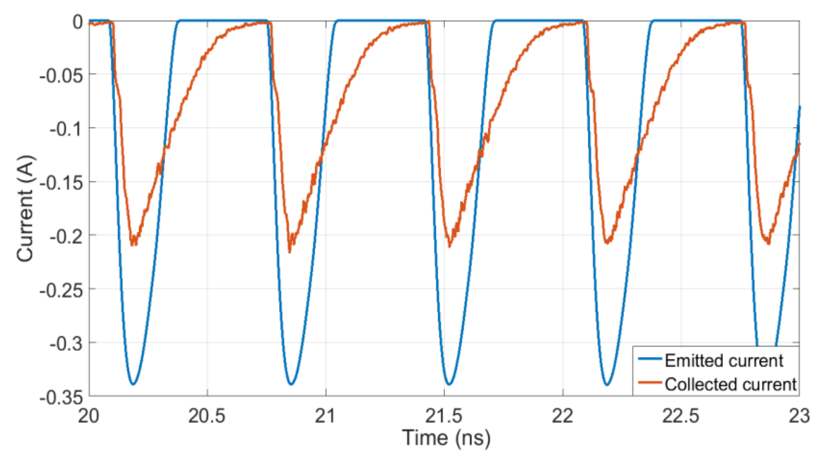
# Beam Dynamics in the Train-Pulse Gun

A modular, grid modulated DC thermionic electron source is proposed to use which may operate in two modes:

- Macro-pulse modulation when source emits the beam during whole macropulse
- Micropulse modulation when source injects the beam by short, 10's ps-length bunches




Beam dynamics simulations have been carried out at the University of Strathclyde using the MAGIC PIC code specifically to design the RF gun.

# Conclusions

- Specifications of electron guns for the RTT linacs have been derived and possible options to meet these specifications are proposed.
- We have established tools/techniques and analysis methods which can be tailored to the final specifications as they develop.
- The proposed scheme of modulated gun allows:
  - Higher capture efficiency
  - Reduced beam loses → reducing parasitic X-ray background
  - Electron beam with low energy spread
  - Increased production of X-rays at the same average beam current
- Still to be done:
  - Detailed start–to–end simulations to optimise electron gun and linac design
  - Explore possibilities to prototype and test this concept.

# Tasks & Status of Development of the Electron Gun

| *Item* | *Contents* | *Current status* |
|---|---|---|
| Beam parameters specifications | - Derived from earlier workshops. Can be changed if different as project progresses. | In progress – 75% completed |
| Beam dynamics simulation in the electron gun | To chose optimal:<br>- Gun operation mode (pulsed or train-pulsed)<br>- Gun modulation frequency<br>- Gun voltage<br>- Cathode parameters (bunch charge, bias and modulation voltage) | In progress – 25% completed |
| Start-to-End beam dynamics simulation in the accelerator | - Beam parameters at the entrance of the accelerating structure<br>- Geometry | In progress – 25% completed |
| Vacuum design of the electron gun | - Specification of the vacuum requirements<br>- Selection of the pumping technology<br>- Selection of the pump | In progress – 25% completed |
| Mechanical design of the electron gun prototype | - Mechanical design<br>- Integration of the source into diagnostic facility | Not started |
| Construction and characterisation of the prototype | - Characterisation of the beam parameters at the entrance of the accelerator structure (beam profile, bunch length etc.) | Not started |

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  - Dr. Shadike Saitiniyazi - Lancaster University /CI
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  - Dr. Lex van der Meer – Radboud University, Nijmegen, NL

# Thank you for your attention!

# 3 GHz 600 mA Train-Pulsed Gun for FLARE FEL

FLARE gun

Grid modulated cathode

Modulation cavity

*Courtesy of Dr. Lex van der Meer, Radboud University, Nijmegen, NL*

# A Bit of Accelerator Arithmetic

- At X-ray target average current $< I > = 75\mu A$ and beam energy $E = 8\ MeV$ average beam power $< P > =< I > E = 600\ W$
- As linac operates in pulsed mode at a pulse repetition rate, for example, $F = 300\ Hz$ every pulse brings electron charge $Q_p = {}^{<I>}/_{F} = 0.25\mu C = I_p \tau_p$, where $I_p$ and $\tau_p$ average pulse current and duration of the pulse respectively
- For a pulse duration $\tau_p = 5\ \mu s$ it gives $I_p = 50\ mA$
- Value $\eta = F\tau_p$=1.5·$10^{-3}$ is called Duty factor
- Power of the individual beam pulse $P_p = EI_p = {}^{<P>}/_{\eta} = 400\ kW$
- For gun:
  - Operating in the pulsed mode pulsed cathode current $I_c = {}^{I_p}/_{\zeta} \geq 100\ mA$, where $\zeta \leq 0.5$ – caption efficiency
  - Operating in the train-pulsed mode with conduction angle $\theta_0 = 30°$ peak cathode current $I_{cp} = I_p\ {}^{360}/_{\theta_0} \geq 600\ mA$