THERMAL LOADS OF WIRE-BASED BEAM INSTRUMENTATION AT ION LINACS

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Abstract

Wire-based beam instrumentation remains a reference for calibration of many other instruments, providing direct and accurate measurements with high resolution. However increasing of a beam power of existing and forthcoming ion linacs results in strict constraints on operation modes acceptable for control and diagnostics. Relevant simulations of wire thermal loads are necessary not only for a mode choice, but also for a preliminary design of such instrumentation. Simulations for different wire materials and various beam parameters are made. Features of the model are discussed. Numerical estimations and conclusions are presented in comparison with some experimental results.

INTRODUCTION

Beam ionization losses are the main target heating mechanism at ion linacs. In wire-based instrumentation excessive heating may cause different problems. Firstly, temperature increase results in rise of thermionic emission, that makes additional electric noise, and accuracy in case of secondary emission based measurements goes down. Secondly, overheating can change metal structure of wire or result in wire breakage. Moreover, thermal expansion affects accuracy.

MODEL

Calculations were done using finite elements analysis in COMSOL Multiphysics package. For the computing geometrical mesh with 1/10 of wire radius in cross-section and 1/50 of wire length in longitudinal direction was chosen.

Temperature dependences of thermal conductivity, heat capacity and total hemispherical emissivity of wire material are taken into account (Figs. 1-3).

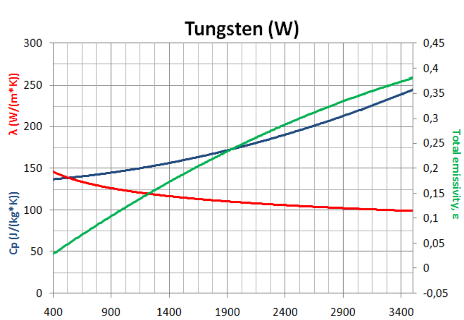

Figure 1: Thermal properties of tungsten.

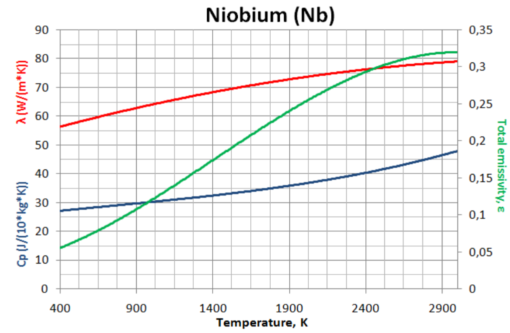

Figure 2: Thermal properties of niobium.

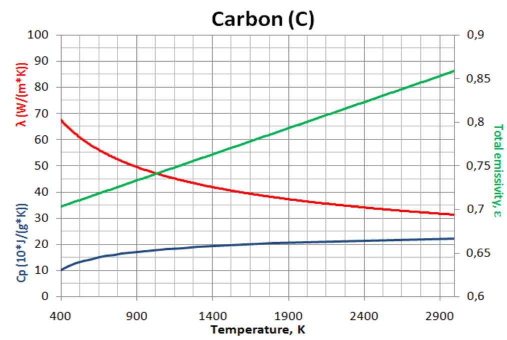

Figure 3: Thermal properties of carbon.

Ambient temperature and initial wire temperature assumed to be 293 K. Considering wire holder being well thermal conductive, boundary conditions can be set as constant temperature 293 K at the wire edges.

Beam is described by: ion parameters, energy, pulse current and duration, pulse repetition frequency, RMS transverse sizes. The wire center supposed to be in the beam center. Function of ionization losses of projectiles are taken from SRIM tables [1]. Volume density of ionization losses (Fig. 4) in the wire is used further as a heat source.

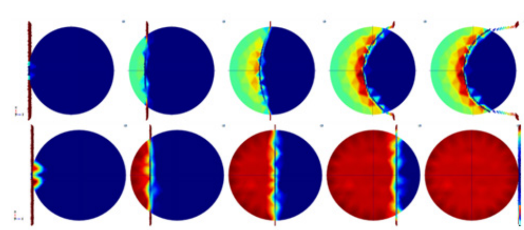

Figure 4: Density of ionization losses for low-energy and high-energy proton beam across the tungsten wire.

The most results are given for tungsten wire with diameter d=100 um in proton beam with RMS size 2x2 mm, unless otherwise specified.

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COOLING BY DELTA-ELECTRONS

One of the possible cooling effects is delta-electrons producing [2]. Delta-electrons are knocked out of wire material and can take away a part of deposited energy of ionisation losses.

Total energy of escaped electrons as well as total energy of ionisation losses was calculated in different cases using self-made code. It was estimated that for low-energy beams cooling effect due to delta-electrons is very small. But for thinner wires this effect increases (Fig. 5): delta-electrons need less energy to reach wire boundary and leave the material.

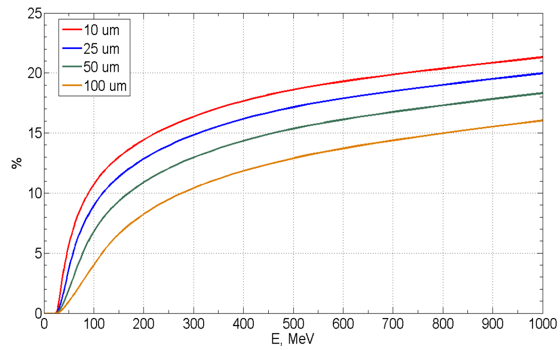

Figure 5: Percentage of deposited proton beam energy removed by delta-electrons for tungsten wires with different diameter.

For tungsten, carbon, and niobium wires results are quite similar (Fig 6). Therefore modeling of wire heating in proton beams with energy less than 100 MeV can be made without considering cooling by delta-electrons at all in order to simplify the model. For higher energy beams this percentage is included in model as a factor in heat source.

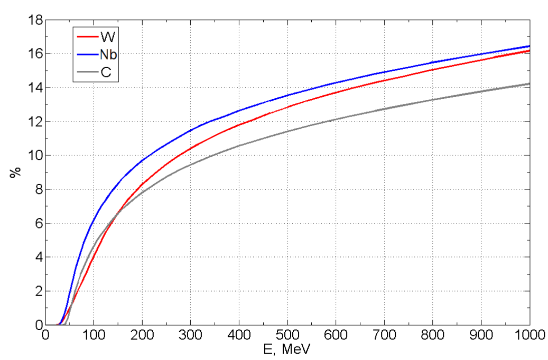

Figure 6: Percentage of deposited proton beam energy removed by delta-electrons for different wire materials.

RESULTS

According to calculations, dependence of maximum wire temperature on beam pulse current, duration and RMS transverse size can be determined as $T \sim \left(\frac{I_{current} \cdot \tau_{current}}{RMS_x \cdot RMS_y}\right)^a$, where index a takes on value between 0.3 and 0.6 (Fig. 7).

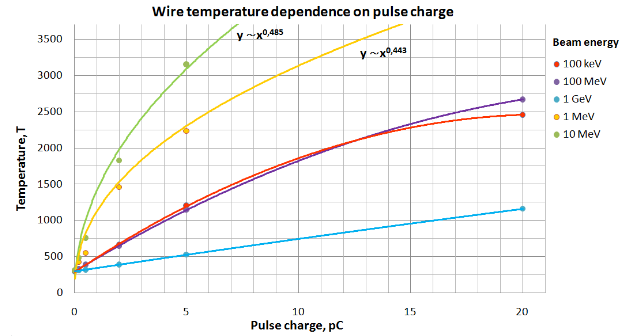

Figure 7: Wire maximum temperature dependence on beam pulse charge.

Choice of wire material and diameter is crucial for preliminary design of beam instrumentation. Materials with high melting point should be chosen for wires. Besides, material atomic charge number is important. Therefore three typical materials can be considered: low-z carbon, mid-z niobium and high-z tungsten. Estimations for different wire materials and diameters are shown at Fig.8.

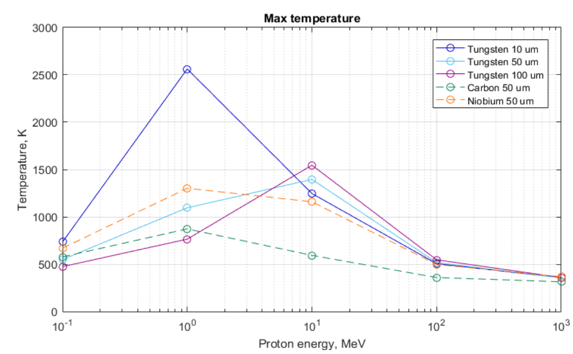

Figure 8: Wire temperature dependence on the material and diameter for proton beam 1 Hz, 10 mA, 200 us.

According to results, thin wires are heated more than thick ones for low energy beams. But for energy beams with energy more than 100 MeV, dependence on wire radius can be neglected. At high energies distribution of ionization losses becomes uniform enough heating power is proportional to d^2 as well as cooling power. Moreover, for niobium and tungsten heating is almost the same: high ionization losses in tungsten are compensated by better thermal parameters. For carbon temperature is lower for all beam energies.

Results for different ion types are given at Fig. 9.

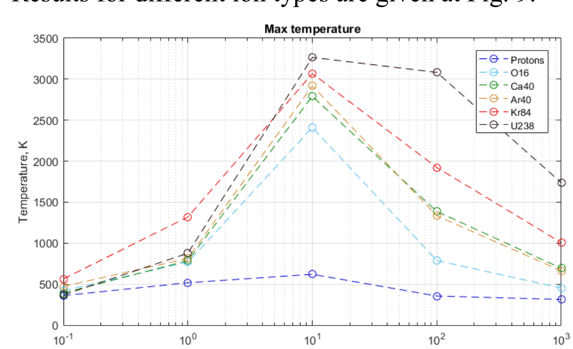

Figure 9: Wire heating for different ion types.

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For higher beam pulse frequency thermal processes don't have enough time to cool the wire between successive beam pulses, thus temperature increases (Fig. 10).

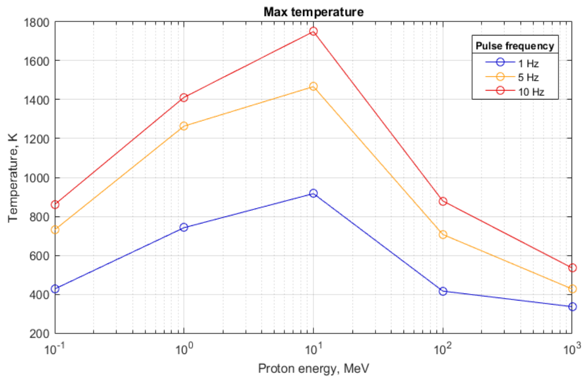

Figure 10: Wire heating for different pulse repetition frequency.

In the model pulses supposed to be debunched, because bunch repetition period is much smaller than typical time of thermal processes, therefore pulse microstructure does not matter.

The feature of wire heating model is that time steps should be inconstant: during the pulse passing through a wire time steps should be less than beam pulse duration. Beam pulse duration can be less than repetition period by several orders of magnitude. Small constant time steps require high computing resources. One of the possible ways to reduce computing time is to use average beam current as constant heating source instead of pulse current.

This approach reduces number of time steps but have an error which depends on pulse repetition frequency. An example for 10 Hz is given on Fig. 11. In this case error is about 180 K, but for the same parameters and frequency 50 Hz this error is less than 80 K. It means that approach of average current is acceptable for maximum temperature estimations for high frequency.

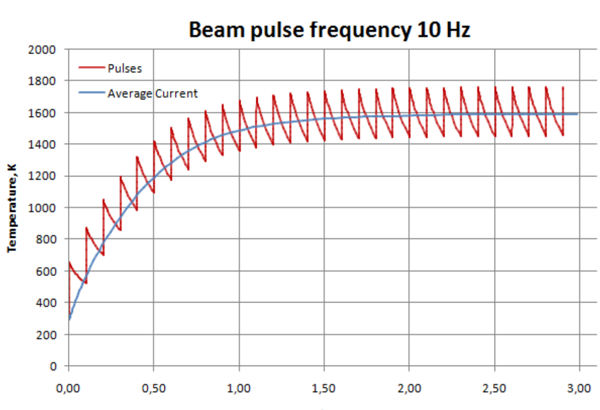

Figure 11: Heating in assumptions of average current and pulses, pulse duration and current are 100 us, 100 mA.

CONCLUSION

The model of wire heating due to ionization losses has been built. Several cooling mechanisms were considered. Less than 25 % of ionization losses energy is removed by delta-electrons for energies below 1 GeV in wide range of wire diameters. Heating rate doesn't depend on wire diameter for high energy beams. But for low energy, massive wires are more preferable in terms of heating. Low-density materials such as carbon are heated significantly less than hard metal wires. Wire temperature is proportional to beam intensity, but dependence is not linear, because thermal processes in wire are not linear.

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