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CRYOGENIC SYSTEMS STUDIES FOR THE MINERVA 100 MeV PROTON SC LINAC PROJECT

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Abstract

The construction of the first phase of the MYRRHA project (MINERVA: 100MeV-4mA proton Linac, LINear-ACcelerator) was recently decided by the Belgium Government. In the long term, the MYRRHA project plans to construct an ADS demonstrator for the transmutation of long-lived radioactive waste. It will include a subcritical reactor of 100 MW thermal power and a CW proton Linac accelerator (600MeV-4mA). The main challenge of this Linac is an extremely high reliability performance to limit stresses and long restart procedures of the reactor. The MINERVA Linac includes 30 cryomodules housing 60 Single-Spoke SC cavities. A cryomodule prototype with its valve box is under construction at IPNO institute. The cavities operate at 352 MHz in a superfluid Helium bath at 2K. Therefore, a reliable SC Linac Cryogenic System is essential. This article presents the preliminary studies in this subject including the analysis of high thermal loads induced by the CW mode operation of cavities (950 W@2K per cryomodule). A Cryogenic Refrigerator with an equivalent power capacity of 2645 W @4.5 K (3970 W with 1.5 overcapacity factor) is proposed. The constrains for the He distribution in the Linac tunnel are also discussed.

INTRODUCTION

The MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) [1] project is the first European prototype a nuclear reactor driven by a particle accelerator, i.e. Accelerator Driven System (ADS). It is proposed by SCK•CEN and it will be installed at Mol, Belgium. This project aims to demonstrate the feasibility of large-scale transmutation. The linear accelerator will provide a 600 MeV proton beam in continuous wave (CW) mode and a current of 4 mA coupled to a 100 MWth subcritical reactor with keff=0.95. In order to maintain the fission chain reaction, it must be continuously fed by an external neutron source: a particle accelerator associated to an internal spallation target. The main challenge of this Linac is an extremely high reliability performance to limit stresses and long restart procedures of the reactor.

The phase 1 of MYRRHA project, also called MINERVA (MYRRHA Isotopes productioN coupling the linEaracceleRator to the Versatile proton target fAcility), has been supported by the Belgium Government in 2018. This phase includes construction of 100 MeV proton Linac with a current of 4mA presented in Figure 1. It is composed of an injector, a section of copper cavities section operating at room temperature, followed by 30 cryomodules housing 60 Single-Spoke SC cavities powered by RF couplers and operating at 2K. Thus, it requires a liquid He distribution system providing reliable conditions for CW Linac.

In this paper we present the preliminary studies in this subject including the analysis of high thermal loads induced by the CW mode operation of cavities, an equivalent power capacity of a Cryogenic Refrigerator and the He distribution system. This work follows the previous studies presented earlier [2] and based on recent experimental results and building plans for MINERVA accelerator.

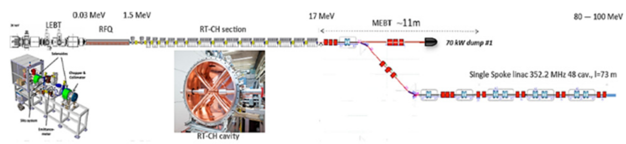

Figure 1: MINERVA LINAC.

CRYOGENIC PARAMETERS OF MINERVA LINAC

Single Spoke Cavities and RF Power Couplers

The design of the Single Spoke cavity has been performed by the Institut de Physique Nucléaire d'Orsay (IPNO), Orsay, France, the main parameters are presented in Table 1. The two first prototypes have been constructed and tested using different preparation and conditioning techniques in 2016-2017. Both prototypes exhibit excellent performances [3] giving an important margin with respect to the MINERVA cryogenic specifications. Two additional prototypes were also procured in 2018.

Table 1: Spoke Cavity Parameters for MINERVA Linac

Parameter	Value
Optimal β	0.375
Frequency	352.2 MHz
Nominal E_{acc}	6.4 MV/m
Q_0	$2 \cdot 10^9$
P_{cav}@ 2K	8.9 W

A new model for RF power couplers has been proposed by the LPSC Grenoble Laboratory and several prototypes are under manufacturing. The RF coupler requires an optimized cooling system to handle a temperature gradient from 2K, cavity coupler port to room temperature at the cryomodule RF connecting port. It is based on two thermal intercepts at 10K and 60 K at defined distances from a coupler window. These thermal intercepts will be connected and cooled by the refrigerator stages at 4.5 K and 40 K.

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General Heat Loads

Heat losses are generated by the SC Linac components such as cavities, couplers, cryostats, valve boxes, transfer lines, etc. These losses are produced at different levels of temperature (2K, 4.5K, 10K, 40K, 60K). Due to the beam operation in CW mode, the dynamic RF losses are largely dominant compared to other SC Linac, operating in pulsed mode with beam duty cycle of only 5 %. The initial evaluation of heat loads for the Spoke SC Linac is presented in Table 2.

Two prototypes produced in 2018 shown excellent $Q_0 > 2{\cdot}10^{10}$ at low field at 2 K. This recent experimental result could allow interesting optimization of the cryogenic power required by the MINERVA. Adopting a High Field (6.4 – 8.3 MV/m) Q_0 of $5{\cdot}10^9$ will reduce the RF dynamic losses at 2K to: 3.74 W per cavity. This reduction leads to Total Heat Losses (including couplers and static losses of 30 cryomodules) at nominal conditions of 614 W, to be compared to 950 W from Table 2.

Table 2: Heat Loads and Cryogenic Power for MINERVA

	Heat losses [W]	T [K]	Equiv. Cryo Power @4.5K [W]
Cryomodules	950	2	2156
Couplers level 1	180	10	180
Couplers level 2	540	60	54
Thermal shields	2550	40	255
Total:			**2645**

CRYOGENIC REFRIGERATOR REQUIREMETNS

In order to define the cryogenic refrigerator size, all the losses are normalized as well to 4.5 K and presented in Table 2. The total equivalent cryogenic power is **2645 W @ 4.5 K.**

An "overcapacity margin" should also be considered. It includes uncertainties in the heat loads estimations, SC cavities defects in production and preparation, and the possibility to enhance cool-down speed. It was proposed a margin factor of **1.5** and consistent to estimations of other projects: 1.33 for Spiral 2 [4] and 1.5 for ESS [5] and for LHC [6]. This gives to the Cryogenic Refrigerator Power for MINERVA of **2645W × 1.5 =3970 W @ 4.5 K.**

The Electrical Power consumption of the Cryogenic Refrigerator is estimated by adopting a Figure of Merit (FoM) of the theoretical thermodynamic efficiency (Carnot Coefficient of Performance COP). This FoM depends on the refrigerator size and the adopted refrigeration cycle. For example, ESS with a Cryogenic Refrigerator Power of 9.5 kW @ 4.5 K, proposes a FoM of 0.26, leading to a conversion factor of 250 W/W. Thanks to similarity of ESS and MINERVA projects, it is proposed to use also a conversion factor of 250 W/W. The corresponding Electrical Power Consumption in this case would be 250W/W×3970 W= 990 kW. Compared to an ideal Carnot coefficient of 65.6 W/W, it represents an efficiency of 26.3 %.

An Exergy Analysis for MINERVA, extrapolated from ESS studies gives:

- 53 % (525 kW) Room Temperature compressors
- 47 % (465 kW) Cold box:
  - 26 % (260 kW) Heat Loads in 4.5 K and 2 K circuits and Thermal Shields
  - 21 % (209 kW) Irreversibility, Dissipation in Turbines, Heat Exchangers, Cold Compressors, Valves

CRYOGENIC DISTRIBUTION

A cryogenic process scheme (Figure 2) is proposed for the MINERVA facility with main components:

- Gas storage
- Room Temperature Compressors with purifiers and oil removing systems
- 4.5 K cold box, including all heat exchangers, turbine expanders and cold compressors
- Cryomodules (cavities) with associated Valve Boxes (heat exchangers and cryogenic valves)

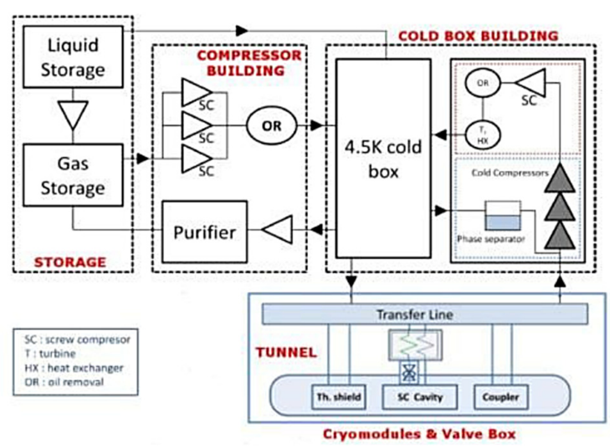

Figure 2: Schema of cryogenic refrigerator configuration.

This scheme is based on a "distributed subcooling system" concept. The main cold box produces super-critical He (i.e. 4.5 – 5K, 3 bars) for cavities and couplers. Each cryomodule is associated to a cryogenic interface (Valve Box) incorporating the subcooling heat exchanger to reduce the temperature and the Joule-Thomson valve to expand and obtain the nominal He bath at 2 K and 30 mbar.

The initial installation of the Cryogenic Plant main components is presented in Figure 3. Based on the preliminary Balance of Plant (BoP) studies for MINERVA facility, 4 areas (Rooms) have been defined to host all cryoplant and SC Linac components:

1. Linac Tunnel (30 Cryomodules with associated Valve Boxes)
2. Cold Box Room (24 × 23 m) including also a LHe Dewar

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3. Tunnel between the Cold Box and the Transfer Line running along the Linac Tunnel
4. Room Temperature compressors (24 × 23 m) including all associated He gas purifiers4
5. Tunnel between the Cold Box and the RT compressors (distance ~ 25 m)
6. A He gas Storage area (24 × 8 m)

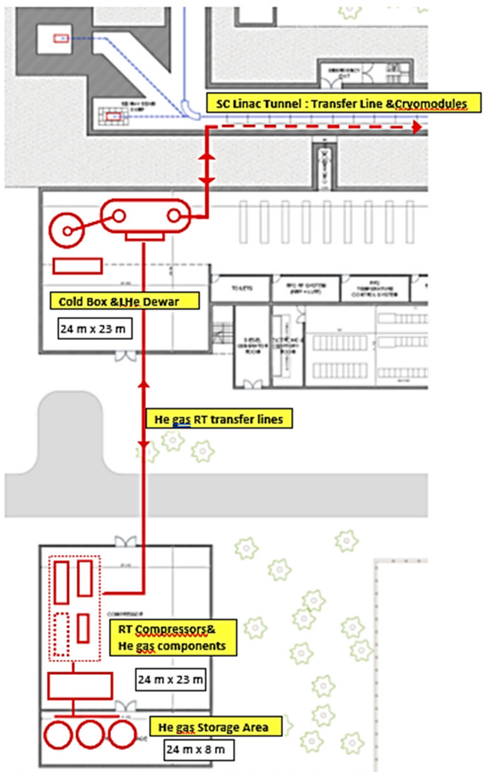

Figure 3: Schema for MINERVA Linac and cryogenic plant buildings.

An initial 3D model showing several cryomodules and associated valve boxes in the Linac tunnel is presented in Figure 4. The connection to the cryogenic line running along the tunnel is shown in Figure 5.

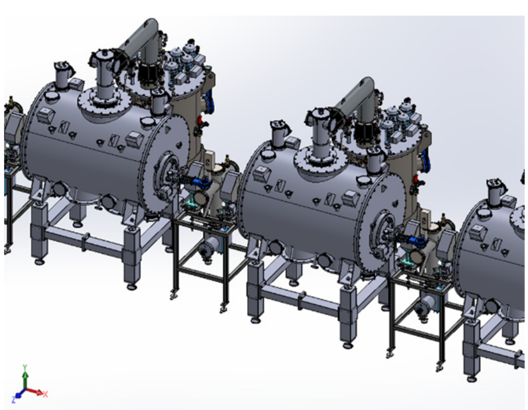

Figure 4: Sequence of MINERVALINAC Cryomodules connected to valve boxes.

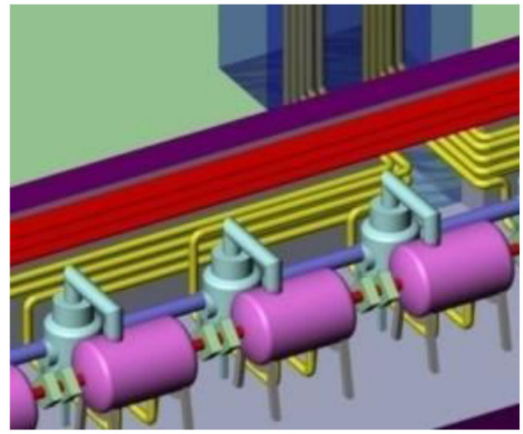

Figure 5: View of the SC Linac tunnel.

CONCLUSION

In this paper we discussed cryogenic system of future MINERVA 100 MeV SC Linac. The presented preliminary studies include the analysis of high thermal loads of 950 W@2K or 2156@4.5Kper cryomodule induced by the CW mode operation of cavities. A Cryogenic Refrigerator with an equivalent power capacity of 2645 W @4.5 K (3970 W with 1.5 overcapacity factor) is proposed. The He distribution system in the Linac tunnel and their main components are also presented.

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