POWER CONVERTERS FOR PARTICLE ACCELERATORS – ESS EXAMPLES

As a prelude to the Senior elevation meeting in Lund a cutting-edge lecture concerning the ESS project was presented by our IEEE member Carlos A. Martins
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Introduction to ESS

The European Spallation Source (ESS) is a multi-disciplinary research facility in the field of materials science currently under construction in Lund, Sweden [1]. Fig. 1 shows an artistic view of the ESS facility campus once completed by 2020.

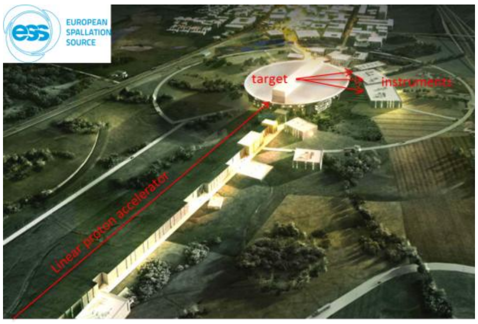


Fig. 1: Artistic view of the future ESS facility

The spallation process will require the construction of the world most powerful Linear proton Accelerator (Linac, Fig. 2) [2]), which will accelerate a beam of protons for a time duration of 2.86ms (beam pulse length). A beam pulse repetition rate of 14 pulses per second is required. Each beam pulse will achieve acceleration energies up to 2 GeV once projected against a rotating tungsten target, representing an average beam power of 5 MW. The neutrons, generated by the interaction of the proton beam against the target will be guided through neutron guides from the target to the instruments halls containing the materials' samples to be analysed.

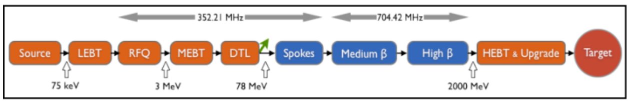


Fig. 2: ESS linear accelerator layout.

FUNDAMENTALS OF PARTICLE ACCELERATION AND THE ROLE OF ELECTRICAL ENGINEERING

The force acting into a charged particle is given by the Lorentz equation below:

$$\vec{F} = q\vec{E} + q(\vec{v} \, x \, \vec{B})$$

From this equation, it is clear that the basic principle of force generation leading to particle acceleration relies in adequate electrical and magnetic fields ($\vec{E}$ and $\vec{B}$ respectively), both quantities being intrinsically linked to the electrical and electronics engineering disciplines.

Linear acceleration

The first term of this equation ($\vec{F_1} = q\vec{E}$), defines an acceleration force collinear with an electrical field which will create a linear acceleration in the same direction of both the force and the electrical field. Modern accelerators use a succession of metallic electrodes with AC electrical voltages applied between these in order to create the electrical fields with intensity and polarity synchronized with the passage of the particle bunches through the gaps formed by each pair of consecutive electrodes (Fig. 3).

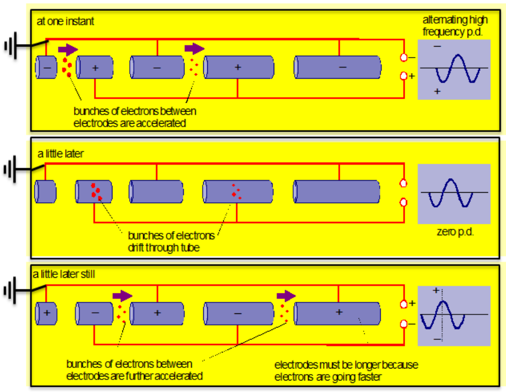
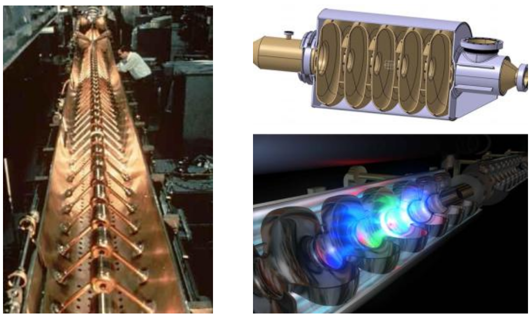


Fig. 3: Principle of linear acceleration in modern particle accelerators.

The metallic electrodes are enclosed by metallic cavities, which in turn are excited by Radio Frequency (RF) generators, like tetrodes or klystrons. Such RF generators/sources need to be supplied with High Voltage (HV) power converters, historically called "modulators".

Different shapes of electrodes can be utilized inside the RF cavities:- cylindrical tubes; elliptical cells (Fig. 4); etc.



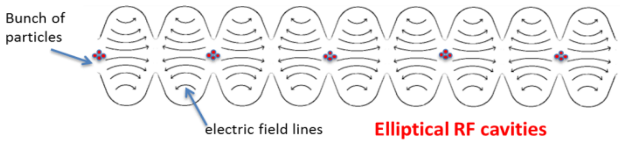


Fig. 4 (top-left): RF cavity tank partially opened with cylindrical tube electrodes. (top-right and bottom): RF cavity tank cut view with elliptical electrodes.

Fig. 5 shows multiple drawings of a typical RF generator (klystron) used to power the RF cavities of the ESS accelerator.

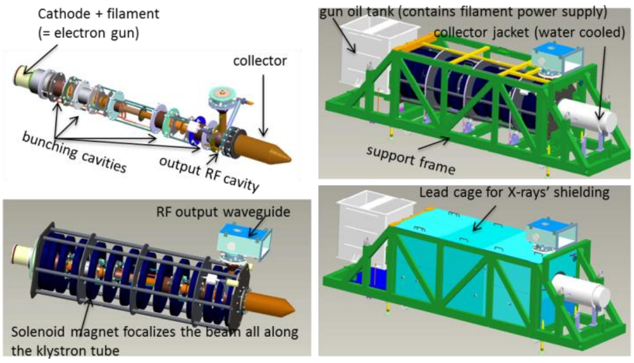


Fig. 5: Different views of a klystron rated for 704MHz / 1.6MW during assembling.

Klystrons (invented in 1936) and RF cavities are conventional pieces of equipment which in the case of ESS do not constitute a technological breakthrough with respect to other similar accelerators. The same does not apply to the power converters (modulators) that will supply the klystrons with HV pulsed power, derived from a conventional 3-phase low voltage AC electrical network. Indeed, such modulators with ESS parameters and performance requirements did not exist in the market and had to be developed from scratch.

Centripetal acceleration

The second term of the Lorentz equation ($\overrightarrow{F_2} = q(\vec{v}\ x\ \vec{B})$), defines a centripetal acceleration with respect to the direction of movement of the particle. This type of acceleration will create a deflection of the particle movement once it passes through a region with a magnetic field. Such deflections can be used for bending, focalizing or steering the beam on a longitudinally axis in order to control its trajectory. Such magnetic fields can be created by different types of magnets with air gaps where the particle beam is passing through (dipoles, quadrupoles, sextupoles, octupoles, solenoids). In some cases, such magnets can be permanent magnets but more often they are electromagnets, i.e. with a winding system wounded around a magnetic yoke fed from a current source (Fig. 6).

Fig. 6: Different types of electromagnets (left: dipole; centre: quadrupole; right: corrector)

Such electromagnets are supplied by electronic power converters that regulate the current through the windings (and indirectly the magnetic fields) with high accuracy (Fig. 7). Some of these power converters might be DC (1-quadrant); others might be pulsed (2 or 4-quadrants) for energy saving reasons.

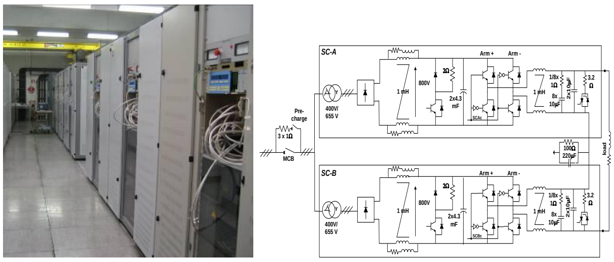


Fig. 7: Example of 4-quadrant power converters used to supply electromagnets.

In the case of ESS accelerator, a total of about 150 RF cavities are needed (124 powered by klystrons, 26 powered by tetrodes). A total of 33 klystron modulators are needed to supply the klystrons and 26 tetrode modulators are required to supply the tetrodes.

Furthermore, a total of about 350 magnets, with the same number of magnet power converters, are needed to bend, focalize and steer the beam from the proton source until the target, all along the 500 meters of the ESS Linac.

DEVELOPMENT OF KLYSTRON MODULATORS FOR ESS

In order to save costs, improve performance and reduce the footprint of the RF Gallery, largely influenced by the klystron modulators, ESS has decided to launch an internal R&D project in collaboration with Lund Technical University (LTH) in view of the development of modular high power modulators able to power up-to 4 klystrons in parallel, each rated for1.6MW RF.

These requirements translate into an electrical pulsed power of 11.5MW to be delivered by each modulator and an average power, absorbed from the AC grid, of 660kVA. Fig. 8 shows a 3D drawing of the klystron modulator developed by ESS and LTH.

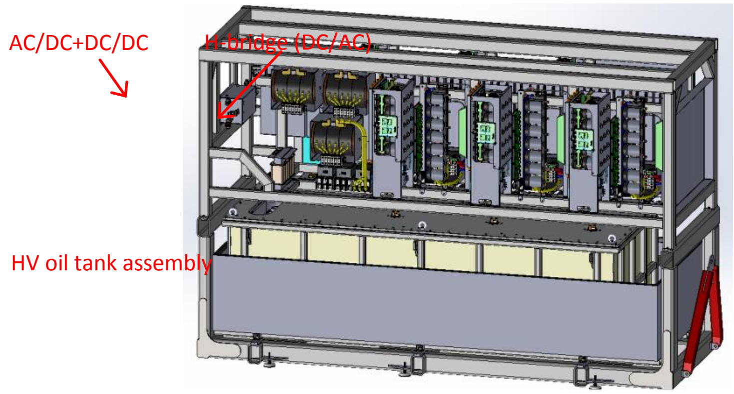


Fig. 8: 660kVA ESS/LTH klystron modulator layout

REFERENCES

1) ESS website: https://europeanspallationsource.se
2) Peggs, S. Et al.,"*ESS Technical Design Report 274-V15*", European Spallation Source publication, April 2013: http://eval.esss.lu.se/cgibin/public/DocDB/ShowDocument?docid=274