Chapter II.15

High-power proton linacs

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High-power proton linacs are envisaged as drivers for numerous applications, such as neutron spallation sources for condensed matter study, neutrino factories, muon colliders, hybrid systems for transmutation or energy production, production of rare isotope beams for nuclear physics studies, etc. These linear accelerators are intended to deliver proton beams of up to several MW and tens of MW power and operate with CW or pulsed high-intensity beams. In the rest of this chapter, these accelerator types will be discussed with a focus on one or two projects as examples to demonstrate the building blocks of accelerators and their applications.

II.15.1 Introduction

Let us start by looking at the needs of human beings. Starting from the most basic needs, our species needs air and water, clean of course, and food, and here we are not talking about a five-course meal in a 3-star Michelin restaurant and a place to live amongst others. On the next level of the pyramid, the needs are more fundamental like safety, security, and sources of energy to name a few. The cognitive development, sciences, and knowledge stand on the top of this pyramid. It will be shown that the accelerators are being developed to address these needs, on all the three levels which were mentioned here; while accelerators like LHC (Large Hadron Collider) [1], or GANIL (Grand Accélérator National d'Ions Lourds) [2] are searching for answers on our most fundamental questions and are advancing the humanity's knowledge, facilities like ESS (European Spallation Source) [3] will be used to study life sciences and will impact the daily life. In between there are projects like MYRRHA [4], aiming to provide safer and even more sustainable solutions to energy needs. Accelerators for medical and industrial applications, not limited to high-power proton linacs are covered separately in Chapter II.16, and electron accelerators are covered in Chapter II.14. In this chapter, the scope will be limited to hadron linacs with an average power beyond at least one hundred kilowatts. Without any doubt, the Livermore RF accelerator [5] can be called the first high-power proton linac with an impressive power of 500 kW. The high-power linear accelerators operating today, e.g. SNS (Spallation Neutron Source) [6], or under construction, e.g. ESS (European Spallation Source) are aiming at several megawatts of power, see Fig II.15.1.

The concept of linear acceleration was first proposed by G. Ising in 1924, suggesting the acceleration of positive ions using spark discharges and drift tubes. However, due to limited electronic devices, Ising was unable to demonstrate his concept. In 1928, R. Widerøe successfully demonstrated the first

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CERN Yellow Reports: School Proceedings, CERN-2024-003, DOI: 10.23730/CYRSP-2024-003, p. 1795.

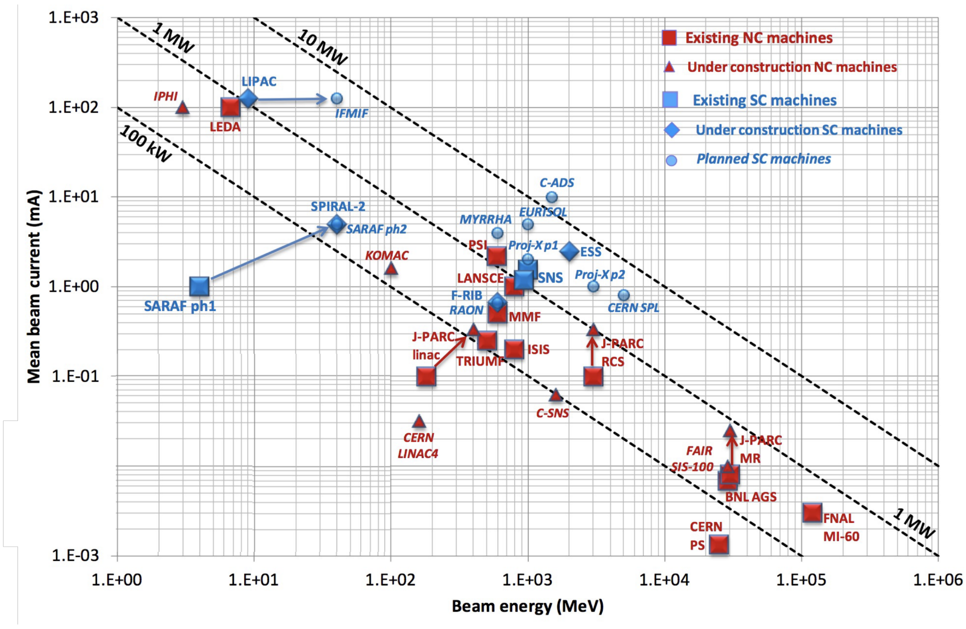

Fig. II.15.1: Energy and beam current of high-power beams (Image courtesy of Jean-Luc Biarotte).

linear accelerator by accelerating sodium or potassium ions using drift tubes connected to high-frequency waves and ground. This development paved the way for future advancements in linear proton accelerators, such as the historic Berkeley 32 MeV proton linear accelerator, which utilized the “Alvarez drift tube”. This development, incorporating the “Alvarez drift tube” and surplus 200 MHz radar components, played a crucial role in shaping the future of proton linear accelerators [7].

The introduction of the radiofrequency quadrupole (RFQ) accelerator [8], initially proposed by Kapchinskii and Teplyakov, marked a pivotal development allowing for the transition from traditional ion acceleration methods like Cockcroft Walton generators. This allowed acceleration of very low energy, but high current ion beams in the 100 mA range. RFQ technology, as depicted in Fig. II.15.2, stands out for its efficient acceleration and azimuthally-symmetric focusing of low-energy ion beams through the use of RF fields, eliminating the need for long transport sections and the limitations imposed by space charge forces characteristic of earlier systems. The RFQ employs strong electrostatic focusing within a narrow channel. The variation in electrode geometry within the RFQ generates changes in both transverse and longitudinal electric fields across the device. As a result, it transforms an incoming DC steady-state beam, simultaneously accelerating and bunching it, all while focusing the beam transversally. Notably, the successful implementation of RFQs has led to remarkable advances in the design and performance of the accelerators, such as progressing from sub-MeV to several MeVs injection enerrgies to DTL or other low energy RF structures.

II.15.2 Applications of high-power hadron accelerators

Hadron linacs, with their capacity to accelerate charged particles, mainly protons and then deuterons and heavier ions, to high energies, have a diverse range of applications. The high-power hadron accelerators play a pivotal role in the exploration of particle physics, enabling scientists to investigate the fundamental building blocks of the universe, they are integral components in the production of intense secondary

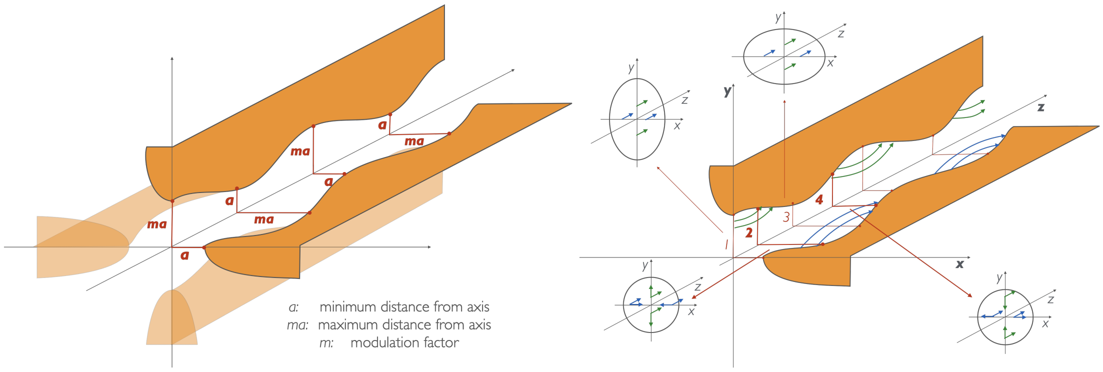

Fig. II.15.2: Schematics of the electrode shape and fields in an RFQ.

particle beams used for a wide range of scientific experiments, and they also drive advancements in materials science, non-destructive testing, and nuclear physics, they offer solutions to both the nuclear waste problem and offer an even safer fission based energy-source. Furthermore, hadron linacs, not necessarily high-power, are invaluable in the field of cancer therapy, delivering precise and powerful proton beams for tumor treatment, making them indispensable tools in shaping our understanding of the physical world and improving the quality of life for countless individuals. We will have a look at a couple of facilities as examples of the applications and the systems used to achieve this. However, we intentionally exclude the high-energy and particle physics as it is covered well in the other chapters.

II.15.2.1 The energy problem

We are using more efficient CPUs on our computers, the light bulbs are consuming a fraction of what they used to consume and transportation is also more efficient, still humanity used $\sim 45\%$ more energy in 2020 than in 2000 due to two factors, the population growth (by $\sim 28\%$) and the increased energy consumption per capita (Source US Energy Information Administration). We are also experiencing that the global temperature is increasing to levels never seen before by humanity, and CO_2 has been known to have a non-negligible impact [9]. There are several initiatives for clean energy worldwide, the fusion energy solutions such as the ITER project under construction in Europe [10], and the next generation of fission energy sources, Accelerator-Driven Subcritical Systems. The accelerators are needed in the former type to test the irradiation of internal surfaces by high fluxes of neutrons and in the latter one to drive the reactor, and also to reduce the existing nuclear waste we have already accumulated. The DONES project in Spain [11], the CiADS in China, and the MYRRHA project in Belgium will be used as examples for these facilities, respectively.

II.15.2.1.1 DONES

The DONES (Demo Oriented NEutron Source) project in Spain is a research project dedicated to the development of a neutron source facility. Its primary objective is to simulate the challenging neutron environment expected in future fusion reactors, with a specific focus on the next generation of Tokamak-based fusion source after the ITER, the DEMO (DEMOnstration power plant) which would be receiving a neutron dose two orders of magnitude higher than ITER. By creating a high-energy neutron source, DONES serves as a vital testing ground for materials, components, and technologies under the extreme

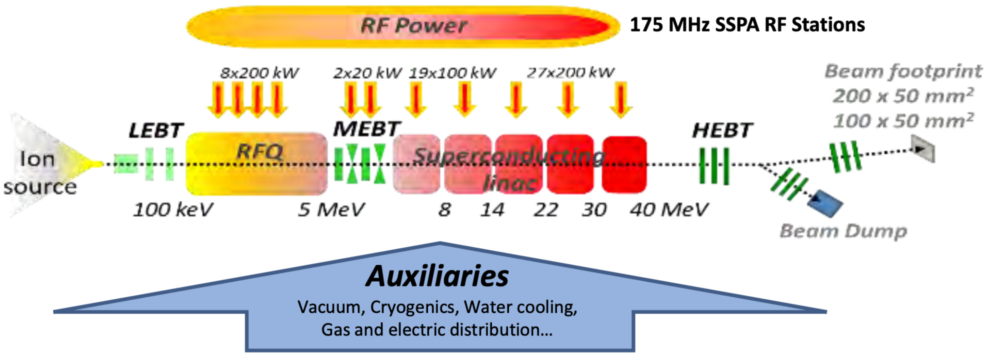

Fig. II.15.3: DONES layout.

conditions of high neutron flux, intense heat, and radiation that would be encountered in a functioning fusion reactor. This is achieved using a 40 MeV beam of deuterons with a high current of 125 mA, operating in CW mode, generating a 5 MW beam on a lithium target and delivering a flux of neutrons. The ECR ion source generates the 140 mA deuteron beam and extracts the beam at 100 keV, followed by a LEBT section to the RFQ which delivers the 125 mA 5 MeV beam to the MEBT section where it matches transverse and longitudinal modes using quadrupoles and buncher cavities to ensure optimal acceleration in the superconducting linac which is composed of two types of half-wave resonators, ultimately reaching the final energy of 40 MeV. It is then directed toward the neutron production target via the High Energy Beam Transport Line (HEBT), (see Fig. II.15.3).

II.15.2.1.2 CiADS

The CiADS (Chinese Initiative on Accelerator-Driven Systems) is a research initiative in China that focuses on accelerator-driven subcritical reactor systems. Its main goal is to develop and advance accelerator-driven systems, which have potential applications in the transmutation of long-lived radioactive waste from conventional nuclear reactors in the first phase and energy production in the next phases. The linac can accelerate a continuous wave (CW) 5 mA proton beam to 500 MeV at a beam power of up to 2.5 MW with state-of-the-art accelerator technologies (see Fig. II.15.4). The CiADS linac consists of a front-end section with normal conducting elements, an ion source coupled with the Low-Energy Beam Transport (LEBT) section, an RFQ which accelerates the beam to 2.1 MeV, and a Medium Energy Beam Transport (MEBT). The superconducting (SC) section accelerates the protons further to 500 MeV, featuring three distinct families of superconducting cavities, two types of half-wave resonators (0.10, 0.19), one type of spoke (0.41) and two types of elliptical cavities (0.62, 0.82). The HEBT system is designed to transport a 2.5 MW proton beam to either the target through the A2T section or to a line-of-sight beam dump. Additionally, HEBT reserves space for up to 10 cryomodules, facilitating the potential increase in energy to 1 GeV. There is a similar project in Belgium, MYRRHA (Multi-purpose Hybrid Research Reactor for High-tech Applications) primarily focused on the development of a versatile and innovative nuclear research facility. MYRRHA's design and objectives are centered around advancing nuclear science and technology for a wide range of applications, including nuclear waste management (see Fig. II.15.5), materials research, and the production of medical isotopes, its full scope has a sub-critical reactor, i.e. a reactor which does not maintain a self-sustaining nuclear chain reaction, and as a

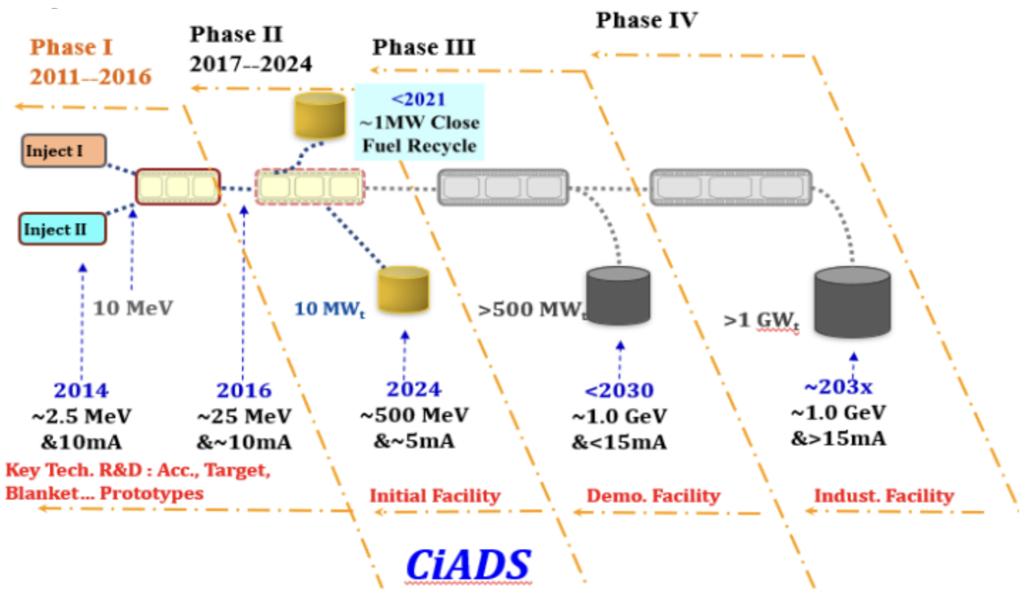

Fig. II.15.4: CiADS layout.

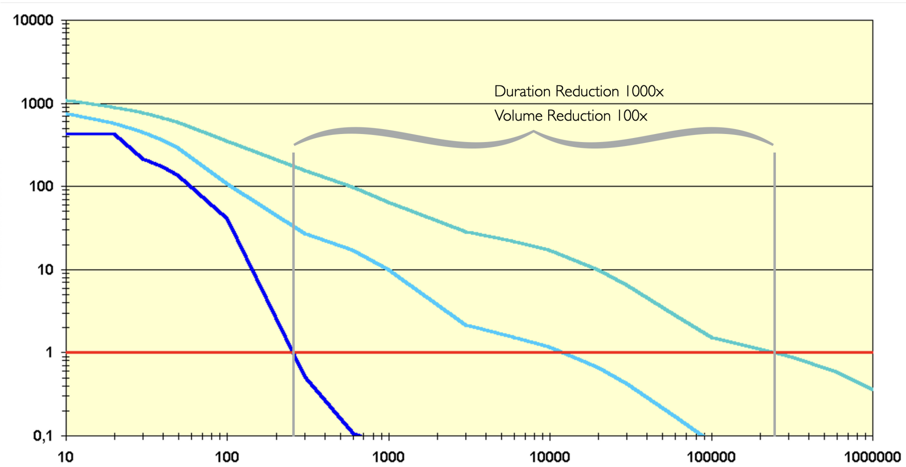

Fig. II.15.5: Reduced radiotoxicity as a function of time for unprocessed nuclear waste (cyan), waste reprocessing (light blue), and including transmutation of waste (dark blue). Vertical axis shows the radiotoxicity normalized to that of the natural uranium, and horizontal axis shows the time in years. (Image courtesy of Hamid Aït Abderrahim and Dirk Vandeplassche).

primary goal will explore the nuclear waste transmutation.

II.15.2.2 Looking beyond the periodic table

The periodic table before 1940 had the uranium as the ultimate element and had holes for some even lighter elements. By then the quest for heavier elements had already begun and in the years to come several new elements were added to the periodic table, several of them as a result of the Manhattan Project. In 1951, the search for unstable isotopes took a new direction when Kofoed-Hansen and Nielsen [12] accelerated a deuteron beam in a cyclotron, impacted a primary target to release neutrons which would lead to induced fission in a secondary target, and then transported the fission products, e.g. a neutron-

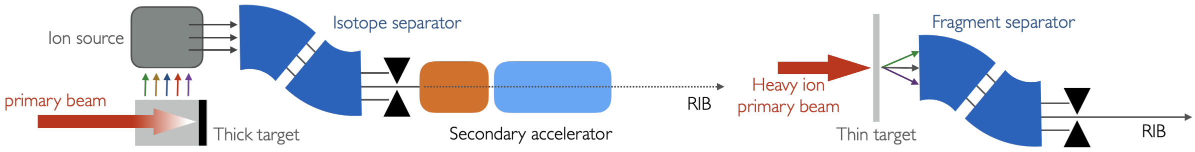

Fig. II.15.6: Sketch of ISOL (left) and In-Flight (right) RIB facilities.

rich krypton gas for further analysis. This paved the way for the radioactive ion beam (RIB) facilities of today. Today we know more than 3000 isotopes where 254 are stable, most of them thanks to the RIB facilities [1]. The application of RIBs is not limited to isotope discovery, we examine the nuclei like never before, studying the neutron halos, superheavy elements, drip lines, nuclear shell structure, exotic radioactivity, and last but not least the r-process. These also deepen our understanding of neutron stars through studying neutron-rich nuclei [13]. The choice between In-Flight and Isotope Separation On-Line (ISOL) methods (see Fig. II.15.6) in RIB production offers distinct advantages and disadvantages. ISOL techniques excel in providing RIBs with good beam quality, characterized by a small energy spread, making them suitable for precise experiments. Additionally, ISOL allows for the generation of pure beams, enhancing selectivity through chemistry. It boasts a higher production rate for extractable species and is particularly efficient for low-energy, light ions, reducing the size of the facility required. On the other hand, In-Flight RIB production offers access to very short-lived fragments, with sub-microsecond lifetimes, establishing a direct link between cross-section measurements and observed production rates—a feature useful for ISOL methods. It can produce beams with energies near those of the primary beam. Nevertheless, ISOL has its limitations, requiring longer-lived isotopes (larger than 10 milliseconds), and encountering beam energy variations within thick targets. There are also safety considerations with the inserted hot cells used. In contrast, In-Flight RIB production provides beams with energy levels near the primary beam and presents significant energy dispersion challenges. While it employs a simpler production target, fragment separation can be sophisticated, and it tends to be resource-intensive, especially when dealing with high-energy, heavy particles, necessitating larger facilities [14].

SPIRAL2

The SPIRAL2 facility, as depicted in Fig. II.15.7, is founded on a high-power, superconducting driver linac capable of delivering a high-intensity, 20 MeV/n deuteron beam, a 33 MeV proton beam as well as a diverse array of heavy-ion beams with A/q of 3 and energies reaching up to 14.5 MeV per nucleon. By employing a carbon converter in conjunction with a 5 mA deuteron beam and a uranium carbide target, the facility anticipates achieving a fast-neutron-induced fission rate of up to 10^{14} fissions per second. Furthermore, when focusing on RIBs within the mass range from $A = 60$ to $A = 140$, SPIRAL2 is poised to outperform existing facilities worldwide by a significant margin, potentially surpassing their RIB intensities by one or two orders of magnitude. Additionally, the facility offers the versatility of directly irradiating the UCx target using beams of deuterons, ^{3}He, ^{6}Li, ^{7}Li, or ^{12}C, particularly beneficial when higher excitation energies are sought to enhance the production rates of specific nuclei of interest [2].

[1]If you are interested to read on the production of trans-uranium elements, I would recommend *Superheavy* by Kit Chapman.

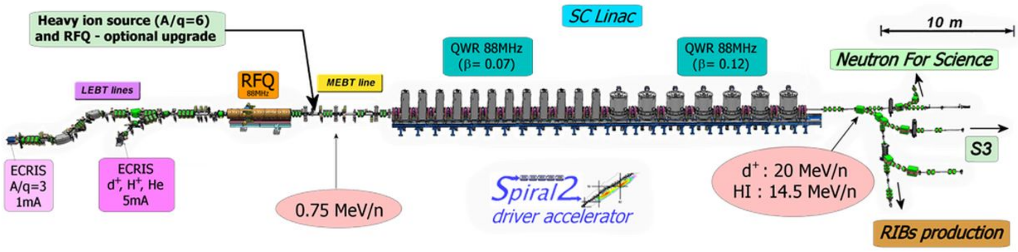

Fig. II.15.7: Schematics of the SPIRAL2 linac at GANIL.

II.15.2.3 Material and life science

For the last example of applications of the high-power hadron linacs we will look at the spallation neutron sources or sources of high-flux neutrons of extremely low-energy. They offer unprecedented insights from the atomic and molecular level from proteins to viruses to pharmaceuticals, batteries to supercomputers, and malted grains to jet engine blades. Equipped with this knowledge, the possibilities to innovate open up in diverse fields of research. Such experiments are performed using neutron scattering techniques, for example, while neutron diffraction can pinpoint the location of atoms and nuclei, neutron spectroscopy would detect motion at an atomic level. What makes neutrons such a versatile tool is a combination of their properties, being neutral they have a deep penetration depth, their dipolar magnetic moment makes them an excellent probe for magnetism and superconductivity, and like any other particle they demonstrate particle-wave duality. In 1932, James Chadwick made a groundbreaking discovery when he finally found the neutron (it was predicted by Rutherford that there should exist a particle with mass but no charge which gave it the name neutron). Through experiments involving the scattering of alpha particles by beryllium, he demonstrated the existence of a neutral subatomic particle within the atomic nucleus, changing our understanding of the atom's structure. Following the discovery, early neutron sources utilized radionuclides, notably radium-beryllium combinations, where the alpha particle emitted from radium would interact with the beryllium to release a neutron (plus a carbon atom). These sources emitted neutrons as a result of radioactive decay. While limited in intensity, they played an essential role in early nuclear physics experiments. Following the discovery of fission by Lise Meitner and Otto Frisch [15], and the developments of fission reactors during WWII, nuclear reactors were developed as robust neutron sources. Reactors like Chicago Pile-1 provided controlled, intense neutron flux for various scientific investigations. The neutron flux from nuclear reactors reached a plateau by 1970, with ILL in Grenoble, France, one of the highest flux sources still under operation. Spallation neutron sources emerged later, employing high-energy proton or deuteron beams directed at heavy target materials. The impact of these sources, including facilities like the Los Alamos Neutron Science Center (LANSCE) in the U.S. or Paul Scherrer Institute (PSI) in Switzerland, was significant. They allowed for versatile and intense neutron production, contributing to various scientific applications, (see Fig. II.15.8). In contrast to the photons (X-ray) which interact with the electron cloud of the atoms (therefore a cross-section $\propto Z^2$) [16], the neutrons interact with the nuclei and can distinguish well between neighboring atoms and even isotopes of the same material (see Fig. II.15.9). This makes the neutron scattering and X-ray scattering experiments, or facilities, complementary. As the three images in Fig. II.15.10 show, the two images next to each other would not only show areas that were invisible in the other image, it can also reveal the

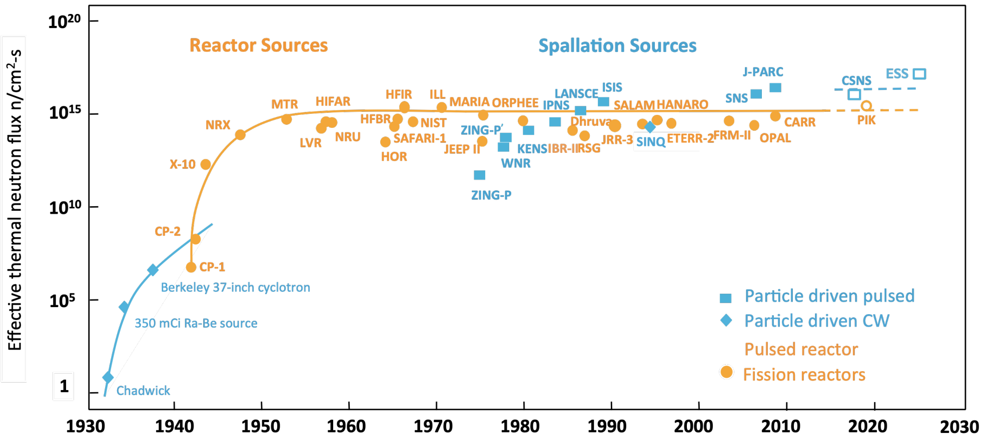

Fig. II.15.8: A history of neutron sources and the evolution of flux over time. Updated by Roland Garoby from Neutron Scattering, K. Skold and D. L. Price, eds., Academic Press, 1986.

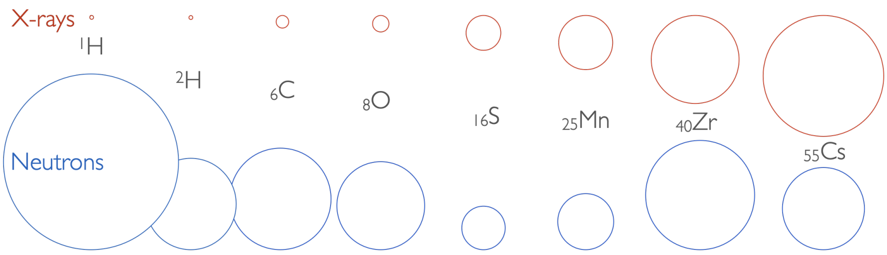

Fig. II.15.9: Visual demonstration of $Z(A)$ dependence of cross section for x-ray vs. neutrons.

material or the building blocks of components without any destructive testing. Neutron research facilities have been crucial in driving advancements across various scientific fields. Key installations worldwide have shaped neutron science, enabling breakthroughs in materials science, nuclear physics, and energy research. This timeline outlines major milestones in the development of global neutron research centers: LANSCE started operations in 1972, marking an early milestone in the field. PSI in Switzerland became operational in 1984, followed by the ISIS Neutron and Muon Source in the United Kingdom in 1985 and SNS began operations in 2006. Japan Proton Accelerator Research Complex (J-PARC) initiated its proton accelerator in 2008, adding to the global landscape of neutron research facilities. China Spallation Neutron Source (CSNS) is a more recent addition, commencing its pilot operation in 2018. ESS under the final stages of construction and installation will be ready for user operations in 2027.

II.15.3 Basic principles of hadron acceleration

The very basic building blocks needed to make an accelerator are a source of charged particles, an electric field for the acceleration of the charged particles, and a magnetic field for guiding and focusing the beam: this would be very similar to saying that to make a rocket similar to the SpaceX ones, one needs a body, an engine and fuel. We all know that the latter is painfully incomplete and we will see that the former description is not any better. With that analogy, as different payloads need different rockets, different applications call for different types of accelerators. In the next couple of pages, we will have an overview of different accelerator types.

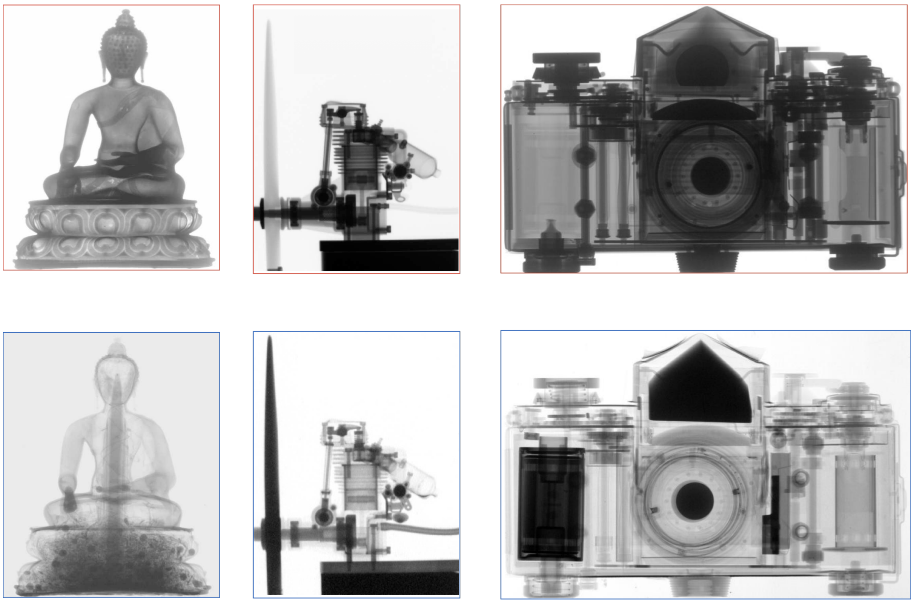

Fig. II.15.10: A demonstration of cross-section difference in X-ray vs. neutron imaging. Image courtesy of PSI/ Eberhard Lehmann; Buddha [17]. Color coding is similar to Fig. II.15.9.

II.15.3.1 Overview of particle accelerators

Accelerators could be categorized based on their shape and the types of particles they accelerate. Linacs have a straight-line design (look at FRIB for a non-straight linac), effectively accelerating charged particles. In contrast, circular accelerators, such as cyclotrons (read more in Chapter I.13) and synchrotrons, employ circular or ring-shaped designs. Cyclotrons use a magnetic field to accelerate particles in a spiral path with no room for a strong transverse focusing, while synchrotrons utilize magnetic fields to keep particles in an almost circular orbit, providing strong transverse focusing while increasing their energy. Another classification criterion is the type of particles they accelerate, electron accelerators are different from hadron accelerators and both are very different from muon accelerators.

II.15.3.2 Components of high-intensity proton linacs

II.15.3.2.1 The ion source

The first stage of acceleration happens right after the ion source. The sources are always (except on tandem DC generators) put on a high voltage which for a modern linac is a few tens of keVs, and for older linacs, like the LANSCE is around 800 keV. The generation of ions in an ion source can be achieved using any of three fundamental processes: electron impact ionization, photo-induced ionization, and surface ionization. Additionally, other atomic and molecular processes, such as charge exchange and molecular dissociation, can contribute to ion extraction. Ion sources encompass various types, including electron bombardment, plasma discharge, radio-frequency discharge, microwave and electron cyclotron resonance, laser-driven, surface, and charge exchange sources, each employing specific physical processes. To understand different types of ion sources, it is important to be familiar with the basic components of an ion source. These components include a main chamber where ionization occurs and ions drift towards the extraction region, a material source that supplies the required ions (such as gas or heated solid/liquid material), an ionization energy source that provides the necessary energy for ionization, and an extraction system that applies an electric field to extract and accelerate the ions. These fundamental components form the basis for various ion source types, which exhibit significant divergence beyond these common elements. Additional systems like vacuum pumping, power supplies, and controls are also necessary for the operation of ion sources. It is very critical for the high-power linacs to have an ion source where the current is stable both within the pulse and from pulse to pulse.

Electron cyclotron resonance ion sources

Electron cyclotron resonance (ECR) ion sources are extensively utilized to generate high-quality multiple-charged ion beams in various applications such as accelerators, atomic physics research, and industrial settings. Over the past few decades, significant advances in ECR ion source design and technology have led to remarkable improvements in their performance, enabling higher charge state ions, intense beams with better emittance, and increased ionization efficiency. The ability to produce CW beams from any element, minimal maintenance requirements, and the absence of cathodes are some of the key characteristics that contribute to the widespread application of ECR sources in the accelerator community [18]. From electromagnetism (see Chapter I.1) we know that the charged particles subjected to a magnetic field follow circular paths perpendicular to that field, and this rotation happens at a specific frequency (f_e),

$$F_c = \frac{mv^2}{r} \; and \; F_b = qvB \;\Rightarrow\; \frac{mv^2}{r} = qvB, \tag{II.15.1}$$

resulting in

$$\omega = v/r = \frac{qB}{m} or \, f_e = \frac{qB}{2\pi m}. \tag{II.15.2}$$

Note that the frequency is not a function of velocity as long as the particle mass is a constant (not relativistic). For electrons, this concept translates into a practical formula, f_e = 28 GHz/T. By using a set of magnetic solenoids, one can generate a magnetic field that creates a resonance at a reasonable RF frequency. One such frequency is 2.45 GHz with readily available RF sources (magnetrons), which are also used for microwave ovens. Using a uniform magnetic field of 87.5 mT creates that resonant condition; however, one usually tapers the magnetic field to have the plasma generated at a volume of interest. ECR ion sources have gained popularity as ion sources, capable of producing a wide range of ion beams. Lower-frequency ECR ion sources are suitable for generating beams of light ions, e.g. protons. These can include high-intensity, high-duty-factor pulsed beams. On the other hand, high-frequency ECR ion sources can produce beams consisting of ions with high charge states [19].

H^- sources

High-power linacs are used very often as injectors for circular machines, like storage rings (e.g. SNS) or synchrotrons (e.g. PS booster). To overcome the limitations imposed by Liouville's theorem (read more in Chapter I.3) the injection to these rings is done using what is called a charge-exchange injection of particles (read more in Chapter I.7) which requires a negatively charged hydrogen ion (a proton with two bound electrons in its s layer) to be accelerated in the linac. The formation processes of H^- ions are diverse and can occur through various mechanisms. These mechanisms include radiative capture which is free electron capture at the electron affinity level of the H^0 atom. Additionally, H^- ions can form through three-body collisions, where multiple particles interact. They may also be created when electrons are captured during charge exchange with other molecules, resulting in the formation of an

H^- ion and a H^0 atom. Furthermore, H^- ions can originate from breaking the bounds within molecules and ions that contain hydrogen. In certain scenarios, such as collisions with electrons and molecules, a process called dissociative attachment can lead to the formation of H^- ions. Lastly, electron capture from condensed materials on the electron affinity level of particles ejected from condensed phases or reflected from condensed materials can also contribute to the generation of H^- ions [20].

II.15.3.2.2 RF acceleration

Now that we have a good-quality beam of charged particles from the ion source, we need to accelerate it to the desired energy and to do that we need cavities. Radiofrequency (RF) cavities are an integral component of particle accelerators, they control the beam behavior in the longitudinal plane and accelerate it. Operating at radio frequencies, they generate electromagnetic fields that allow precise manipulation of the beam's longitudinal phase space. By applying an RF voltage, particles gain energy when passing through the cavity at the right phase, or get focused longitudinally. RF cavities are essential for achieving specific beam energies and can be customized to suit the particle type, energy (velocity), transverse size, beam current, and the overall energy consumption of the facility. Such needs would also define if normal conducting or superconducting cavities are used and at which energy one switches from a normal conducting cavity to a superconducting.

NC cavities

RFQ

If we wanted to talk about only one NC RF structure, it would be the RFQ, as almost any other NC structure has a SC counterpart[2]. The RFQ accelerates the beam from very low energies right after the ion source to reasonable energies for other accelerating structures to continue the acceleration, keeps the beam focused transversely, and bunches the DC stream of ions coming from the ion source to the right frequency. Modern hadron accelerators use RFQs as their first accelerating and bunching structure, they can provide beams of high quality and high current and offer a bunching efficiency of more than 90%, while the classic methods are limited to less than 60–70%. There are two main types of RFQs, four rods and four vanes, (see Fig. II.15.2): the longitudinal modulation of the electrodes (vanes or rods) creates a field in the direction of propagation.

The transverse profile of the vanes in combination with the RF mode of operation shapes the field lines for transverse focusing, in other words, both acceleration and bunching are achieved by the RF field and the vanes. RFQs work in the TE_{21} mode (in TE mode, the electric field is perpendicular to the beam direction of propagation). The RFQs can efficiently accelerate particles from a β of around 0.5% to a β of around 12%, making them useful for protons and heavier ions, but not for electrons.

DTL

The Drift tube linac uses "drift tubes" to protect the particles from the RF field during the decelerating phase of the RF field and operates in 0 mode, i.e., the field in all cells has the same direction (see Fig. II.15.11). The acceleration happens between the drift tubes, in the gaps, to keep the beam synchronous with the right phase of the RF field, the gap-to-gap distance increases linearly with the beam velocity. To increase the RF efficiency of the DTLs, permanent magnet quadrupoles which are more compact than electromagnets are housed inside the drift tubes, and these will provide the transverse fo-

[2]The INFN-LNL developed an SC RFQ, but that has never been used.

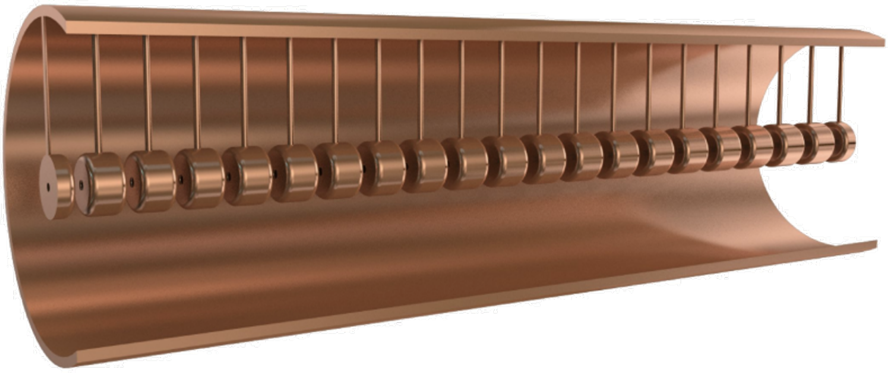

Fig. II.15.11: 3D rendering of a DTL (courtesy of Ciprian Plostinar).

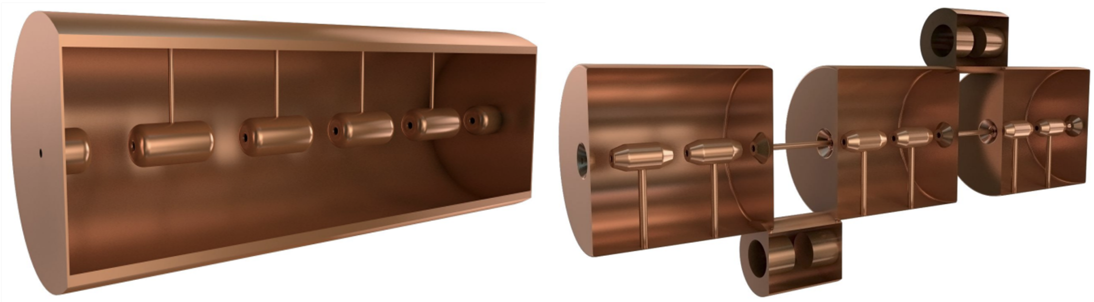

Fig. II.15.12: Renderings of other "DTL type" structures, from left, Separated DTL as used in J-PARC, Cavity coupled DTL as used in LINAC4/CERN (courtesy of Ciprian Plostinar).

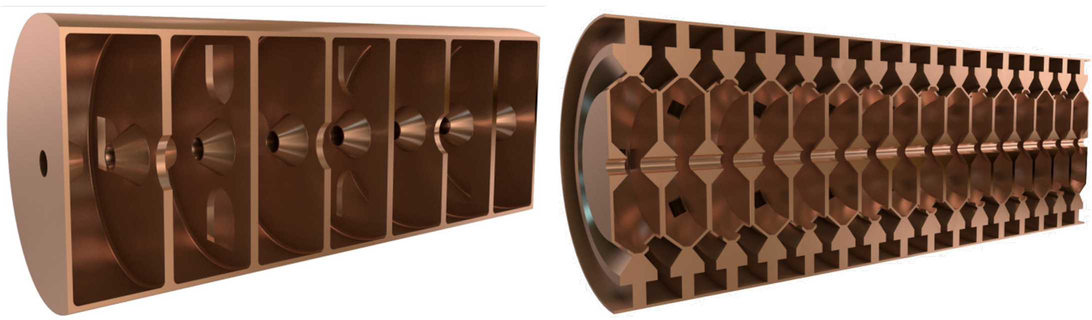

Fig. II.15.13: NC structures for higher energies, left: PIMS, right: ACS (courtesy of Ciprian Plostinar).

cusing. The DTLs are efficient from a β of around 4% to a β of around 50%, and are designed for frequencies of $\sim$50-400 MHz. They are most efficient at the lower end of this energy range, and that's why mutations of them have been developed for the higher end, for example, the CCDTL for the 50-80 MeV at CERN and the SDTL for 50-180 MeV at J-PARC, (see Fig. II.15.12). Other cavity types are used at higher energies, for example, the Annular-coupled structure at J-PARC to accelerate the beam to 400 MeV and the Pi mode structure at CERN's LINAC4 for a final energy of 160 MeV, (see Fig. II.15.13).

SC cavities

The NC structures, even when optimized for the best energy transfer to the beam, still suffer from the ohmic losses on the cavity surface which increase with the square of the accelerating field. Such losses could reduce the efficiency of these structures to less than 50%, i.e., more than half of the input RF power, is converted to heat which adds complications for cooling and would render the facility less sustainable. This problem does not exist with SC cavities, read Chapter II.5 on superconducting RF cavities. The SC cavities can also offer a larger beam aperture, which would reduce the beam losses, and as they have fewer coupled cells they offer a higher flexibility for energy acceptance and against cavity failure, read Chapter III.9 on accelerator driven systems for more discussions on availability. The SC cavities need cooling to cryogenic temperatures, and the cooling system works at 100% duty cycle, i.e., its operation is not a function of beam or RF presence, and the energy consumed for cooling is not insignificant, read Chapter II.7 on cryogenics for superconducting devices.

Cryomodule

A cryomodule, short for "cryogenic module", is designed to house and maintain the SC cavities at extremely low temperatures needed for transition to the superconducting state, which for pure niobium cavities is 9.2 K. Key features of a cryomodule include (see Fig. II.15.14):

1. Superconducting RF cavities: cryomodules encase superconducting RF cavities, the helium vessel which is delivering the cold liquid helium to the external surface of the cavity, the magnetic shield that protects the cavity from stray magnetic fields, including that of Earth, and several layers of thermal shield.
2. Power couplers: to feed the RF power to the cavity is equipped with a power coupler that separates the vacuum of the cavity from the atmospheric pressure in the RF distribution system (waveguides, coaxial lines).
3. Cryogenic cooling: cryomodules are equipped with a sophisticated cryogenic cooling system that delivers the helium, keeps the temperature stable, depending on the design liquifies the gaseous helium at the interface to the cavity, and provides gaseous helium for cooling of non-SC components that need cooling, e.g. the thermal shield.
4. Vacuum enclosure: to minimize energy losses due to heat convection of air molecules and avoid the creation of ice blocks inside the cryomodule, the units are maintained under high-vacuum conditions.
5. Tuning system: each cavity within the cryomodule is equipped with a system that is capable of deforming the cavity in a controlled way to maintain the resonant frequency of the cavity.
6. Structural and support elements: cryomodules are designed to withstand mechanical stresses, provide structural support to the enclosed components, and maintain the alignment of the cavities within the tight requirements needed for high-power linacs.

II.15.3.2.3 RF power generation

The RF power that is needed for a reliable and controlled beam acceleration is generated, regulated, and transported by the RF system. In the case of the ESS linac, this system from the wall plug to the RF coupler is composed of a high-voltage generator that generates a high-voltage, ripple-free DC pulse matching the pulse length needed for the beam plus the cavity filling time and stabilization of the field, a device which converts the high voltage DC to the RF wave at the right frequency, a system which distributes this RF power to the coupler and all of these systems are connected to another system which

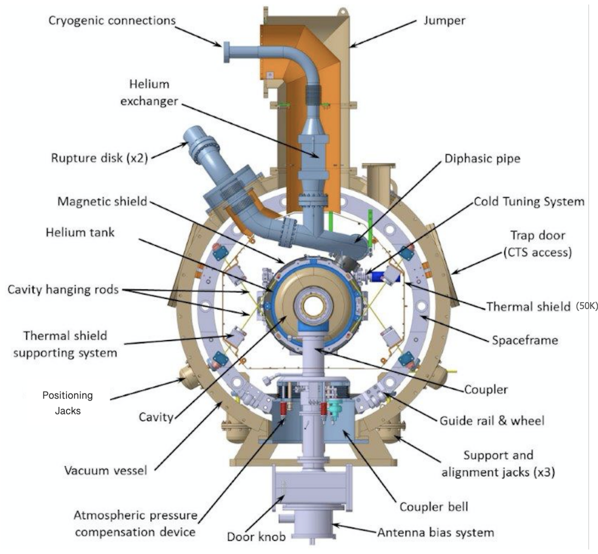

Fig. II.15.14: Cryomodule example and its components.

regulates the amplitude and phase of the RF wave at the cavity by adjusting different input variables, these systems are called Modulator, Klystron, RF distribution system and the Low-Level RF (LLRF), respectively. One can have a different architecture based on the frequency of the RF, peak and average power needs, and the availability requirements, but in essence, the following systems are needed, a DC rectifier, a DC-RF converter, a distribution system, and a system to regulate. **DC generation**
HVDC modulators have a specific purpose: they are designed to convert low-voltage, high-current AC power into high-voltage, high-power DC signals. This transformation is essential to effectively drive the RF amplifiers and, in turn, the RF cavities within the accelerator. Their primary role is to elevate the voltage from the power source to the levels needed for RF power generation, which is then used to power RF amplifiers that produce high-power RF signals. In addition, HVDC modulators often play a crucial role in shaping RF power pulses, particularly in applications requiring pulsed beams. They are engineered for best energy efficiency, minimizing energy losses during voltage transformation and ensuring a substantial portion of the input power is efficiently converted into HVDC. Due to the critical nature of RF power in accelerator operations, HVDC modulators are meticulously designed for high reliability and stability to maintain consistent beam performance. In ESS, to meet the specified requirements, a novel stacked multi-layer (SML) modulator was designed with four power electronic conversion stages, divided into two parts (see Fig.II.15.15). The first stage uses an active rectifier to convert incoming AC power into clean and synchronized DC power, ensuring minimal power distortions. The second stage, a DC/DC converter, replenishes the capacitor banks. It monitors and controls the bank voltage to provide constant power, which is essential to maintain uninterrupted accelerator operation, even under high-power demand. Multiple such systems operate in parallel, significantly enhancing power capacity. The output stage transforms the power into a high-voltage AC square wave, amplifying it to 115 kV, 100 A before delivering it to the klystron in pulses of 3.5 ms long at 14 Hz [21]. This system guarantees precise and flicker-free power for reliable beam control and experimentation.

RF generation

The next step within the RF chain is the conversion of the DC voltage to RF waves, this can be done with

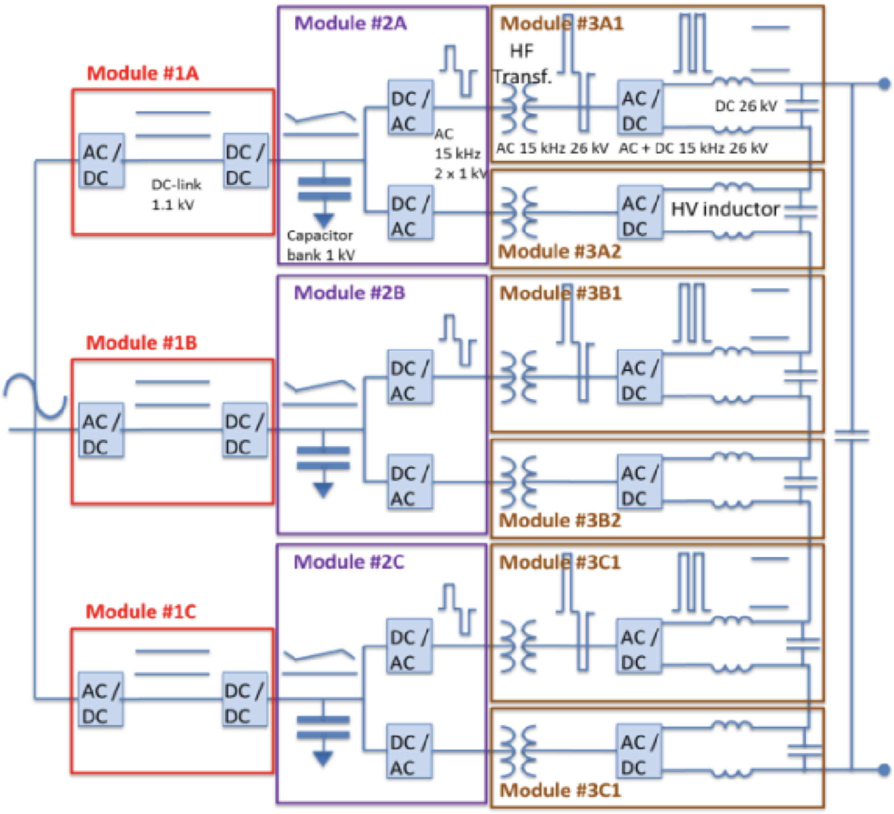

Fig. II.15.15: SML modulator topology

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several devices, e.g. klystron, tetrode, IOT, solid state amplifier, etc., each suitable for a certain functionality. The first three belong to the vacuum tube group of RF amplifiers and the latter as the name stands is based on solid state (transistor-like) amplifiers. In the following the klystron functionality will be explained. **Klystron**: searching for a way to help planes land blindly or in low visibility, the Varian brothers invented the Klystron in 1937, which then got application in Radar systems and eventually accelerators after the War. They operate using the velocity modulation principle as can be seen in Fig. II.15.16. The cathode generates the electron beam which gets accelerated via the HV delivered by the modulator (115 kV in the ESS example), while being transported via the axial magnetic field provided by the set of solenoids, it passes through the RF field generated within the cavity by the input RF which accelerates a part of the beam and decelerates another part. This velocity modulation causes the electron beam to bunch, this process could be enhanced by having more than one bunching cavity. When the beam is fully bunched, it passes through the last cavity which would extract the energy from the beam in the form of high-power RF.

Following the development of integrated circuit technology, the metal–oxide–semiconductor field-effect transistor (MOSFET) devices could be created. The development has continued and is still being pursued, with newer and higher output power MOSFETs. The lateral diffusion MOSFETs (LDMOS[3]) are commercially available nowadays with a power output capability of $\sim$ 1 kW, and a good DC to

[3]An interesting fact about LDMOS is that their production involves ion-implantation, a process which requires low-energy accelerators.

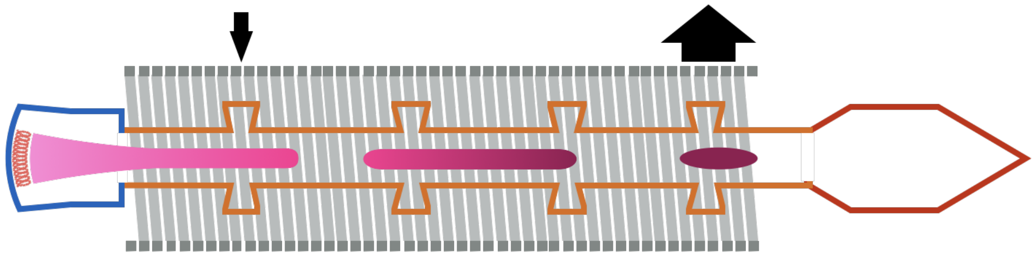

Fig. II.15.16: A schematic view of a klystron. Red filament: cathode, orange structure: the tube, grey spiral: solenoids, red hexagon: beam dump, grey inward arrow: RF in, black outward arrows: RF out, pink ovals: electron beam being bunched (going left to right).

RF efficiency of $\sim 70\%$. Such a system is fed by a dedicated DC power source, but the power output from each device is very small. To overcome that, combiner cavities in different shapes are being used, e.g. cylindrical with several tens of LDMOS sources at the circumference, the power from the combiner cavity is then extracted to be fed to the cavities. A major advantage of these solid-state power amplifiers (SSPA) is that upon failure of a single transistor, the rest of the system could continue the operation, and the units could be hot-swappable which makes the system extremely available and reliable, useful for applications such as the accelerator-driven systems (ADS), see Chapter III.9.

RF distribution system

The RF power generated at the RF source should be transported to the cavity without leakage and with high efficiency, this is only one of the tasks of the RF distribution system. It protects the system against reflected power from the cavity through for example circulators. A circulator has a three-port design, and between each two ports, it acts similar to a diode circuit in electronics which allows a directional flow of current. They mostly operate based on the Faraday effect, which involves the rotation of the polarization plane of electromagnetic waves in the presence of a magnetic field, which is usually provided by a permanent magnet. As a consequence, they can transport the RF wave from the klystron to the cavity, but a reflected wave will be guided to a matched RF load which absorbs the RF wave and needs active cooling. The RFDS could also merge power from two sources to feed a single cavity, can split the power from one source to several cavities and in both cases has the ability to adjust the phase difference amongst different paths.

Low-Level RF

The low-level RF is in charge of regulating the phase and amplitude of the field as seen by the beam, to achieve this the LLRF samples the input RF to the klystron, the output power from the klystron and the field in the cavity, a feedback loop adjusts the input RF's phase and amplitude within the pulse to make sure the field seen by the beam remains at the set value. A challenge in the high-power linacs which separates them from other accelerators is the stringent requirement on the field control. For example in the case of ESS, the jitter on phase and amplitude is required to be less than 0.1° and 0.1%, respectively.

II.15.3.2.4 Transverse focusing

To confine the charged particles within the aperture of the accelerator, we need to focus the beam transversally. Without focusing, the repulsive Coulomb force between the particles and the emittance would cause the beam to diverge rapidly and become too wide to be confined within the accelerator

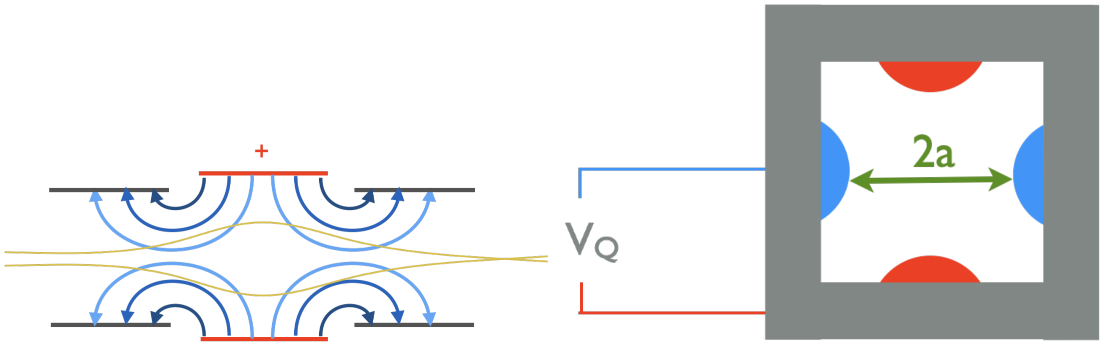

Fig. II.15.17: Schematic view of; (left): an einzel lens, the beam goes from left to right; (right): an electrostatic quadrupole, the beam goes into the screen.

aperture, causing beam loss and if the energy is high enough, a beam loss would lead to prompt radiation and activation of the accelerator. Depending on the momentum of the particles involved several focusing devices could be used, magnetic quadrupole (either an electromagnet or permanent quadrupole [22]), magnetic solenoids, and electrostatic lenses [23], which could either have axial or quadrupolar symmetry. The different types of focusing elements are typically used at different beam energies, looking at the focal lengths of these four lens types, one can see that those relying on electric fields are better tailored for lower velocity particles (do you remember the Lorentz force?) and those relying on magnetic fields are better suited for higher energies/relativistic particles. The cylindrically symmetric electric lenses usually have one or two gaps, the latter is also known as an einzel lens (see Fig. II.15.17, left). The focal length in such a lens is independent of the polarity and is given by $f_{\text{einzel}} = \frac{pv}{qEL}$, where v, p and q are the particle's velocity, momentum, and charge and E and L the electric field between the two poles and the lens' length. One can notice that the particle leaves the lens with the same energy it entered, i.e., no net energy gain. Another focusing lens used at low velocities is the electrostatic quadrupole, (see Fig. II.15.17, right), with a focal length of $f_{\text{EQ}} = \frac{pva^2}{2qV_{\text{Q}}L_{\text{Q}}}$, where L_{Q} is the quadrupole's length. The main applications of these devices are at electrostatic accelerators such as DESIREE [24] where electrostatic quadrupoles are used to focus a low-energy ion/molecular beam, or in injectors/low energy beam transport lines such as that of the SNS. Similarly one can use a magnetic field to focus the beam, either a field with axial (a solenoid) or quadrupolar symmetry (a magnetic quadrupole) (see Fig. II.15.18). Read more about the design of quadrupoles in Chapter II.3 on normal conducting magnets.

The focal length of the solenoid, independent of the sign of the current, is given by $f_{\text{sol}} = \frac{4p^2}{q^2B^2}\frac{1}{L_{\text{sol}}}$ and that of the magnetic quadrupole by $f_{\text{MQ}} = \frac{p}{q}\frac{R^2}{2\mu_0 nI}\frac{1}{L_{\text{Q}}}$. Similar parameters as above are used, with the addition that μ_0, B are the vacuum permeability and the magnetic field.

II.15.4 High-intensity hadron accelerators: design and operation

II.15.4.1 Considerations for high-intensity operation

From an operational point of view and the possibility of performing hands-on maintenance on the high-power linacs without unreasonable cooldown time, it is important to keep the losses as low as possible as any beam loss results in radiation emission when the beam energy is above the Coulomb barrier, the prompt radiation will consist mainly of gamma or neutron radiation. At lower energies, the

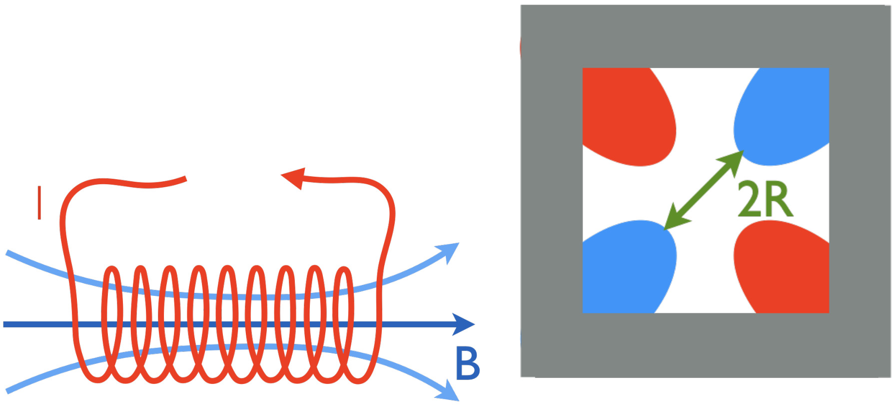

Fig. II.15.18: Schematic view of; (left): a solenoid , the beam goes from left to right; (right): a magnetic quadrupole, the beam goes into the screen.

bremsstrahlung, in the form of X-rays, will always be present. At high energies above the Coulomb barrier, residual radiation could be generated; this causes the activation of materials in proximity to the accelerator, which is primarily composed of gamma radiation. In proton accelerators, limiting beam losses to 1 W/m will cause a dose levels of less than 1 mSv/h measured at 30 cm from the exposed surface of the accelerator after four hours of radiation cooldown following a 100-day operation period [25]. The activation in electron machines is approximated to be around 5% of that induced in a proton linac, while for ions heavier than protons the activation per lost ion tends to be higher [26].

In the case of high-power accelerators, such as the ESS linac, precise design is essential to prevent the unwanted excitation of particles into the beam halo. The development of a beam halo poses a significant risk to the maintainability of the linac. Additionally, the design must be tailored to minimize emittance growth, a critical factor in preventing particle loss as the process of emittance growth could also lead to populating the halo region with even more particles, such particles would approach the accelerator's acceptance and ultimately will be lost at the system's boundary, whether transversally on the beam pipe, or longitudinally out of the RF bucket; the latter would lead to transverse loss subsequently. The ESS linac represents a state-of-the-art in the field of high-intensity proton linacs, specifically tailored to meet these difficult challenges. The design and execution of the linac and transfer lines are entirely planned to minimize the chances of particles entering the beam halo region and to keep emittance growth at a minimum. These measures are vital for preserving the accelerator's integrity and efficiency, thereby preserving both the equipment and the quality of the particle beam, especially in demanding high-power applications.

II.15.4.1.1 Beam dynamics design in high-intensity linacs

The beam dynamics design of the ESS linac was governed by providing low loss, controlled emittance growth, and efficient acceleration of the beam. These lead to the application of the following rules:

- The zero current phase advance per period shall be limited to less than 90°, in the transverse plane this is to avoid envelope instability in a quadrupole focusing channel [27].
- The average phase advance (phase advance per period divided by the period length) variation

should be smooth. The phase advance is proportional to the square root of the focusing force, keeping its variation smooth ensures that the external forces remain continuous and smooth. Lack of this would cause the space charge to redistribute the beam to a new equilibrium, causing emittance growth.

- The tune depression is being kept above 0.4 to limit the number of mismatch excited resonances [28]. The tune depression is defined as the ratio of phase advance to the zero current phase advance, and the smaller the value, the stronger the impact of the space charge of the beam.
- Finally, the ratio of phase advances in the transverse plane to the one in the longitudinal plane should follow a certain rule, this is to keep the tune-depressions at the three planes to be as close as possible to avoid depressing the tune in one plane at the expense of other planes [29].

II.15.5 Summary

Some of the applications of high-power protons linacs were briefly mentioned. That was followed by a rapid overview of the components of the linacs and their functions. The operational aspects on the beam loss, maintainability and availability lead to the beam physics' rules of thumb for the design of such accelerators. The reader may wonder what distinguishes a high-power linac requirement from a low-power accelerator. It is a combination of factors which makes that separation, keeping the losses below the limit of 1 W/m, the space charge and beam loss control, becomes increasingly difficult with increased beam power. These in themselves lead to tighter tolerances on the alignment of components, stability of the field's phase and amplitude in RF cavities or the gradient of focusing elements. Larger apertures are also used to keep the ratio of beam aperture to RMS beam size as high as possible, and the beam current from the source is near jitter free.

II.15.6 Question and exercises

1. What are the main components of a high-intensity proton accelerator, and how do they work together to accelerate particles?
2. How do the principles of beam dynamics change when operating a proton accelerator at high intensities, and what are some of the resulting challenges that arise?
3. Describe the scientific research that can be enabled by a high-intensity proton accelerator and give examples of specific discoveries that have been made using such machines.
4. Research and write a brief report on one of the major high-intensity proton accelerators.
5. Use a particle accelerator simulation program to explore the principles of beam dynamics in a high-intensity proton accelerator and report on your findings.
6. Conduct a literature review on a specific scientific topic enabled by high-intensity proton accelerators, such as the study of neutrino oscillations. Summarize the key findings and implications of the research.
7. Participate in a group discussion on the future of high-intensity proton accelerators, considering factors such as technological advancements, funding priorities, sustainability, and scientific goals.

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