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The Energy Efficiency of Proton Driver Accelerators

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Outline

High power proton driver accelerators are used to generate secondary particles at high intensities, such as pions, muons, neutrons and ultracold neutrons or neutrinos.

The applications of these facilities have a broad spectrum in the fields of particle physics and condensed matter physics. Another industrial application under discussion is transmutation with accelerator driven systems. On the other hand, the production of megawatt-class proton beams implies the consumption of electrical power on a large scale. New projects and operating facilities must focus on improving the energy efficiency with a higher priority. This is especially true for linacs suggested for ADS-type applications, which may have to deliver >10 MW beams. With this workshop we are aiming to support such developments towards higher efficiency. The goal of this workshop is to consider the whole power conversion chain from grid to the secondary radiation needed at the experiments. In addition, important auxiliary systems of proton drivers are covered, such as cryogenic facilities.

In the first session the motivation for energy efficienct accelerator technology was summarized. Then the major applications of proton drivers were reviewed – accelerator driven systems, particle physics research at the intensity frontier and neutron sources for condensed matter physics. In four sessions the energy efficiency topics beam targets, RF generation, accelerator concepts and auxiliary systems were discussed.

[1] EuCARD2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

Tab. 1: Operating and planned facilities that utilize a high intensity proton driver accelerator.

	Neutrino	Muons	Neutrons	ADS	RIB‘s
Cyclotron	Daeδalus[1]	**PSI-HIPA** **TRIUMF**	**PSI-HIPA**	AIMA[2] TAMU-800[3]	**TRIUMF** **RIKEN**
Rapid Cycling Synchrotron (RCS)		**J-PARC**	**J-PARC** **ISIS** CSNS		
Fixed-Field Alternating Gradient Acc. (FFAG)				**KURRI** +ongoing studies[4]	
s.c. Linac	PIP II [5]	PIP II [5]	SNS ESS ISNS[6]	ADSS[7] CIADS[8]	FRIB

1 Decay-at-Rest Experiment for δcp studies, Laboratory for Underground Science, MIT/INFN-Cat. et al
2 Accelerators for Industrial & med. Applications, reverse bend cyclotron, AIMA company
3 Cycl. 800MeV, flux coupled stacked magnets, s.c. cavities, strong focusing channels, Texas A&M Univ.
4 FFAG studies, e.g. STFC, talk by S.Machida
5 SRF linac, Proton Improvement Plan-II (PIP-II), Fermilab, Batavia
6 Indian Spallation Neutron Source, Raja Ramanna Centre of Advanced Technology, Indore, India
7 Accelerator Driven Sub-critical System at Bhaba Atomic Research Centre (BARC), Mumbai,India
8 China Initiative Accelerator Driven System, Huizhou, Guangdong Prov. & IMP, Lanzhou, China

Physics – Requirements

Particle physics requires highest intensity particle beams for most precision measurements, searches and symmetry tests that can be performed at high and low energies. In this context, proton machines of highest possible intensities have the largest impact. The existing powerful proton driver facilities PSI, J-Parc, FNAL, TRIUMF, and SNS provide high intensity secondary particles beams like pions, muons, neutrons, and neutrinos. Furthermore, proton drivers are deployed for (rare) isotope production, e.g., for medical applications.

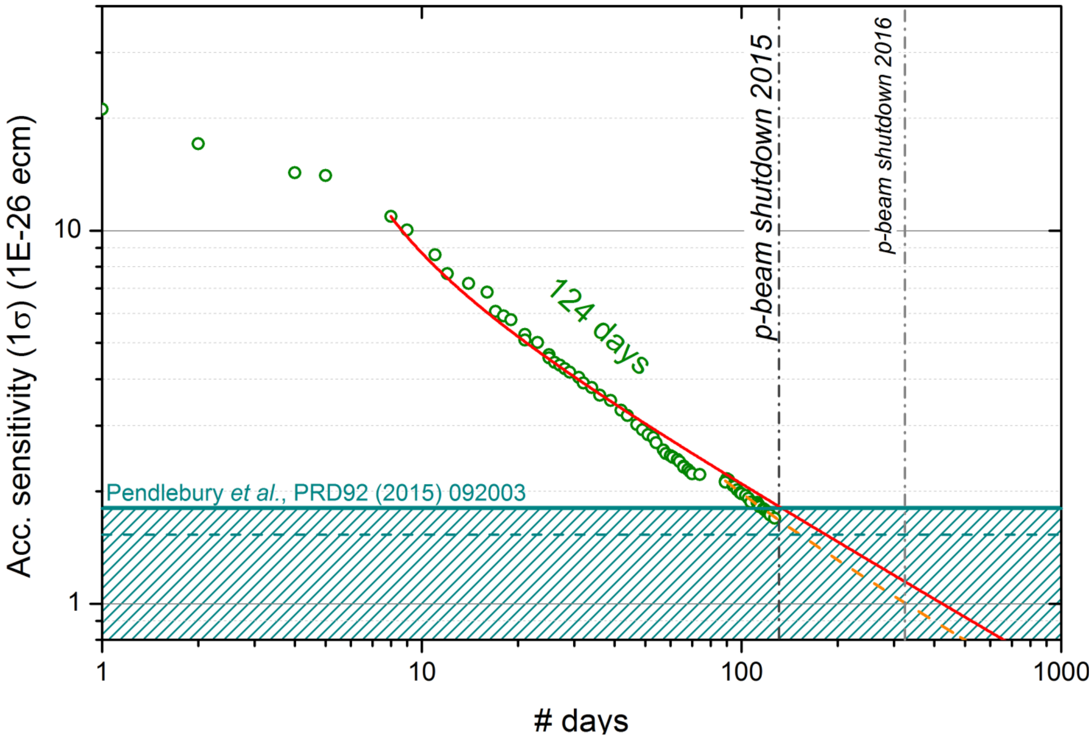


Figure 1: Accumulating sensitivity of the ongoing search for a neutron electric dipole moment at PSI using ultracold neutrons (www.psi.ch/nedm).

An Acclerator Driven System (ADS) represents a novel type of a subcritical reactor for power generation and/or transmutation of nuclear fuel (Figure 2). Energetic particles provided by an accelerator are used to induce a nuclear reaction which releases more energy than needed for driving the accelerator. Carlo Rubbia proposed this concept based on a proton cyclotron and a target with Thorium as a fuel [C. Rubbia et al, CERN/AT/95-44 (ET)]. A facility based on the Thorium cycle requires an accelerator that can provide a proton beam with particle energies ideally above 900 MeV and a beam power of more than 10 MW. For a reasonably efficient ADS, a minimum energy efficiency of 0.2 of the particle accelerator is desirable.

Existing facilities could demonstrate the feasibility of ADS up to the 100 MW level already today. Planned facilities like the European Spallation Source are only a factor of 2 away in power required for an industrial demonstration of a thermal power of several 100 MW. The reliability of the accelerator with an extremely low trip rate, beam losses, and costs are further challenging requirements, especially for industrial applications.

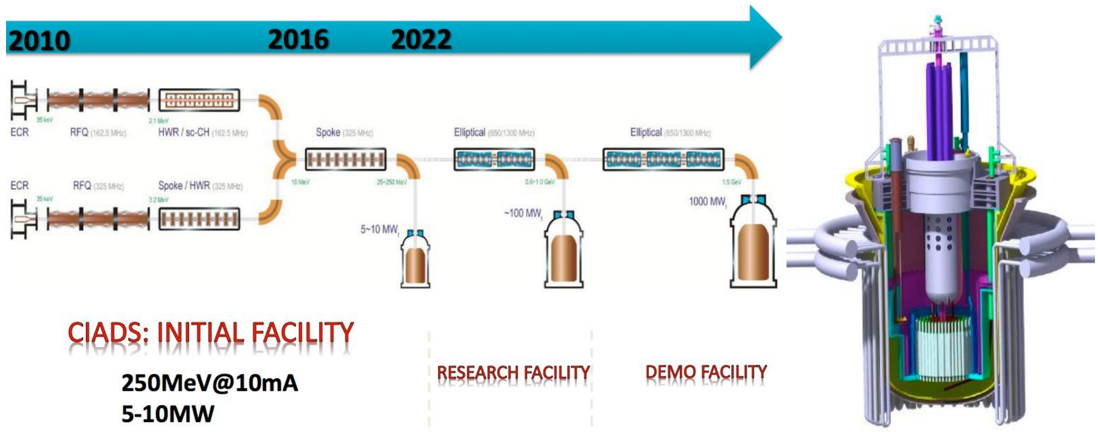


Figure 2: Chinese Accelerator Driven Advanced Nuclear Energy System (ADANES) project with two parallel injectors, the target and the blanket (on the right) proposed as a complete energy system integrating nuclear waste transmutation and energy production (Physics 2016 Vol. 45 (9): 569-577).

Materials Science is arguably the main research area that uses secondary particles generated by high-intensity proton accelerator. With Muons a wide scope of experiments ranging from fundamental to solid state physics can be performed. By implanting muons into, e.g., new semi- and/or superconducting materials the microscopic and electronic structure of the material can be determined on an atomic scale.
Neutrons produced in a spallation source are typically used for scattering experiments to determine both, the structure and the dynamics of condensed matter. Furthermore, non-diffractive methods like imaging techniques are also being applied with increasing relevance to industrial applications. Especially imaging techniques require a high flux of secondary particles and thus a high intensity primary beam.

For any proton driver facility the energy efficiency is not only given by the power consumption of the accelerator but also by the yield of the secondary particles that reach the experiment. Examples are detector efficiency and neutron guiding technology. For specific neutron production applications a factor of 10 in brightness can be achieved by optimizing moderators and neutron guides that have a strong impact on the yield of neutrons.

Beam Targets

Beam Targets, or better target stations, transform accelerated protons into secondary particles. One of the main performance measures, and therefore indicators of efficiency, of such target stations is the intensity of secondary particle beams. In general, the type of desired secondaries determines the basic layout of these target stations. However, common parts to these target stations are the production targets, optimized for maximum output of secondary species of interest, followed by devices that act on the phase space properties of the secondaries, guide them towards experimental stations and shielding to block and reduce unwanted background.

For instance, the target station of spallation neutron sources consist of one or several thermal/cold moderators close to the spallation target placed inside a reflector. The target-moderator-reflector assembly is surrounded by bulk shielding, only penetrated by openings towards experiments which are often equipped with neutron guides. Neutrino target stations aim for the production of pions or higher mass mesons in large amounts which then decay into muons and neutrinos. Magnetic horns placed downstream or directly surrounding the pion production target increase the density of the charged pions emerging in forward direction by collecting and focusing pions emerging under larger forward angles. The pions decay in large decay volumes/tunnels; at the end of the decay volumes a beam stopper is placed to stop primary protons and unwanted secondaries to reach the near (and far) detectors. For the production of rare ion beams two basic principles are currently employed, the isotope separator online, ISOL, and the in-flight method. ISOL type rare ion beam facilities (RIB) consist of a production target connected to a heated transfer line for an efficient extraction of rare ions from the target, leading to an ion source, a magnetic mass separator and an optional post-acceleration stage again followed by a separator system to select the species of interest. The in-flight method produces the rare ions by bombarding a fragmentation target with heavy ions. The fragements of interest are then selected by mass and charge in a fragment analyzer system with an integrated degrader system. Thereafter, the rare ion beam can directly be guided to experimental stations or can be stopped and re-accelerated, again separated by the charge over mass ratio to then be used in experiments.

The overall efficiency of any of these target stations shall be defined as the product of the efficiencies of each integral part. The efficiency of the production targets (ε_{Target}) is proportional to the yield (N_{prod}) of secondaries produced, i.e.

$$\varepsilon_{Target} \sim N_{prod} = \sigma_{prod} \cdot N_{Target} \cdot I_{Beam}$$

with σ_{prod} the production cross section, N_{Target} the number of nuclei in the production target and I_{Beam} the beam intensity. Ideally, the production volume of the secondary particles should be as compact as possible, as the brightness of secondaries is maximized. Hence, the proton beam profile should be small. However, this leads to stringent conditions for cooling of the production target. In order to evacuate the induced power, large amounts of coolant need to be used, diluting the target. In addition, the radiation damage induced in the target will lead to a deterioration of material properties, such as thermal conductivity, and embrittlement of the target material. These material parameters will directly influence the target lifetime and as a consequence also the target efficiency.

Spallation Targets

Currently there are four operating spallation neutron sources in the world and two new facilities under construction. The operating facilities are: ISIS in the UK with two operating target stations of 180 kW (Target Station 1) and 60 kW (Target Station2), SINQ and UCN at PSI in Switzerland with a beam power of 1.0 MW and 10 kW respectively, SNS at the Oak Ridge National Laboratry with a 1.4 MW short pulsed beam and the Material and Life Science Facility (MLF) at JPARC with an envisaged beam power of 1 MW. Besides the spallation sources at PSI – SINQ and UCN - ISIS, SNS and MLF are operated in a (short-) pulsed mode. The two facilities currently under construction are the Chinese spallation source, CSNS, in Dong Guang and the European Spallation Source (ESS) being built in Lund, Sweden.

For spallation neutron sources the optimum proton beam energy lies in the regime between 0.8 - 3.0 GeV; above 3.0 GeV π^0 production leads to an energy 'drain' from the hadronic into the electromagnetic cascade making neutron production per incident MW less efficient. Generally, comparing the different production mechanisms for neutrons spallation is the second most efficient, with only laser controlled D-T fusion being more efficient in terms of energy deposition per produced neutron. Basically there are two target types that have been used up to now in these sources. Liquid metal targets use the spallation material, a high Z material for high neutron yields, as a cooling medium by keeping it liquid and pumping it through a heat exchanger. Up to now two materials have been used, mercury, being liquid at room temperature, and lead bishmuth eutectic (LBE) with a melting temperature of ~ 126˚C. The second target type consists of solid materials cooled by a separate cooling agent, e.g. light or heavy water. The advantage of the liquid metal targets over the targets with a separate coolant is that the spallation material is not 'diluted' by the coolant and moderation inside the target does not occur. A disadvantage of the liquid metal targets is the onset of shock waves and resulting cavitation erosion of the target shroud with increasing beam power in pulsed operation. The choice of target type depends on the peak power deposition, which will induce a peak temperature increase, see Figure 3.

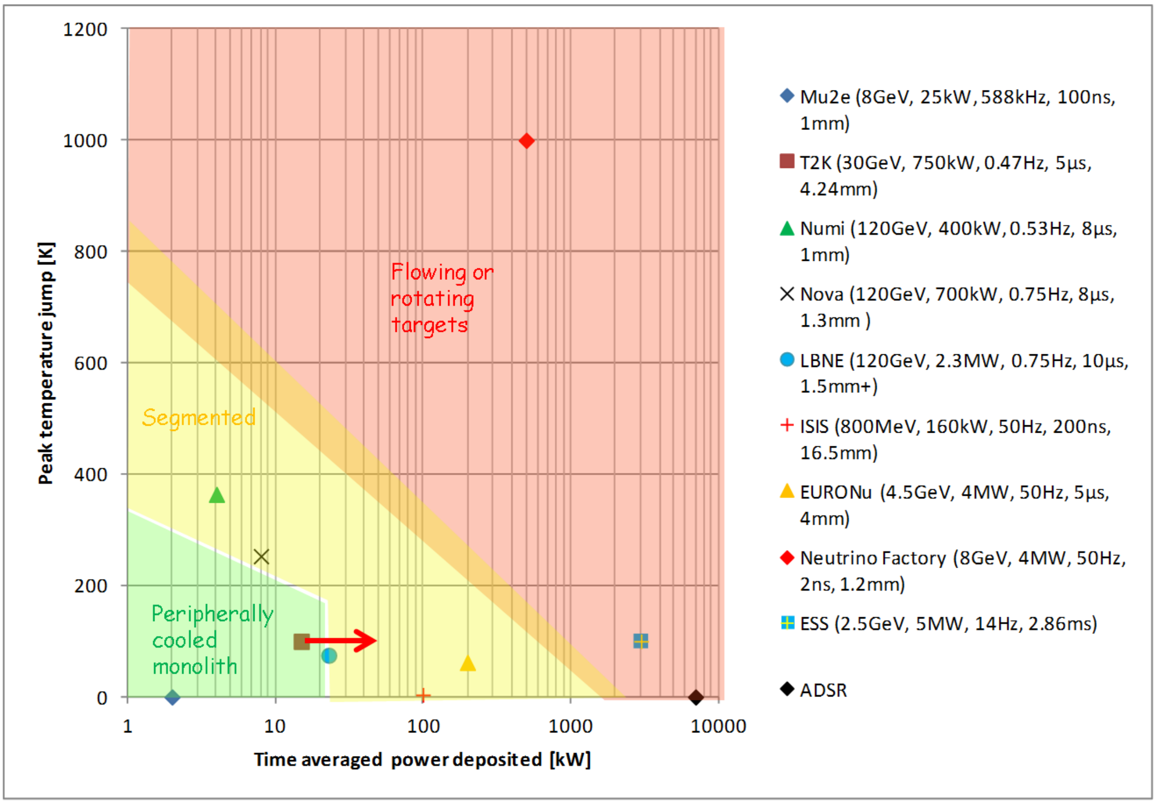


Figure 3: Time averaged power deposition vs. temperature jump.

Generally, the lifetime of spallation targets is limited by radiation damage effects such as embrittlement, decrease of thermal conductivity, swelling, creep and pitting damage in combination with stresses induced by thermal cycling and fatigue. In order to increase the target lifetime large beam profiles can be used or, as planned in the cae of ESS, a rotating target can be used. However, increasing beam profiles decrease the 'neutron production brightness' and the target efficiency consequently. The overall efficiency of a spallation neutron source can be factorized in the efficiencies of its integral parts – target, moderator, reflector, neutron-guide system, shielding, and neutron detector at the experiment– as

$$\varepsilon_{ss} \sim \varepsilon_{beam} \cdot \varepsilon_{target} \cdot \varepsilon_{mod} \cdot \varepsilon_{ref} \cdot \varepsilon_{guide} \cdot \varepsilon_{shield} \cdot \varepsilon_{det}$$

The ratio of detected over produced neutrons at the spallation neutron source SNS in Oak Ridge is on the order of 3×10^{-10}. At the Swiss spallation neutron source SINQ the ratio is similar.

Besides the efficiency as given above also the uptime of a facility over the total elapsed time shall be considered in a general figure of merit.

Rare Isotope Beam Targets

Rare ion beams can currently be produced by two methods, the Isotope Separation Online (ISOL) and the in-flight method. The in-flight method uses a primary heavy ion beam hitting a fragmentation target, usually a low Z material, for instance Carbon. Fragments emerging from the target are then separated by means of a magnet and degrader system, the so-called fragment analyzer. Subsequently, the fragments can directly be used in experiments or be post accelerated. The ISOL method uses a production target from which the rare isotopes diffuse to an ion source and are subsequently mass separated. In contrast to other production targets, such as spallation, muon or neutrino targets, specific target compositions are used to maximize the output of requested isotopes. Moreover, in order to allow for an efficient effusion and diffusion of isotopes from the target to the ion source the targets need to be uniformly heated and the transfer line to the ion source heated or cooled, depending on the ion of interest. The intensity of ions will therefore depend on the production efficiency and on the diffusion and effusion efficiency as well as on the ionization efficiency. For $^{32}Ar^{7+}$ the combined extraction efficiency

$$\varepsilon_{extr} = \varepsilon_{diff+eff} \cdot \varepsilon_{ion}$$

was measured to be on the order of 10^{-6}.

The major challenges for the operation of rare isotope production targets using the ISOL technique are the high power deposition densities due to stopped primary beams, the radiation damage induced by the primary beam in the container materials and the operation of the ion source, which is complicated by evaporation of target material due to the high power. The optimization of ISOL targets is highly complex as many different physical processes besides the production have to be considered; these are high diffusion rates which need high operation temperatures and therefore heated targets, high thermal diffusivity and conductivity and permeability for the diffusing isotopes. Hence different target types are employed; disk targets are composed of thin targt disks, increasing the diffuson of produced isotopes out of the target material, molten metal or molten salt targets or even two-step targets, where the isotops of interest are produced by interacting of secondary particles created in a dedicated production target. All target types are studied and undergo constant improvement at the RIB facilities at TRIUMF, ISOLDE (CERN), SPES and IBS-RSIP. An intensive study of the two step target concept has been conducted in the framework of the EURISOL project and successful tests of the concept have been performed at ISOLDE (CERN).

The main life-time limiting factors for these targets are thermomechanical challenges due to the high power densities and large power gradients in the system, the pulsed operation and corrosive processes between target and container materials. In addition, radiation damage leading to deterioration of thermo-physical and mechanical properties such as the thermal conductivity, tensile strength, resistivity, and others is a sever life-time limiting factor. Additionally, microstructural changes of the material such as swelling, creep and radiation assisted corrosion are observed. Hence, studies are being carried out to search for better, more radiation resistant target materials, e.g. SiC.

For the in-flight method, using ion beams, rotating production targets and beam dumps are currently investigated. Examples for these rotating targets studies are NSCL-FRIB, GSI-FAIR and GANIL-SPIRAL-II. One of the materials of choice is Carbon as a rotating wheel or rotating multidisk geometries.

Neutrino Targets

The basic setup of neutrino target stations consists of a production target, usually thin and long, which is positioned in or close to a magnetic “lense” system, commonly called horn system, to increase the yield of pions emerging from the production target in forward direction. Those pions subsequently decay in a decay tunnel into muons and neutrinos. At the end of the tunnel system a beam dump system is installed that stops pimary particles, i.e. protons and other unwanted particles contributing to back-ground signals. Usually there are two detector systems, a ‘near’ detector not too far behind the beam dump and a ‘far’ detector several hundred or thousand kilometers from the production site.

Technical challenges for the target system are cooling, of the production target and also the surrounding horn magnets. Some facilities use edge water-cooled target, made from low Z materials, i.e. Beryllium or Carbon. The target is usually a thin, long structure to lower the absorption probability for produced pions. High Z materials would increase the pion yield, however need more cooling; hence composite targets, of Carbon and high-Z materials at the downstream tip of the target are considered. The required cooling power strongly depends of the power density induced by the primary proton beam. Studies on the impact of the proton beam size on the pion production show that small radius targets achieve higher pion yields; however, the smaller beam size then increases the induced power density. Besides water-cooled targets also targets cooled with gases are in operation. At T2K at J-PARC a He-cooled Graphite target is operated, currently with a beam power of 350 KW. However, the design beam power is 750 kW. The first target was replaced after 4 years of operation, receiving 6.5×10^{20} protons. The pulsed beam induces stress waves in the target material which lead to high stress values especially in cases where the proton beam is not perfectly centered on the target. In addition to stress due to the proton beam of course the neutrino targets also suffer from radiation damage phenomena, reducing strength and thermal conductivity of the target materials.

Recommendations

The definition of a single figure of merit for the efficiency of a production target is impractical. A major measure of course is the number of produced secondary particles per indiced primary particle. However, one always needs to find compromises between a maximum particle production, thermal and structural demands for the integrity of the target and container materials as well as other life-time limiting factors such as radiation damage. The optimization of targets via trial and error experiments is not a viable way as it is much too expensive and facilities need to provide beams to their users. Hence, simulations of the different aspects of production targets are indispensable. The optimum would be simulations starting at the ion source of the accelerator and ending with the particle of interest inside the user's detector, covering all ascpects thermal, stresses, particle production and others. Today such simulations are not (yet) feasible. Nevertheless, subproblems can be solved using different code systems, treating different physical phenomena. Further development of all these code systems for instance Monte-Carlo particle transport codes, Finite Element Simulations of temperature and stress fields, Computational Fluid Dynamics simulations and Molecular Dynamic simulations of the evolution of radiation damage of the lattice structure of materials, are vital for the development of more efficient production targets. In addition, their coupling, i.e. the information transfer from one simulation to another is also becoming more and more important and, therefore, must not be forgotten.

The higher the deposited power in target materials becomes, the lower expected life-times of production targets will become due to material property deterioration, such as loss of thermal conductivity, loss of strength and increase of hardness. All production targets, be it spallation targets, targets for the production of rare ion beam or neutrino production targets share basic similarities such as the dissipation of power and the material deterioration due to radiation induced effects. These effects and their impact on important parameters such as strength and conductivity have to be better understood and unfolded. Hence, collaborations such as RADIATE and workshops like IWSMT (International Workshop on Spallation Material Technology) are of large importance to share acquired knowledge and improve production target efficiencies.

RF sources

Modulators

Modulators transform the AC electricity from the electrical network to the DC voltage needed to drive CW or pulsed RF sources. Most systems are either i) pulse transformer based devices, or ii) RF transformer based devices. Stacked multi-level modulators of the latter kind, which are being developed for ESS (Figure 4) can achieve up to 92% efficiency with several Megawatts of output power and very short rise times (~110 us), whereas pulse transformer based systems achieve between 85-90% efficiencies with typically longer rise times (e.g. 300 us). It was found that basically all modulators are in the 85-92% efficiency range, independent of their output power (e.g. for single solid state 1 kW modules or multi-MW klystrons), DC voltage (<1 kV up to < 100 kV), or pulse length. As the efficiency during the pulse is already very high, further improvements can only be made in shortening the rise time, which will shorten the overall RF duty cycle and therefore improve the overall efficiency.

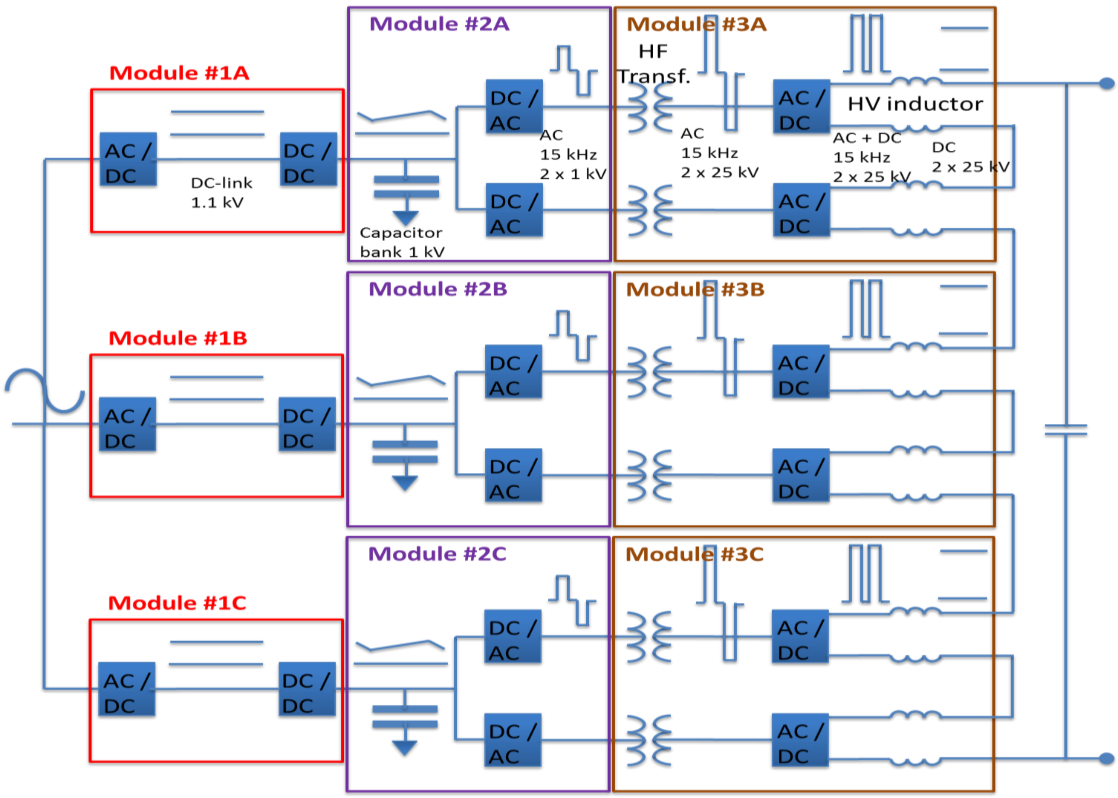


Figure 4: Topology of stacked HF transformer based modulator developed by ESS (Carlos Martins, ESS).

Klystrons

Klystrons are today's workhorses for high-power proton machines. The technology is well established and covers frequencies above 300 MHz with output power values in the MW range. Typical performance values are given in Table 2. Their advantages are: i) long life-time of up to 40 kh, ii) large gain (input amplifiers are in the range of some 100 W), iii) high output power. Some well-known disadvantages are: i) High-voltage needed for the cathodes, generally above 100 kV, which means that oil tanks are needed for electrical break down protection, ii) they need expensive and sophisticated modulators, iii) large size for low-frequency devices (Figure 5) iv) the gain curve goes into saturation, which means that in order to have some operational power margin, klystrons are typically operated below saturation, where their efficiency drops below the one quoted by the vendors. FNAL, DESY and others have recently successfully employed klystron linearization algorithms, which allow operation closer to saturation and which therefore allow higher efficiency operation.

At present, the working point efficiency is typically in the range of 50%. In the last few years a new R&D effort started, using modern beam simulation tools in order to optimise the energy conversion of the electron beam(s) in the output cavities. This approach promises to push efficiencies (at saturation) to 80% or even towards 90%. The use of core-oscillations, hollow beams, or adiabatic bunching shows promising results in simulations and first prototypes are already under production. Higher efficiency will also allow using lower cathode voltages, removing the need for oil tanks and allowing for simpler modulators with faster rise times.

Operation below working point: Efficiency drops from around 55 – 65% at saturation to around 50% at the working point. Further reduction in output power usually yields a severe loss in efficiency.

Recommendation: The R&D on higher efficiency klystrons using modern electron beam physics tools is already very active and should be continued. Also, the R&D effort on linearization algorithms should receive continued support.

Figure 5: 352 MHz klystrons by Thales and CPI as used in Linac4 and foreseen for the ESS warm linac (Chris Lingwood, Lancaster University).

Table 2: Performance examples of klystrons

RF source type	Gain [db]	Op. output power pulsed [kW]	Rise /Fall time [us]	Pulse length range[us]	Rep rate range [Hz]	Op. output power CW [kW]	Efficiency (DC/RF) at working point [%]	High voltage needs [kV]	Frequency range [MHz]
Single Beam	40-5	1000-3000	300 ns	4 ms		<1200 kW	55 (65 max)	~90-120kV	0.3GHz-1.5GHz
MB	40-5	10,000-15,000 kW (up to 1.5 ms at least	300 ns	4 ms		< 1200 kW (no point)	60 (70 max)	~90-120kV	0.3GHz-1.5GHz
Future Single Beam		-		-			70	40-60 kV	0.3GHz-1.5GHz
Future MB							80	40-60 kV	0.3GHz-1.5GHz

Solid-State Amplifiers

Solid-state amplifiers promise to combine cost-efficient RF power generation with the advantages of a modular system, which may allow the hot-swapping of single faulty modules during operation. They are found in a power range between 10 and 200 kW (see Table 3) and some systems already operate at higher power values. Frequencies range from 0 to 2.5 GHz and typical efficiencies for complete systems including power supplies are in the range of 45 – 55% with with better values for frequencies below ~700 MHz (see Figure 6). The field is under active development and potential increases in efficiency depend on the development of new transistors and the reduction of losses when combining multiple modules. At present solid-state systems are competitive for power values below 100 kW, but they seem to be too expensive and too inefficient for larger power values. So far the transistor development is mostly driven by industry and future amplifiers based on Silicon Carbide transistors, such as the Siemens project to develop a 352 MHz amplifier for several 100 kW, promise to increase available output power and efficiency.

Operation below working point: only moderate loss in efficiency

Recommendation: More R&D on the actual loss mechanism in transistors would be beneficial and should help in the development of higher efficiency devices.

Table 3: Performance examples of solid-state amplifiers

Project	Gain [db]	Op. output power pulsed	Rise /Fall time [us]	Pulse length range [us]	Rep rate range [Hz]	Op. output power CW	Efficiency (DC/RF) at working point [%]	High voltage needs [kV]	Frequency range [MHz]	Comment
ELBE		16 kW	0.02/0.06	0.001 - 100	0-CW	16 kW	47%	-	1300	
R&K		16 kW	0.01/0.01	any	0-CW	16 kW	36%	-	1300	forced air/water
Tomcod		-		-	CW	10 kW	45%	-	700	up to 80 kW
R&K		-		-	CW	20 kW	?	-	509	forced air/water
PSI		~70 kW	0.045	any	0-CW	~70 kW	~50%	-	500	grid to RF
Cryoelectra		-		-	CW	45 kW	51%	-	500	
LNLS		-		-	CW	25 kW	57%	-	472	
ESRF		70 kW		any	1 - CW	70 kW	55%	-	352	DC-RF
Soleil		30 kW		any	0-CW	30 kW	50%	-	352	DC-RF, 180 kW
Tomco		-		-	CW	10 kW	55%	-	350	up to 110 kW
Cryoelectra		-		-	CW	16 kW	46%	-	118	
Siemens		-		-	CW	18 kW	75%	-	72.5	
Cryoelectra		-		-	CW	115 kW	57%	-	72.8	
R&K		60 kW		any	0-CW	60 kW	56%	-	1.8	
State of the art		**10 - 100 kW**	**10-60 ns**	**any**	**any**	**10-100 kW**	**45-55%**	**-**	**0-1300**	
Potential performance										
R&D: Siemens/ESS		48 kW		3000	14 Hz	-	>60%	-	352	up to 400 kW

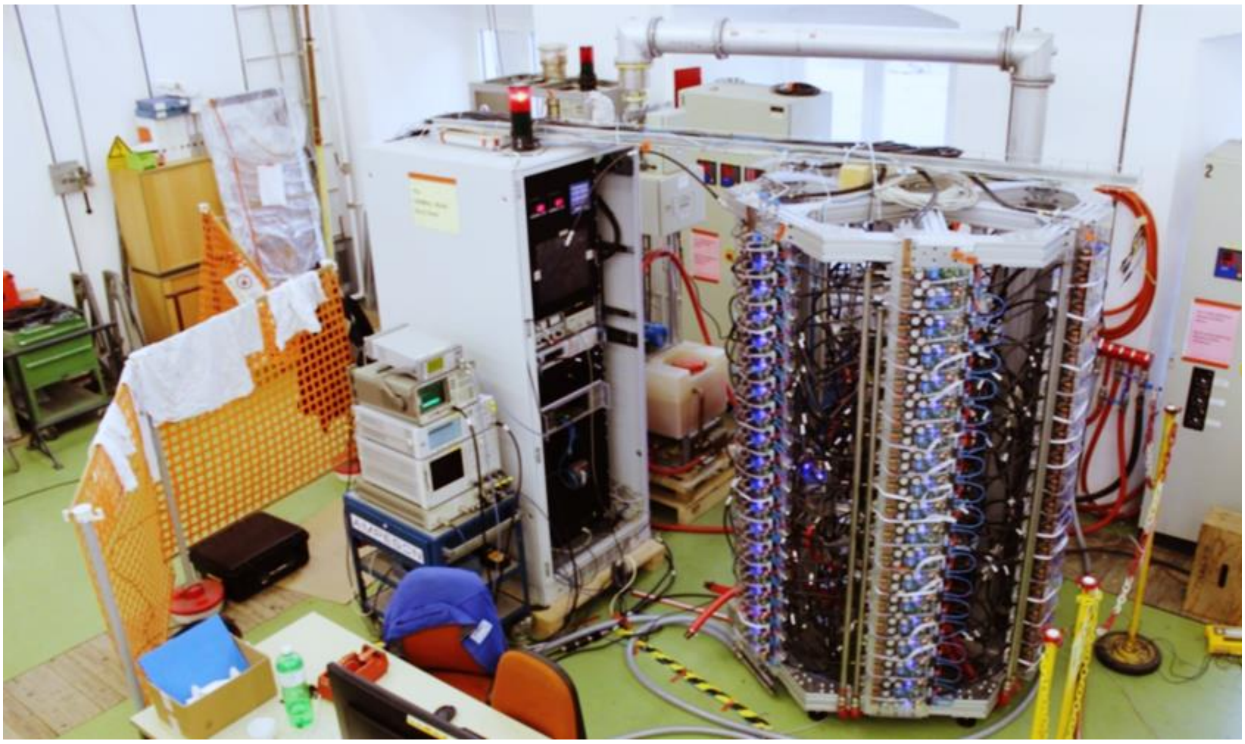


Figure 6: 65 kW, 500 MHz solid state amplifier at PSI (Marcos Gaspar, PSI).

Magnetrons

Magnetrons power microwave ovens, which are used in private households (see Figure 7) or for industrial applicances. In accelerators they are so far only used in machines, where a single RF source can cover the power needs (e.g. electron machines for medical applications). The combination of multiple devices requires a precise phase and amplitude control, which has not yet been achieved for multi-cavity accelerators. Due to their low cost, high efficiency and their relaxed requirements for pre-amplifiers, magnetrons are highly attractive (see 18) but so far we have heard of only two R&D activities (Lancaster Universtiy, Muons Inc. and Fermilab) to employ magnetrons for accelerators. A proof of principle experiment with microwave-oven-type sources has shown that phase/amplitude control is indeed possible and this should be followed up by more R&D on higher-power devices.

Operation below working point: magnetrons are constant output power devices. Operation below working point may decrease the efficiency considerably, which should be studied further.

Recommendation: Increase of R&D on amplitude/phase stabilisation of magnetrons and explore the potential for higher-power devices.

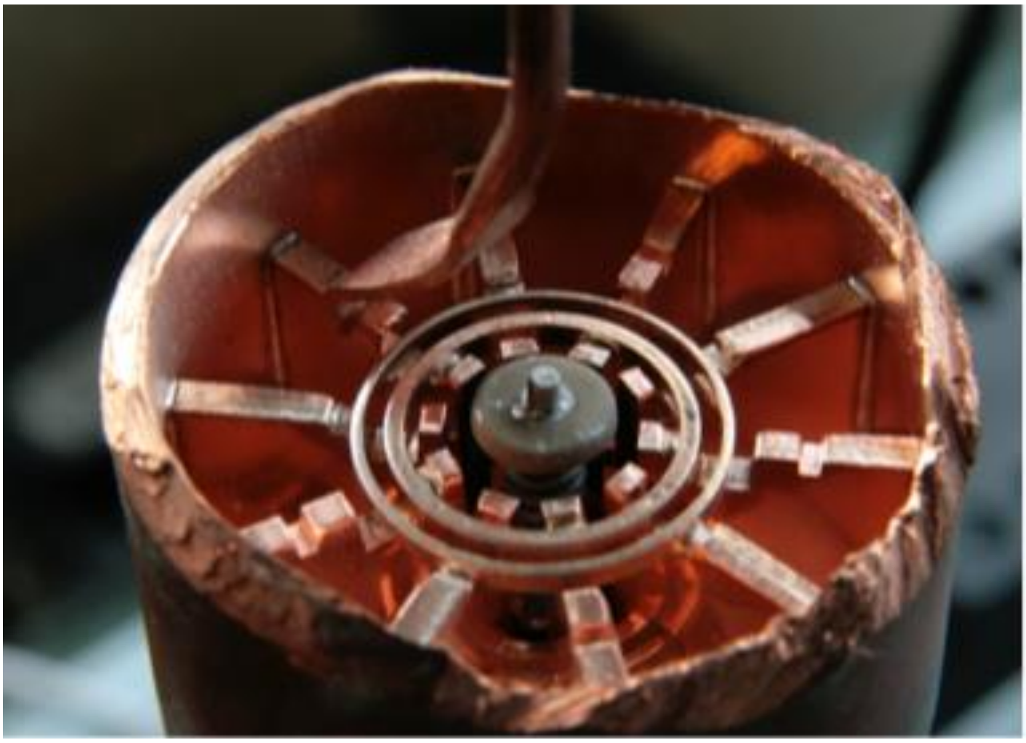


Figure 7: Cross section of a typical microwave cooker magnetron (Brian Chase, FNAL).

Table 4: Performance examples of magnetrons

RF source type	Gain [db]	Op. output power pulsed [kW]	Rise /Fall time [us]	Pulse length range [us]	Rep rate range [Hz]	Op. output power CW [kW]	Efficiency (DC/RF) at working point [%]	High voltage needs [kV]	Frequency range [MHz]	Comment
State of the art: CPI ECONCO	25	?	?	-	-	100	80	20	826 - 929	tube only
CCR/CPI	25	100	?	10 ms	10	10	80	22	1300	tube only
Performance potential?	25	100				100	60		400	AC-RF

Gridded tubes: tetrodes, diacrodes, IOTs

Tetrodes are used in many accelerators today (see Figure 8). With a performance reaching into the MW range, usable at CW or any pulse rate, they are suitable for frequencies up to around 400 MHz with an efficiency of around 70% (see Table 5). The development of

Diacrodes has so far been very limited. The operational models have a similar performance reach than tetrodes but can in principle go up to slightly higher power values and should be suitable for higher frequencies. IOTs exist so far only for power values below 100 kW. However, they are usable over a large frequency range up to over 1 GHz with the same efficiency as tetrodes. Prototyping of multi-beam IOTs, which promise to reach the MW level, has only just started within the frame of an ESS-CERN collaboration. First tests of industry developed MB-IOTs are expected in 2016.

All gridded tubes are very tolerant to fluctuations of their high voltage supply (10-20%) and they have extremely short rise times, which makes short pulse operation more efficient than for klystrons. In pulsed mode gridded tubes can be overdriven to achieve higher peak power, which is not possible for klystrons.

Operation below working point: only moderate loss in efficiency

Recommendation: Continuation of R&D on MB-IOTs.

Figure 8: 200 MHz tetrode combination in operation at the CERN SPS since 1976 (Eric Montesinos).

Table 5: Performance examples of gridded tubes

RF source type	Gain [db]	Op. output power pulsed [kW]	Rise /Fall time [us]	Pulse length range [us]	Rep rate range [Hz]	Op. output power CW [kW]	Efficiency (DC/RF)@ working point [%]	High voltage needs [kV]	Frequency range [MHz]	Comment
Tetrode: state of the art	14-16	4000	ns	any	any	1500	70	10-25	30-400	
Diacrode: state of the art	14-16	3000	ns	any	any	2000	70	20-30	30-400	
IOT: state of the art	20-23	130	ns	any	any	85	70	36-38	?-1300	
MB-IOT: performance potential	20-23	1300	ns	any	any	150	70	50	704	prototype testing in 2016

Conclusion on RF sources

- **AC-DC conversion** usually has an efficiency between 85% and 92%, regardless of the required output power. Modulator rise times have an impact on the overall efficiency (e.g. HV klystron modulators).
- **Frequency ranges:** Tetrodes and diacrodes are usable up to around 500 MHz and can provide MWs of output power (less for higher frequencies). IOT's can be used from 500 MHz to around 1.3 GHz but are presently limited to <100 kW. Klystrons are used between 300 MHz and 10 GHz with power ratings between 100's of kW up to 10's of MW (depends on duty cycle). Solid state amplifiers can be used between 0 and 2.5 GHz with output power presently up to 200 kW (less above 700 MHz). Magnetrons are suitable above 300 MHz and are so far limited to <100 kW.
- **Efficiencies:** Magnetrons claim up to 85%, which still has to be proven for complete systems. Gridded tubes work at 70% , klystrons at around 50% (working point) and solid state amplifiers reach around 55%. Adding cooling systems to all of the above RF sources typically reduces the quoted effiencies by a factor of ~0.75.

Recommendations for RF source R&D

1. The potential of magnetrons needs to be fully explored. They promise to deliver high-efficiency at low capital investment cost. More R&D effort is urgently needed.
2. The recently started R&D on high-efficiency klystrons needs to continue and prototypes need to be built and characterised.
3. Existing R&D programs on multi-beam IOTs and high-power solid-state amplifiers should continue. MB-IOT's have the potential to extend the frequency range of

gridded tubes into the GHz range, while increasing their power output to the MW level at 70% efficiency. Solid state can develop into an alternative for klystrons for lower power applications.

4. For all systems, except maybe for gridded tubes, R&D into minimizing the controls overhead can provide significant gains in efficiency.

Accelerator concepts

The type and parameters of an accelerator of a proton driver are determined by the exact application which determins the choice of beam energy, average power, and time structure. However, for a given type and boundary conditions efficiency is a crucial factor.

The goal of the session was to discuss the crucial parts affecting efficiency for different accelerator concepts of the proton drivers, the wall-plug efficiency limits for MW-range proton drivers, potential routes for efficiency improvement and new technologies that should be developed for this.

GeV-scale energy range and MW-power range was considered. The applications cover the generation of neutrinos, muons, neutrons for research purposes and accelerator driven systems.

Only few accelerator concepts are suited for high intensity proton beam production:

- Cyclotrons and Fixed-Field Alternating Gradient accelerators (FFAG)
- Rapid Cycle Synchrotrons (RCS)
- High intensity pulsed linear accelerators
- CW Superconducting RF linear accelerators

High intensity accelerators in operation today are:

- Cyclotron (High Intensity Proton Accelerator Facility PSI)
- SRF Linac (Spallation Neutron Source, ORNL)
- RCS and Main Ring (Japan Proton Accelerator Research Complex, J-PARC)

The main drivers for accelerator efficiency are the RF source efficiency, the efficiency of the accelerating process itself, the Magnet system, cooling and/or cryogenic systems as well as auxiliary systems.

1. Cyclotron, Joachim Grillenberger (PSI)

The efficiency drivers of the PSI cyclotron were analysed. The PSI Ring cyclotron is the basis of the high intensity proton facility providing the CW beam for a wide range of diffent applications – neutron and muon experiments, medical application, etc.
The PSI cysclotron has the following basic parameters:

Accumulated particles: protons
Energy: 590 MeV
Beam current: 2.4 mA
Beam Power: up to 1.4 MW
Number of turns: 186
Number of sector magnets (normal conducting): 8.
Number of resonators: 4 accelerating (50 MHz, 850 kV/p), 1 Flattop (150 MHz, 550 kV/p)

The cyclotron and the facility layout are shown in Figure 9 and Figure 10.

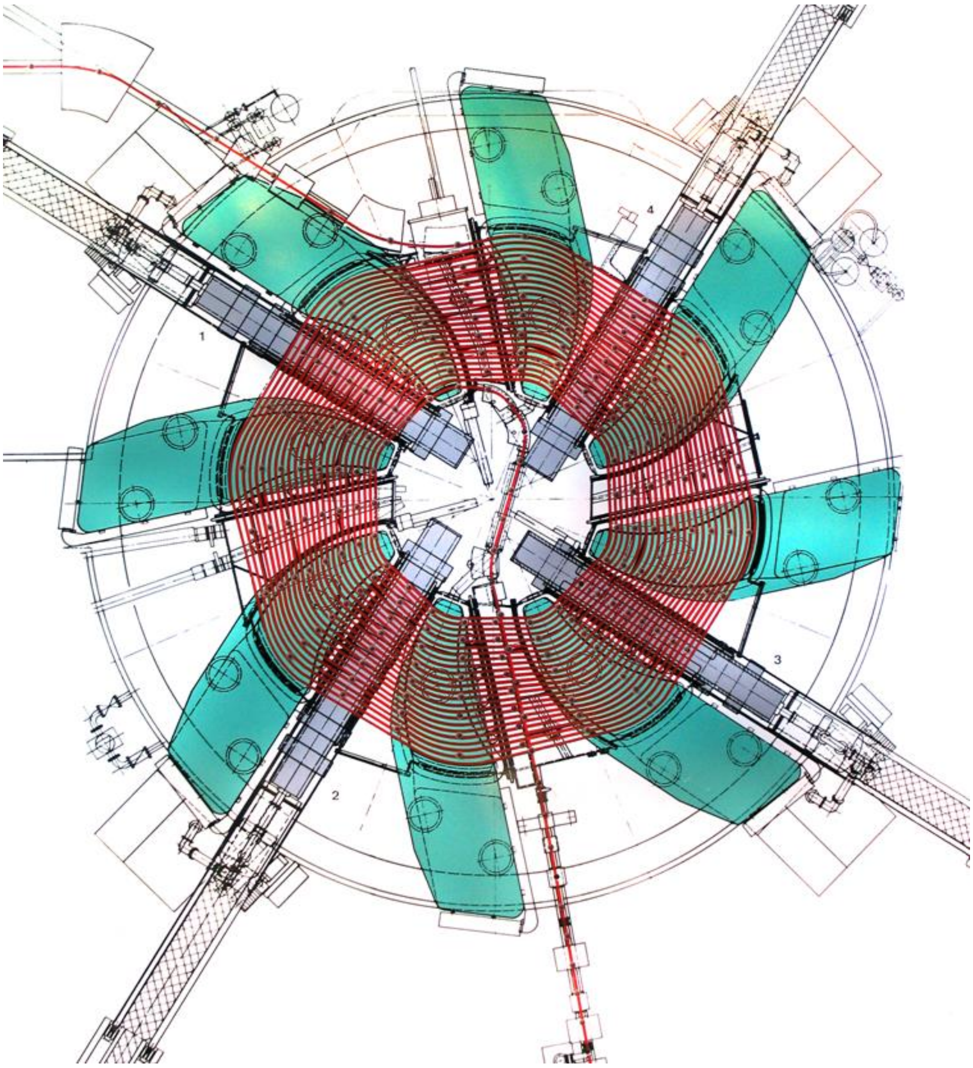


Figure 9: The 590MeV isochronous cyclotron at PSI with a diameter of 15m.

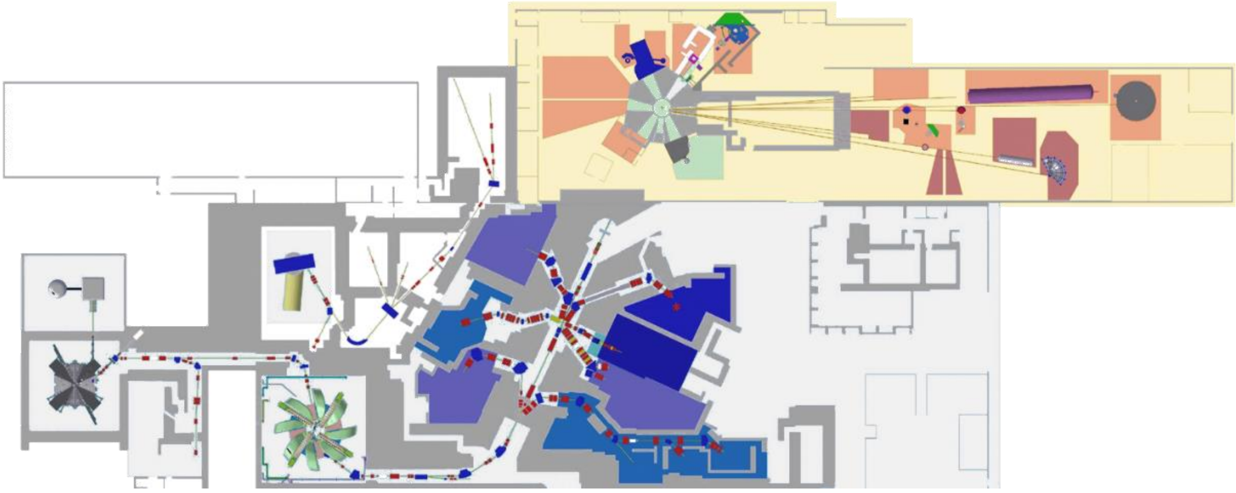


Figure 10: PSI cyclotron facility layout showing Muon beamlines and the neutron source with instruments in the upper part of the graphics.

At the PSI HIPA facility 13% of the total power drawn from the grid is converted to beam power. The total power consumption from the public grid is about 10 MW. The main efficiency drivers are the RF system (4.1 MW), magnets (2.6 MW), and auxiliary systems (3.3 MW). The power consumption breakdown is shown in Figure 11.

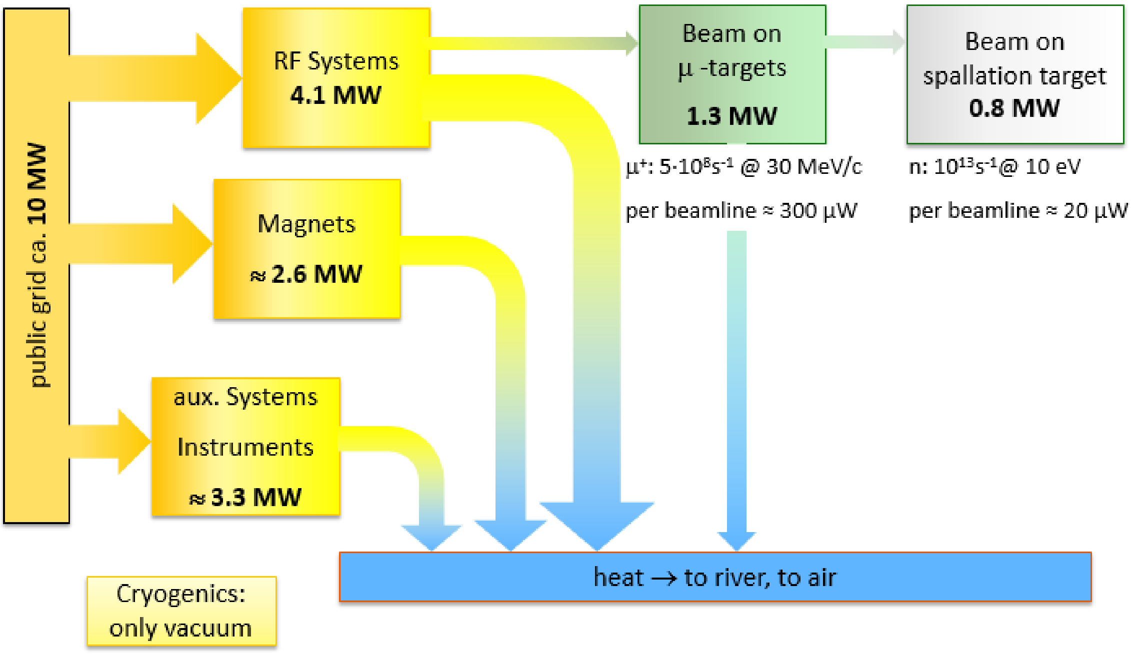


Figure 11: Breakdown of PSI HIPA facility power consumption.

Neglecting secondary beamlines and experimental facilities, the efficiency of the bare accelerator is 19%. Furthermore, it was shown, that increasing the beam current to 3 mA would lead to an even higher efficiency of 21% since the base load remains constant and the beam load increases roughly linear with the beam current. A cyclotron providing a 10 MW beam at 0.8..1 GeV seems feasible with similar technology.

2. Pulsed linac, Sang-Ho Kim (SNS)

An SNS linac provides the beam for the neutron spallation source. The SNS linac has the following basic parameters:
Accelerated particles: H^-,
Accumulated particles: proton
Energy: 1 GeV
Average beam current: 1.4 mA
Beam Power: up to 1.4 MW
Repetition rate: 60 Hz
Macro-pulse width: 1 msec
Average macro-pulse beam current: 26 mA
Room-temperature linac accelerates from 2.5 MeV to 186 MeV
Superconducting linac accelerates from 186 MeV to 1 GeV.

The overall SNS machine layout and the beam time-structure in the linac and the ring are shown in Figure 12. A fraction of 5.3 % of the total power drawn from the grid is converted to beam power. Figure 13 shows the breakdown of electric power consumption by systems at SNS during 1.4 MW operation. The Linac portion of the power consumption is 16.3 MW and the overall efficiency (from the grid power to beam power) of the Linac is 8.6 %. The operation of the high voltage power supplies for high power RF systems consumes the largest portion of the electric power, followed by the operation of the cryogenic plant. The efficiency of each RF structure in the Linac depends on various parameters such as pulse structure, beam duty factor, beam velocity, beam current, type of RF structure, operating gradient, available RF power, etc. In the SNS case, efficiencies of the warm RF structures range from 4 to 8 %, while those of the SRF structures at the present operating condition range 10-20 %. There are intrinsic parts that give rise to inefficiency due to the nature of the pulsed operation of the Linac such as settling times of the high voltage power supplies/RF systems and cavity fill time.

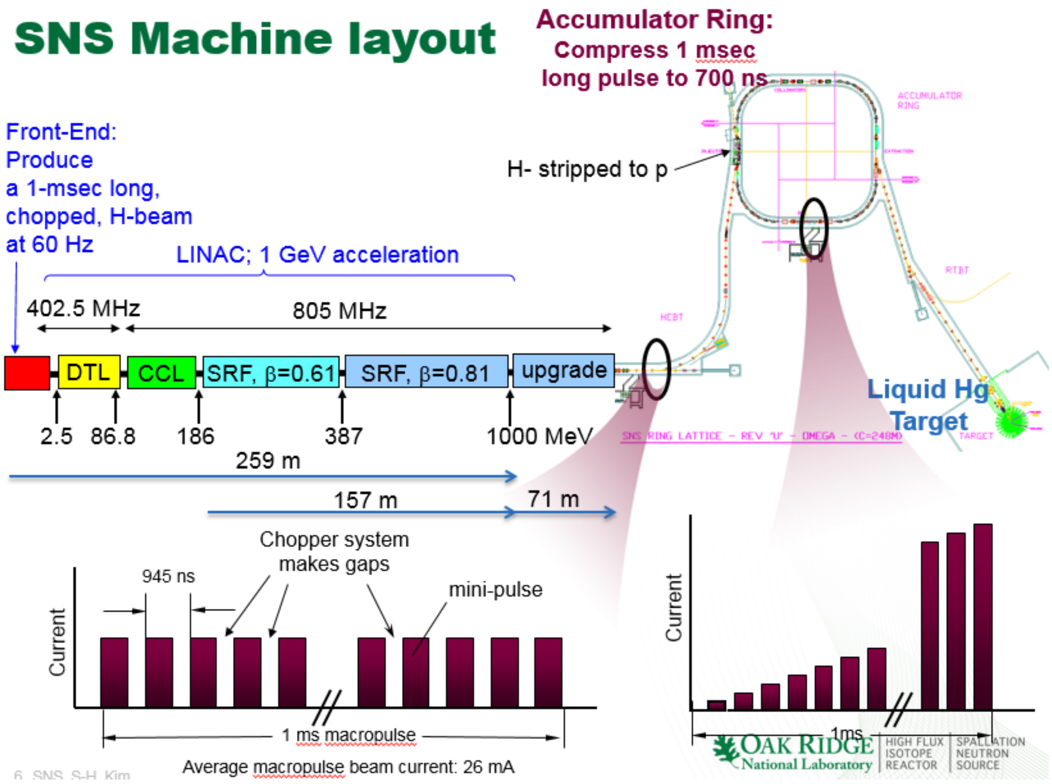


Figure 12: The SNS linac layout and the beam time structure.

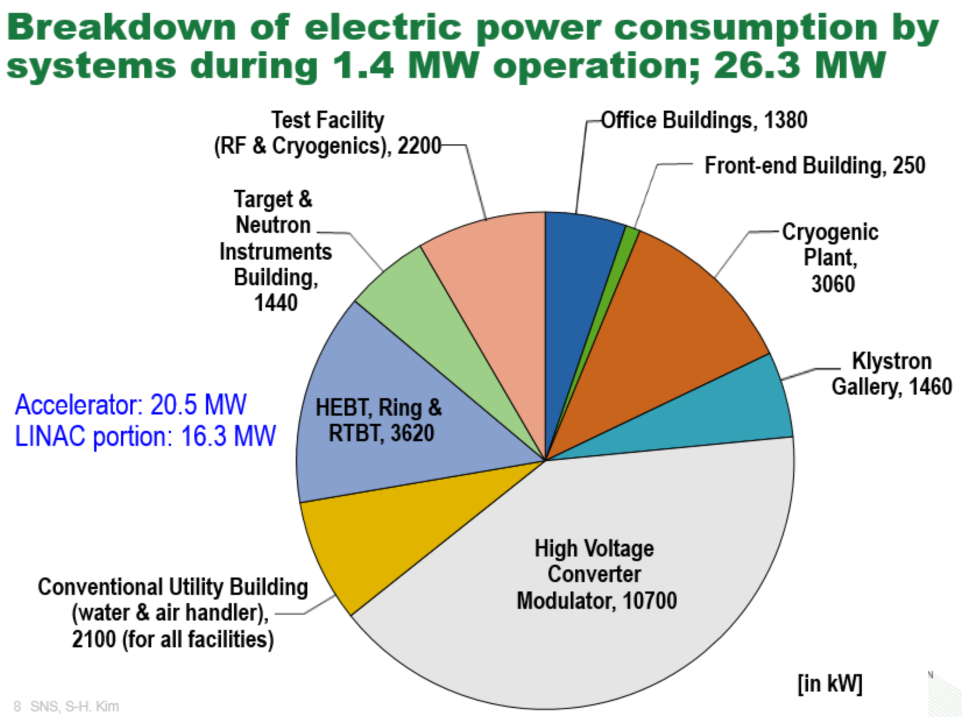


Figure 13: Power consumption breakdown of the spallation neutron source (SNS)

Figure 14 shows an example of the power flow of a SRF cavity during operation. All powers in the figure are time averaged powers. The operational setup for SRF cavities at SNS is not for higher efficiency but for the higher performance. Since one high voltage power supply feeds multiple klystrons, lower performing SRF cavities results in lower efficiency. If all cavities' operating gradient is limited by available power, the machine setup would be the constant RF power per cavity that gives much higher efficiency.

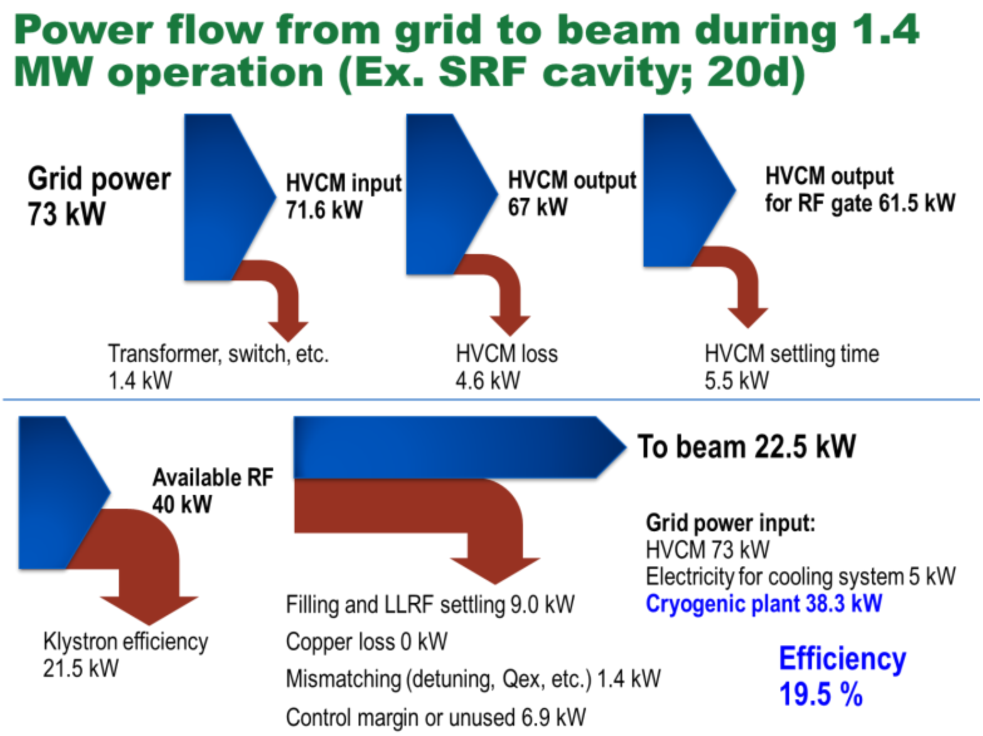


Figure 14: Example of power flow of a SRF cavity.

The pulsed SRF Linac demonstrates a high efficiency of up to ~20% at 1.4 MW, 1 GeV (RT machine for the same parameters has ~7%). There is a room for further improvement. For example, the SNS cryogenic plant is designed for 9 additional cryomodules with 50% margin. Thus, the utilization of the cryogenic plant is inefficient at the present operating condition. The SNS has plans for a proton power upgrade (PPU), which will double the beam power to 2.8 MW. For the energy upgrade, seven additional cryomodules will be installed in the reserved space at the end of the linac tunnel to produce a linac output energy of 1.3 GeV. The average macro-pulse beam current for the STS will be 38 mA which is about a 40 % increase from the present beam current for 1.4 MW operation. In the PPU operation scenario based on the SNS operational experiences, the energy efficiency of the SCL portion would be higher as can be seen in Figure 15. The efficiency improvements come from less scattering of SRF cavity accelerating gradients, a better high voltage power supply configuration, a reduced RF control margin, and an efficient utilization of the cryogenic plant.

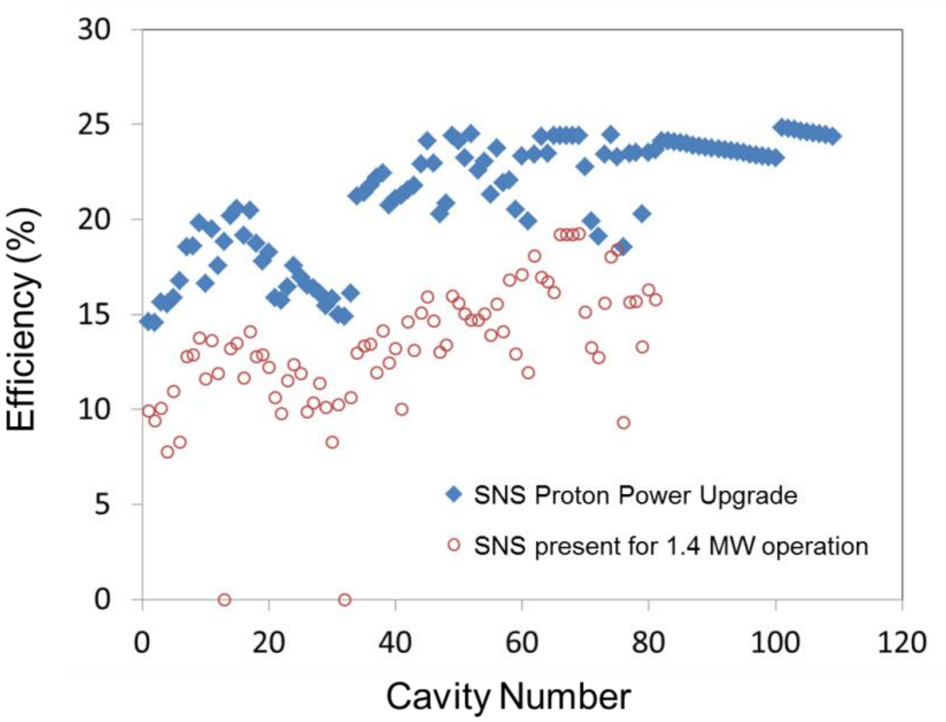


Figure 15. Efficiency comparison of individual SRF cavities between the present setup for 1.4-MW operation and the Proton Power Upgrade (plan) for 2.8-MW operation.

3. RCS and Main Ring Synchrotron, Masahito Yoshii and Yuichi Morita (J-PARC)

The J-PARC accelerator facility is a unique complex providing a pulsed proton beam for neutrino experiments as well as for a wide range of other applications (see Figure 16).
The J-PARC facility contains a 400 MeV room temperature linear accelerator, and two synchrotron rings, a 3 GeV Rapid Cycle Cynchrotron (RCS), and a 30 GeV Main Ring Synchrotron (MR).
The linac has the following parametres:

- Accelerated particles: H^- (negative hydrogen)
- Energy: 400 MeV, SDTLs and ACS
- Peak current: 30 mA ~ 50 mA (for 1MW at 3GeV)
- Repetition: 25 Hz (additional 25 Hz for the future ADS application)
- Pulse width: 0.5 ms (beam pulse), 0.65 ms (for RF pulse)

  The linac layout is shown in Figure 17.

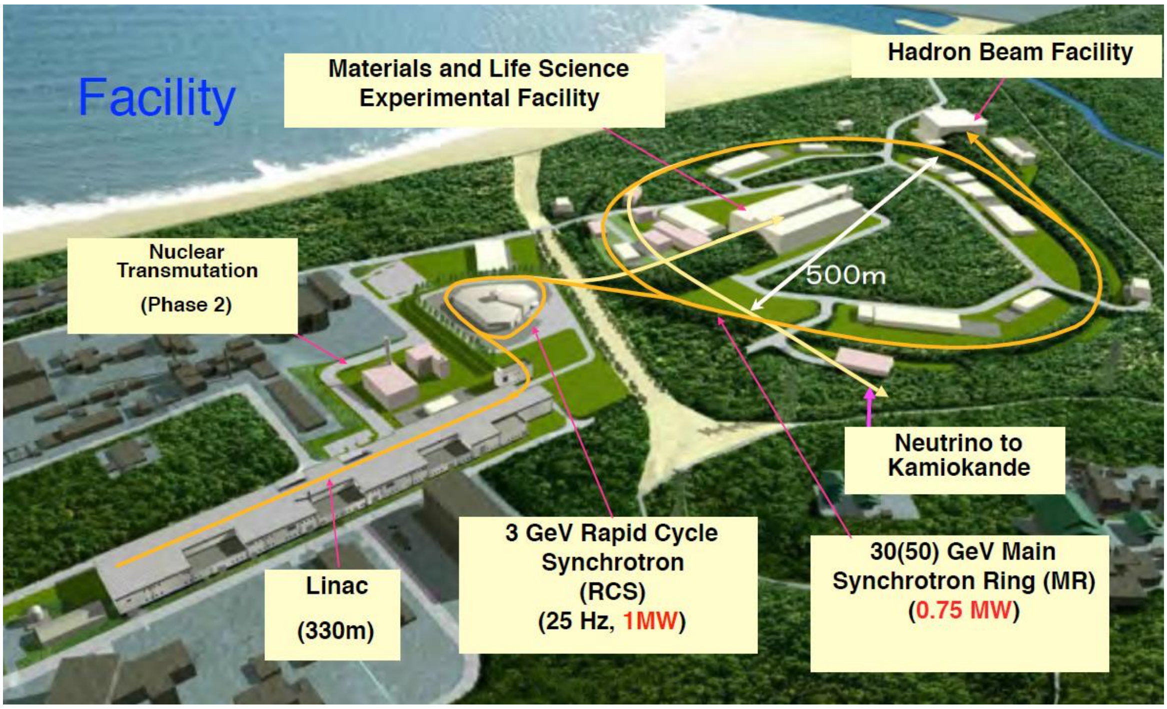


Figure 16. Overview of the Japan Proton Accelerator Research Complex (J-PARC).

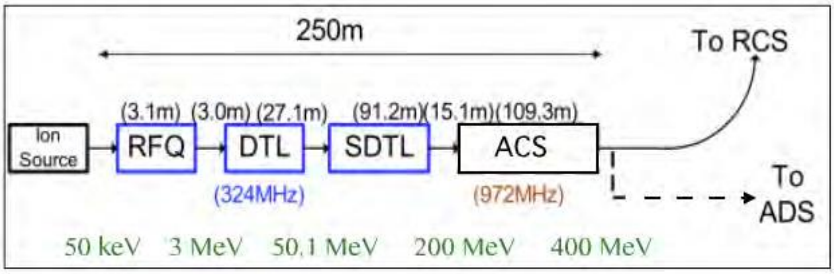


Figure 17: J-PARC linac layout.

The 3 GeV Rapid cycling synchrotron (RCS) has the following parameters:

- Circumference 348.3 m
- Injection energy 400 MeV
- Extraction energy 3 GeV
- Repetition rate 25 Hz
- Output beam power 1 MW
- Harmonic number 2
- Accel. peak voltage 420 kV

The main Ring synchrotron parameters are shown below:

- Circumference 1567.5 m

- Injection energy 3 GeV
- Extraction energy 30 [50] GeV
- Repetition rate 1/2.48s [1/3.64s]
- Output beam power 0.75 MW
- Harmonic number 9
- Accel. peak voltage 280 kV

  * a number in [ ] shows an original design value

The synchrotrons have the following features:

- Transition free lattice: the missing bend structure
- RCS: high transition gamma
- MR: imaginary transition gamma
- Magnetic alloy loaded cavity:
- High field gradient > 20kV/m
- Multi-harmonic feed-forward_beam-loading compensation
- MR: Slow and fast extractions for nuclear and particle physics experiments

The power consumption diagram is shown in Figure 18.

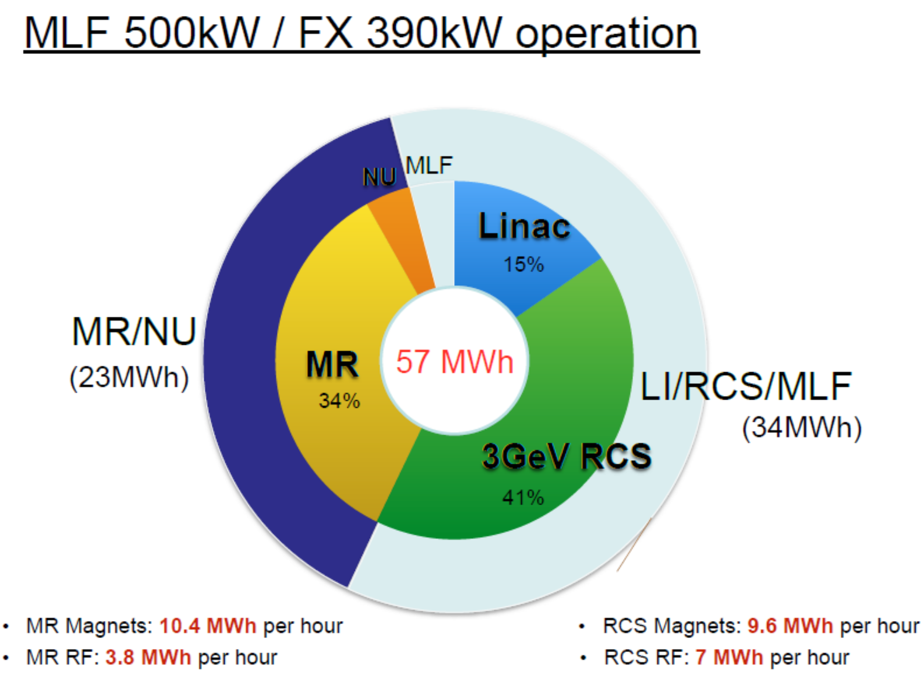


Figure 18. The power consumption diagram for J-PARC accelerator facility.

RCS is favorable to provide a high power pulsed proton beam having the energy of exceeding GeV, though the overall efficiency is several % at most. Increasing a repetition rate of an accelerator is the way to effectively develop beam power, like the J-PARC MR approach to the beam power upgrade. To realize 0.75 kW output beam power with a proton beam energy of 30 GeV lower than the design value, the cycle of the MR aims to make short to 1.3 seconds or less.

Two topics that relate to this upgrade are introduced.
- New power supplies with capacitive energy storage for the main magnets are under development. The power variation at the electrical system keeps its present value even after the upgrade.
- High gradient RF cavities loaded with high performance magnetic alloy (FT-3L)_cores started to be installed. The total loss with these cavities is half of that with existing cavities.

4. Fixed-Field Alternative Gradient Accelerator (FFAG), Shinji Machida (Rutherford Appleton Lab)

The alternative concept of a MW- power range, GeV - energy range accelerator for proton drivers was considered also. It is a Fixed-Field Alternative Gradient Accelerator (FFAG).
An FFAG has a number of advantages attractive for its application for proton drivers:
• Reasonable size of DC magnets (smaller than a cyclotron).
• Low operation cost due to superconducting (superferric) or permanent magnets. The field strength is moderate (~2 T) so that accelerator size is similar to synchrotrons. Cryo-cooler operation is the goal.
• Average beam power increases by high repetition operation.
• CW operation is not aimed (CW FFAG becomes very much like a cyclotron), but there is longitudinal focusing and bucket.
• An FFAG has both accelerator and storage ring in a single circular lattice. Output beam pulse structure can be controlled by the RF programme. For example, beam stacking at the extraction energy can produce a lower rep rate pulse.
• Staged beam power-up with a proper RF installation scenario. Repetition rate and beam intensity are controlled by RF, not the lattice magnets. Adding RF cavities in line with
1) User request,
2) Target readiness,
3) Beam loss handling, etc.
• For target test only, 1 Hz with the same bunch charge for the final goal by stacking small charge to simulate the maximum peak intensity. 100 Hz with lower peak charge to simulate the maximum average intensity.
Only two machines are in operation and they are still not high intensity: one is at Kyoto University and the other at Kyushu University. As a proton driver, one needs research and development.

5. CW SRF Proton Linacs, Dave McGinnis (European Spalation Source)

CW and high duty factors SRF Proton Linacs are under consideration for different applications.
• High Energy Physics and Intensity Frontier Physics:
  – Looking for rare processes so beam brightness is of ultimate importance
  – Filling colliders, Neutrino physics, etc., require pulsed structures
• Neutron Sources:
  – Beam brightness is extremely important also

– Latest generation neutron spallation sources are pulsed at a very low duty factor (<10%)

• Accelerator Driven Systems.

There are a number of projects of CW proton drivers – PIP II (Fermilab, USA), ADSS (BARC, India), CIADS (IMP, China). There, the following major issues for CW and high duty facor SRF linacs exist:

- Normal to SCRF crossover point
- Cryogenic Load
- Cavity bandwidth
- Power amplifier choice
- Civil Engineering choices
- Schedule

The SCRF linac design choices are dictated by the following issues:

- Surface electric and magnetic fields should not exceed reasonable limits in order to prevent field emission and quench.
- The number of cavities of different types as well as break points between the linac sections having these types of the cavities should be optimized in order to minimize the cost of R&D, capital and operation cost (i.e., maximize efficiency).
- The normal to SRF crosspoint should be optimized taking into account the efficiency, cost, and reliability.

- Cryogenic load:

For CW and high duty factor operation, the cryogenic load is among the crucial issues affecting the linac efficiency and the capital cost of the facility. The cryo load $P_d \propto 1/Q_0$, where Q_0 is the unloaded quality factor. Thus, for CW operation high Q_0 is desirable to decrease cryo load. In order to increase Q_0, N-doping technology has been developed at Fermilab. It evolved from discovery to proven technology. It is a basic technology for the LCLS II SRF CW electron linac operating at 1.3 GHz. First 16 N-doped dressed cavities for Jlab and FNAL prototype cryomodules achieved world record values: average Q_0 at operation acceleration gradient of 16 MV/m is 3.5e10 at 2 K. However, it is necessary to finalize the technology proof at proton driver frequencies (~700 MHz). In Figure 19 Q_0 is shown versus the acceleration gradient for the N-doping recipe “2/6”.

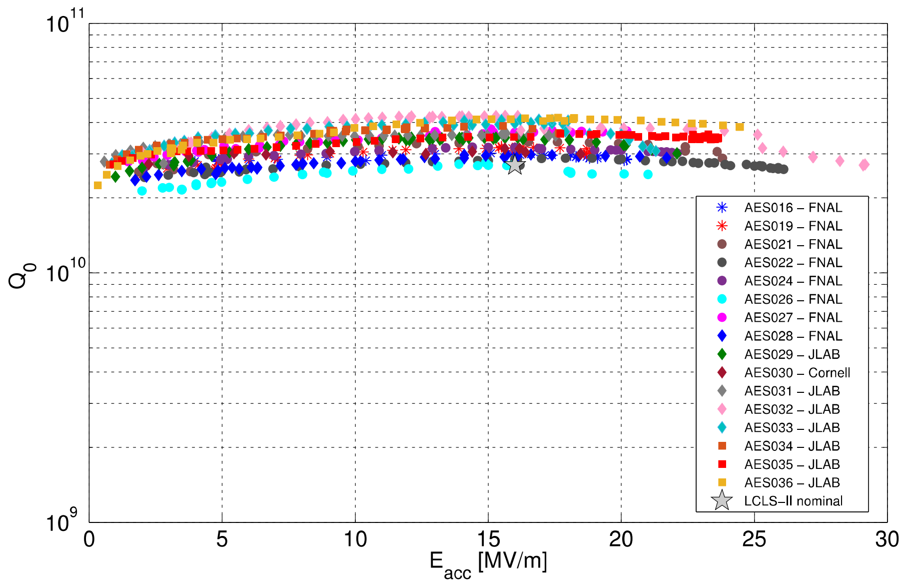


Figure 19. Q_0 versus the acceleration gradient for dressed LCLS II cavities (A. Grassellino).

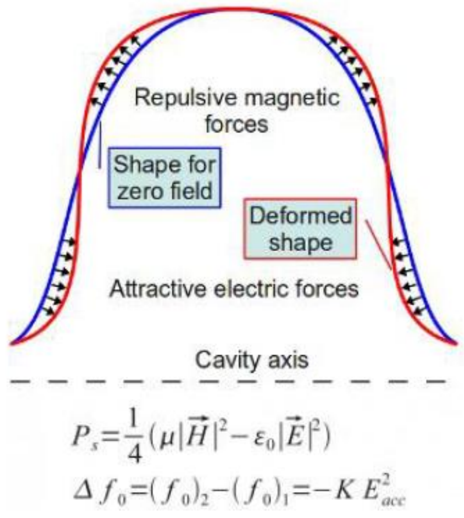
- Lorentz Force Detune and Microphonics:

However, for a given beam power, a high duty factor gives a small beam current. Light beam loading implies light coupling of the RF source to the cavity, which in turn, results in extremely narrow cavity bandwidth (tens of Hz for 1 MW range, 1 GeV energy range proton linac like PIP II). Because of the enormous gradients in superconducting cavities, the radiation pressure deforms the cavities (Lorentz Force Detune, Figure 20). Small changes in amplitude in the cavity can cause the cavity to quickly go out of tune. In addition, because of the narrow bandwidth cavities are very sensitive to mechanical noise - microphonics (pumps, fans, etc.) Both, LFD and microphonics require advanced controls on piezo tuners or extra RF power.

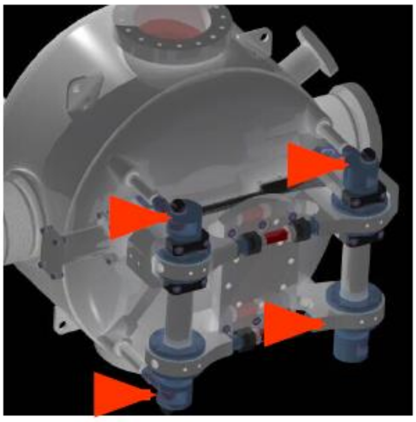
- Proton Impacts on Niobium

The De Broglie wavelength of 50 MeV protons is ~4 fm, similar to the nuclear radius of Nb. Therefore, impacts do not just disrupt the crystal lattice, but also change the elemental composition because of fracture or spallation of the Nb nuclei leading to new species, Zirconium, Yttrium, Strontium, etc. The following questions should be addressed:

- What is the scale of this effect?
- How does this affect the behaviour of the SC cavity?
- What are the implications for SC acceleration of proton beams?



a)



b)

Figure 20: a) Lorentz Force Detune (LFD) mechanism, and b) piezo tuner for LFD and microphonics mitigation.

- General Concerns on SRF for Proton Drivers:

Superconducting RF is the latest fashion in accelerator technology

- SNS, ESS, LCLSII, PIPII
- In the limit, the best conditions for an SCRF Linac is in CW
- It costs power to keep the Linac cold.
- Keep it running!

Guidelines for choosing SRF for Proton Drivers may be the following:

- Duty factor > 10%
- Dynamic / static load > 5
- Minimal energy > 400 MeV ?
- Maximal energy < 2 GeV ?
- Average Beam Power > 1 MW
- $T_{flattop}$ / T_{fill} > 5
- The Cumulative Energy Demand < 2 years ?

Here, the Cumulative Energy Demand is the ratio of the energy required to produce SCRF including life cycle costs to the beam power of the linac.

Summary on accelerator concepts:

A number of MW class proton driver accelerators are in operation today. The used concepts are cyclotron, SRF linac, and rapid cycling synchrotron.

It is challanging to introduce a single basic criterion of the efficiency for different types of accelerators based on the experience of existing accelerator facilities considered above. The types and parameters of accelerators used in different facilities depend strongly on the applications these accelerators are designed for. The designs of the considered operating accelerators were chosen in order to provide reliable operation of the entire facility at the required parameters. Optimization of the power consumption of an accelerator itself was not the primary task. The entire facility power consumption is also determined by the applications – auxiliary systems, instruments, etc., and may differ significantly from the consumption of the accelerator itself. On the other hand, these facilities were developed gradually, some concept decisions were made in different historical situations, which does not allow to maximaze the overall facility power consumption efficiency. In this situation, in order to show what one may expect for accelerators only, it is possible to consider the fraction of grid power converted to beam power, i.e., the ratio of the delivered beam power over the accerlator power consumption, including RF, magnetic system, cooling/cryogenics, but neglecting auxiliary systems and experimental facilities.

Table 5: Fraction of grid power converted to beam power for considered accelerator facilities:

	PSI cyclotron	**SNS Linac**	**J-PACR Linac and RCS**
Beam energy	590 MeV	1000 MeV	3000 MeV
Beam Power	1.3 MW	1.4 MW	1 MW
power consumption	4.3 MW RF + 2.6 Magnets = 6.9 MW	16.3 MW Linac, RT + SRF	8.6 MW linac + 7 MW RF +9.6 MW Magnets = 25.2 MW
Fraction of grid power converted to beam power	19%	8.6%	4%

However, if the application and, thus, parameters, are well-defined – e.g., ADS - the accelerators and facilities will be optimized in a similar way, and one may carefully scale the power consumption of considered accelrators to required parameters, estimate resulting efficiency, compare possible types of accelerators and select the most suitable, taking into account, of course, other criteria.

Note that all the considered acelerators have a lot of room for power consumption improvement, see above.

Energy efficienct technologies are developed in the fields of superconducting technology including High Temperature Superconductors, SRF and Room-Temperature cavities with low losses and low RF power overhead, including high Q_0 and resonance control for SRF. The use of permanent magnets for beam transport systems would save power. Cycling accelerator components need efficienct and reliable energy storage systems, for example capacitive energy storage for cycling synchrotron magnets.

New or alternative ideas and approaches should be developed for both new and explored basic accelerator parameters. Prominent examples are the studies on fixed-field alternating gradient (FFAG) accelerators.

Radio frequency sources are an important part affecting efficiency for all the considered accelerator concepts. Promising technologies include magnetrons, phase modulation, high-efficiency klystrons. We consider RF sources in a separate section in this report.

Conventional Systems and Cryogenics

The conventional and cryogenics systems session focused on two main topics; i) energy efficiency in cryogenic systems and ii) energy management. Energy management was covered by two presentations where the first presentation gave an overview of how to implement energy management in any kind of organization as well as the steps one should follow in order to analyze, baseline and follow up in a systematic way. The second presentation on energy management concerned the “virtual powerplant”, which can loosely be defined as a group of electrical consumers/producers of different kind and timescales (time constants). By shifting loads and production the overall load appears as fairly stable to the regional grid.

The introductory session listed the most common conventional systems, such as electrical distribution systems, cooling, HVAC, vacuum, and cryogenics. The design of conventional systems is highly depdendent on user requirements, such as temperature, noise, stability, accuracy, etc. It is definatley beneficial to consider energy efficiency from the beginning of the design rather than fixing the design later. In order to avoid over or under sizing the systems it is recommended to involve end users together with engineers from the conventional disciplines in the design. By allowing e.g. temperature changes between summer and winter great savings can be done. Generally, electrical systems, cooling and heating systems, HVAC, etc. are readily available with many features. Genrally it is recommended to use state of the art industrial components and best practicies.

Cryogenic systems are significant users of electricity, especially large plants, such as for s.c. accelerators. Unfortunatley, due to the laws of thermodynamics and other engineering challenges cryogenic plants are inherently inefficient and require significant electrical power in order to provide sometimes very small refrigeration capacities. Approximately 250 W/W (consumed W per W of refrigeration at 4.5 K) should be achieveable for large cryogenic plants. This translates into an efficiency of about 26% of the Carnot efficiency. The cryogenic operation temperature (2 K, 4.5 K, etc.) should be chosen considering the fact that the electrical consumption is about 3 times larger for cooling at 2 K compared to 4.5 K. Some systems/labs make use of liquid Nitrogen pre-cooling in order to boost the cooling-down phase of operations. However, liquid Nitrogen pre-cooling is more beneficial for liquefaction loads than compared to refrigeration loads.

State of the art cryogenic plants include variable frequency driven compressors as well as cold compressors, but the detailed layout depends on heat loads and requirements regarding low load operation. Heat recovery from cryogenic plants is definitely viable and may supply significant amount of heat, e.g. for heating of buildings.

The "efficiency considerations in cryogenics" presentation listed numerous recommendations that should be considered when designing, procuring, and commissioning of a cryogenic plant. Another consideration, with regard to commissioning, is staging of the installation. For example, cryomodules may be installed over a significant period and thus requiring a cryogenic system with high turn down capacity. Moreover, in relation to the cryomodules; the cryomodule shield temperature should be optimized with regard to the whole cryogenic system, not merley the single cryomodules.

Energy management is an integrated approach that looks at technical systems but also considers managerial and organizational issues. ISO 50001 can be used as is or adapted to the organization.
A number of steps should be followed when setting up an energy management system, e.g. baselining consumtion, identify key performance indicators, measure and follow-up. With this approach energy consumption can be mapped and followed-up in a systematic way.

As briefly mentioned above "the virtual power plant" is an interesting approach to close connection between energy consumer and producer. It is likely that in the future our energy production will be more dependent on external conditions such as wind and sun and thus will fluctuate more. It would thus be interesting to know if something like a scientific facility can be "turned down"? At GSI a group looked at their consumption and saw possibilities for load balancing, e.g. one improvement could be done by changing the operation cycle of the main synchrotron magnets. However, as presented, changing cycles required re-engineering of the coolings systems, the control system would be more complex, reliability may be decreased, etc..

To summarize, there are definitely promising options for efficiency improvements and pursuing load balancing but the advantages have to be analyzed with regard to risks and other issues.

Executive Summary

The workshop on proton driver accelerator efficiency covered all aspects of energy efficiency in such facilities, from grid to the rate of the desired secondary radiation. The chain of major power conversion components involves RF generation, accelerator concepts, beam targets and cryogenic/conventional systems. The following topics have been identified as promising technologies and R&D efforts that should be fostered:

high Q_0 and high T_c superconducting cavities: Cryogenic cooling power is a major contribution to total consumption of s.c. high-duty factor and CW linacs. By either improving the quality factor, or by raising the operating temperature, the cryogenic cooling power can be significantly reduced. New methods should be developed to treat the Nb surface (N-doping, Nb3Sn coating, etc.) as well as new ideas for improvement of other techniques (e.g., Nb over Cu, etc.).

resonance control of the narrow-band superconducting cavities: resonance control of the narrow-band SRF cavities reduces the RF power consumption. The active (piezo control) and passive (improving of the cavity mechanical properties) methods should be developed.

magnetron: the magnetron is known for high efficiency of ~90%, but it could not be used for accelerator applications due to instable phase and amplitude behavior. New techniques to operate magnetrons in injection-locked mode with amplitude control methods for driving SRF acceleration cavities should be developed.

klystron: New approaches to achieve a radical improvement of klystron efficiency should be investigated. In particular the Bunching-Alignment-Collecting (BAC) technique may allow raising the klystron efficiency beyond 90%.

cryogenic and conventional systems: It is recommended that every lab appoints an energy manager and sets up an energy management plan. This would facilitate comparison of performance between research labs as well as increase focus on energy consumption issues. Also consider behavioural and organizational aspects. Key Performance Indicators should be developed. Energy consumption and flexibility can be improved by choosing state-of-art components and modern controls, e.g. frequency driven pumps. Regarding future s.c. accelerators it is recommended that the cryomodule operation temperature is considered as this can impact energy consumption significantly. E.g. 2 K operation requires much more power compared to 4.5 K and this relates to the development of new s.c. cavities.

targets: The conversion of proton beam power into a rate of secondary particles is an important part of the energy conversion chain. Often this step has a lot of potential for optimization, typically more than the potential of enhancing beam power. On the other hand targets are complex multi-physics problems and besides the conversion efficiency also thermomechanical problems and reliability aspects are to be considered. Computer aided simulation tools are the key for optimizing all kinds of targets. In particular for neutron

sources good results were achieved for integrated optimizations of spallation target / moderator assemblies. Specific optimizations can be done for certain ranges of neutron energies. In case of muon production targets the optimized arrangement of strong magnetic fields in the vicinity of targets, for example horn magnets or strong superconducting solenoids, can help to achieve a much more enhanced capture efficiency.

Workshop website: http://indico.psi.ch/event/Proton.Driver.Efficiency.Workshop
EnEfficient website: http://psi.ch/enefficient