CONTENTS

PREFACE

It is my great pleasure to welcome you to the workshop "Energy for Sustainable Science at Research Infrastructures", which is jointly organized by CERN, ERF-AISBL member laboratories, ESS and in cooperation with the ARIES program. The Paul Scherrer Institut is happy to host this important workshop on its research campus in Villigen, Switzerland.

Climate change poses a fundamental threat to our society. As individuals, we are reminded every day to change our habits and reduce our ecological footprint. In addition, society rightly demands that science not only provides solutions to ecological challenges, but that it should also leave behind the smallest possible footprint on the way. It is no longer sufficient to argue that science needs energy. Rather, the public must be convinced that science can achieve savings that are a multiple of the energy we currently use, by providing society with more energy-friendly technologies for the future.

For these reasons, this series of workshops are both topical and highly relevant. On the one hand, it is important to show the public what contribution research infrastructures make to the development of sustainable technologies and, on the other, to communicate what efforts are being made to construct and operate these infrastructures in an energy-efficient manner. The workshops should also provide the leading actors in the field of large research infrastructure the opportunity to exchange and come up with for novel ideas and technological developments for more efficient infrastructure in the service of science.

With this in mind, I wish you stimulating discussions and the achievement of results that will provide our community with even greater credibility in arguing that these infrastructures make an indispensable contribution to a more sustainable world. (A formidable task if asked to demonstrate on the quantitative level!)

I would like to express my sincere gratitude to the organizers, speakers and chairs for all their efforts and I wish you a most successful and productive workshop.

Thierry Strässle
Director a.i. of PSI

WELCOME

With the climate very much in the spotlight, this fifth Energy for Sustainable Science at Research Infrastructures, ESSRI, workshop comes at an important juncture. Many facilities represented here are looking to the long-term future, and it's vital that we do it with energy efficiency in mind. In some sense, we are ahead of the curve, having launched this series in 2011. That has allowed the community that came together as a result to reach maturity, and it has helped to foster a change of mindset within research infrastructures. It is fair to say that we are all more environmentally conscious today than we were eight years ago. Tangible examples of the progress we've made are embodied in European programmes such as Eucard-2 and ARIES, both of which look at the future of accelerator-based infrastructures, and both of which build-in sustainability considerations for future facilities from the outset.

At this workshop, we will share our evolving experience in energy management. One example that has come of age in our community since the last time we met is the use of waste heat. While at laboratories such as CERN, heat recovery is being retro-actively installed, in plans for new facilities, it is increasingly being considered at the planning stage. We will also be looking at exciting new technological developments for our facilities: high temperature superconducting cables, for example, which are being developed for power transfer to accelerator magnets and could also benefit a much wider society. Superconducting radio frequency structures, a key element for high intensity accelerators, are another example of highly energy-efficient ingredients of potential future facilities. In recent years remarkable achievements have been made to understand and reduce the cryogenic losses of these devices, which has potential to reduce the overall power consumption of research infrastructures significantly. These are just two examples, but there are projects looking at energy efficiency across the full spectrum of accelerator technology, and we look forward to discussing them in Villigen.

The examples above illustrate how research infrastructures are striving to become more efficient users of energy, sometimes with significant positive implications for society as a whole. We should not, however, forget that many participants in this workshop represent neutron and light sources, facilities that conduct research directly into technologies for sustainability, such as energy storage. This will form another important strand of our deliberations at this workshop.

Research Infrastructures are a crucial pillar of our modern knowledge-based societies. They host cutting-edge research across a wide range of scientific disciplines, and are home to some of the greatest scientific and technological discoveries and innovations of our time. It is our duty not only to carry out research of the highest standard, but also to do so with the greatest respect for the environment. That is the reason that CERN, the ESS and the members of the Association of European-level Research facilities launched this workshop series in 2011. Since then, our community has grown to include sustainability experts and policy makers as well as those representing research infrastructures. And our audience now includes all who have a stake in sustainable scientific research. It gives us pleasure to see how this initiative has flourished, and to welcome you all to our fifth workshop. We have important work ahead of us as we discuss key challenges and identify sustainable pathways for the research infrastructure landscape. This workshop has much to contribute to this important task.

Frédérick Bordry
Director for Accelerators and Technology CERN

Mike Seidel
Head Large Research Facilities PSI, a.i.

INTERNATIONAL SCIENTIFIC COMMITTEE

Carlo Bocchetta, ESS
Frederick Bordry, CERN
Serge Claudet, CERN
Florian Gliksohn, ELI-DC / ERF
Joachim Grillenberger, PSI
Frank Lehner, DESY
Carlo Rizzuto, CERIC-ERIC
Thomas Schmidt, PSI
Mike Seidel, PSI

PROGRAMME
5TH WORKSHOP ON ENERGY FOR SUSTAINABLE SCIENCE AT RESEARCH INFRASTRUCTURES

Organized by CERN/ERF/ESS in cooperation with ARIES. Hosted by PSI.

THURSDAY, 28 NOVEMBER 2019

	Plenary Session
	Room: Auditorium WHGA/001 | PSI West
	Convener: M. Seidel, PSI
09:00	Welcome – Th. Strässle, PSI Director a.i.
09:10	Introduction & goals – F. Bordry, CERN
09:30	The Swiss energy strategy 2050 and energy research landscape – S. Oberholzer, Swiss Federal Office for Energy
10:00	Research on sustainable energy at PSI – Th. Schmidt, PSI
10.30	Coffee break
11:00	Large systems energy storage – Michael Düren, University Giessen
11:30	Efficient infrastructure to run supercomputers and how the lesson learned can be applied to other scientific instruments – L. Gilly, CSCS
12:00	Realisation of a new research infrastructure in Belgium: MYRRHA - O. Van der Borght, SCK-CEN
12:30	Sustainability considerations of present and future accelerators and infrastructure at DESY – W. Leemans – DESY
13:00	Lunch / Foyer Auditorium

THURSDAY, 28 NOVEMBER 2019

	Parallel session Sustainable technology developments by RI's		Parallel session Energy management at research infrastructures I
	Room: Auditorium – WHGA/001 | PSI West		Room: PSI Education Center - OSGA/EG6 | PSI East
	Convener: F. Lehner, DESY		***Convener: C. Bocchetta, ESS***
14:30	Study of surface effects in s.c. accelerator cavities using muon spectroscopy – A. Suter, PSI		Compact accelerator driven neutron source in the European landscape: efficiency and sustainability aspects – F. Sordo, ESS Bilbao
14:55	Increasing the energy efficiency of particle accelerators by using superconducting radio frequency niobium-3 tin cavities – R. Porter, Cornell Univ.		Energy consumption and sustainability of operations at the extreme light Infrastructure – A. Weeks, ELI
15.20	Application of fuel cells for UPS – F. Büchi, PSI		Reducing energy costs and environmental impacts for research infrastructure – The SKA case study – A. Schutte, Jodrell Bank Observatory
15:45	Shining X-rays on a reactor: a necessary step to rationally design or optimize (electro-) catalysts – M. Nachtegaal, PSI		District heating and use of waste heat recovery at the ESS – S. Strömberg, Eon
16.10	Coffee break / Foyer Auditorium		Coffee break – PSI Restaurant OASE

	Parallel session Energy efficient technologies I		Parallel session Energy management at research infrastructures II
	Room: Auditorium – WHGA/001 | PSI West		Room: PSI Education Center - OSGA/EG6 | PSI East
	Convener: A. Weeks, ELI		***Convener: C. Bocchetta, ESS***
16:40	Efficiency considerations of solid state pulse modulators – J. Biela, ETHZ		Energy monitoring and heat recovery at DESY – J.P. Jensen, DESY
17:05	Energy management for national high magnetic field facility in Grenoble – F. Debray, LNCMI		Energy consumption considerations in the beam physics design and optimization of the ESS Linac – M. Eshraqi, ESS
17:30	Low loss s.c. cavities – F. Gerigk, CERN		Energy Management at ALBA – J. Casas, ALBA
17:55	MgB_2 based power transmission lines for the powering of the HL-LHC superconducting magnets – A. Ballarino, CERN		Closeout
18:20	Closeout		
18:45	Workshop dinner, PSI Restaurant OASE		

FRIDAY, 29 NOVEMBER 2019

	Parallel session Energy efficient technologies II		Parallel session Cryogenic systems and conventional cooling
	Room: Auditorium – WHGA/001 | PSI West		Room: PSI Education Center - OSGA/EG6 | PSI East
	Convener: A. Weeks, ELI		***Convener: S. Claudet, CERN***
08:30	Status of high efficiency RF power sources – Outcome of Uppsala workshop – R. Ruber, Uppsala Univ.		Technology and economics of He refrigerations using the example of ESS – John G. Weisend
08:55	Challenges of a megawatt CW class solid state power amplifier for the SPS at CERN – E. Montesinos, CERN		Energy efficient helium-neon refrigerator for FCC – L. Tavian, CERN
09:20	Permanent magnets for light sources – J. Chavanne, ESRF		Recent studies on water consumption and improvements on cooling towers effluents – S. Deleval, CERN
09:45	High current pulsed magnets for energy efficient beam transport systems – P. Spiller, GSI		Efficiency versus sobriety: optimized cryogenic design of stand-alone superconducting magnets – P. Lebrun, ESI
10:10	Coffee break / Foyer Auditorium		

	Plenary session
	Room: Auditorium – WHGA/001 | PSI West
	Convener: F. Bordry, CERN
10:40	Lifecycle assessment: usefulness for and applicability to research infrastructures – M. Margni, Polytechnique Montréal (remote presentation)
11:10	Ecological diversity – T. Welander, ESS
11.40	Summary sustainable technology developments by RI's – F. Lehner, DESY
11:55	Summary energy management – C. Bocchetta, ESS
12:10	Summary energy efficient technology – A. Weeks, ELI
12:25	Summary cryogenic systems and conventional cooling – S. Claudet, CERN
12.40	Closing remarks – M. Seidel, PSI
13:00	Lunch / Foyer Auditorium
14.30	PSI facility tour
16.30	End

ABSTRACTS
THURSDAY, 28 NOVEMBER 2019

PLENARY SESSION

The Swiss energy strategy 2050 and energy research landscape

Stefan Oberholzer, Swiss Federal Office of Energy

As in many other countries, climate change and sustainable energy are key topics in the Swiss political debate in this national election year 2019. Economic and technological developments as well as political decisions at home and abroad are currently leading to fundamental changes in the energy markets. Since 2011 the Swiss government therefore developed the «Energy Strategy 2050» in order to guarantee a secure energy and electricity supply and at the same contribute to the reduction of Switzerland's energy-related environmental impact. A first step was the adoption of a new Energy Act by a popular referendum in 2017 with a first set of measures to increase energy efficiency and foster renewable power, going along with a ban on new nuclear power plants. A new CO2-act is under political debate with a growing political acceptance for extended measures such as fuel taxation. In summer 2019 the Swiss government also declared the target to reduce the net carbon emissions of Switzerland to zero by 2050.

A transformation of the energy system will open up new opportunities for economic development and for innovation. The research that is essential for innovation has thus been expanded in a targeted manner in the context of the launch of Energy Strategy 2050. Besides highlighting some key elements of the Swiss energy and climate policy, this presentation shall also give a brief overview on Swiss research and technology developments in the energy area, where the Swiss Federal Office of Energy SFOE plays a central role in promotion and coordination.

Research on Sustainable Energy at PSI

Thomas Schmidt, PSI

The Research Division Energy and Environment at PSI investigates the environmental and socio-economic consequences of energy use and creates options for resource-efficient energy conversion with lowest emissions and environmental impact in the light of the Swiss Energy Strategy 2050. In this context, Research in Energy and Environment strives for an environmentally friendly, resource efficient and economic energy provision and use. We pursue research on sustainable energy technologies with low CO2 footprint, conversion to secondary energy carriers, chemical and electrochemical energy storage, and their impact on environment, climate and economy in our six different Laboratories (Bioenergy & Catalysis, Electrochemistry, Sustainable Chemistry & Catalysis, Atmospheric Chemistry, Environmental Chemistry, and Energy System Analysis).

In this presentation, a short journey through our activities will be given with the focus on our research related to large research facilities like SLS and SINQ.

Large systems energy storage

Michael Düren, University Giessen

In a renewable energy system, the handling of the volatility of wind and solar power is challenging. Large energy storage systems are needed, but the most cost-efficient solutions go beyond the benefit of one single technology by using synergies between several measures: Spatial and temporal variability can be compensated by the combination of large distance energy trading (using overlay high voltage DC grids and/or gas pipelines), by energy storage, and by demand site management. The cost efficiency of the combined measures profit from sector coupling, as different sectors (electricity, heat and mobility) have different space-time patterns and a time-shift of consumption can be preferably realized in heat and mobility applications. The energy storage has to be efficient and cheap. The dilemma, that efficient storage is usually not cheap is partially solved in the “dual storage model”, where two types of storage are used: Daily fluctuations are compensated by an efficient short-term storage, while seasonal fluctuations, which require huge storage use long-term storage, realized by cheap gas tanks. The renewable gas (or liquid) will be generated by power-to-gas or biomass, and for a transition period natural gas can be added. The short-term storage system is realized by demand-controlled hydro, pumped hydro, batteries and certain heat storage systems. In the pumped hydro storage sector, unconventional ideas like the conversion of open pit mines (e.g. lignite) to large pump storage systems or the generation of artificial pump storage islands in the open sea are proposed.

Efficient infrastructure to run supercomputers and how the lesson learned can be applied to other scientific instruments

Ladina Gilly, CSCS

«They say that you become what you think about most of the time. This figure of speech applies itself very well to the endeavour of creating energy efficient infrastructures. The fact that CSCS today runs a highly efficient data centre that is specially tailored to meet the specific needs of High Performance computing is not a coincidence, but a direct consequence of these two topics having been focal pillars of the project from the very first discussions. Having set these two topics as clear cornerstones to the project, all decisions that were taken in the design and construction phase where considered with them in mind. Consistently adhering to these two cornerstones throughout the project ensured that the resulting infrastructure, systems as well as maintenance and management methods optimally reflect and enable these goals. This talk will provide an insight into how the CSCS data centre project was formulated and pursued to ensure maximum energy efficiency and optimal fit with HPC.”

Realisation of a new Infrastructure in Belgium: MYRRHA

Oliver van der Borght, SKN – CEN, MYRRHA Project

SCK•CEN is at the forefront of Heavy Liquid Metal (HLM) nuclear technology worldwide with the development of the MYRRHA accelerator driven system (ADS). MYRRHA is serving since the FP5 EURATOM framework as the backbone of the P&T strategy of the European Commission based on the "4 building Blocks at Engineering level" and fostering the R&D activities in EU related to the ADS and the associated HLM technology developments.

At the same time MYRRHA is conceived as a flexible fast-spectrum pool-type research irradiation facility cooled by Lead Bismuth Eutectic (LBE), and was identified by SNETP (www.snetp.eu) as the European Technology Pilot Plant for the Lead-cooled Fast Reactor. MYRRHA is proposed to the international community of nuclear energy and nuclear physics as a pan-European large research infrastructure to serve as a multipurpose fast spectrum irradiation facility for various fields of research such as; transmutation of High Level Waste (HLW), material and fuel research for Gen.IV reactors, material for fusion energy, innovative radioisotopes development and production and for fundamental physics. As such MYRRHA is since 2010 on the high priority list of the ESFRI roadmap (http://www.esfri.eu/roadmap-2016).

Since 1998 SCK•CEN is developing the MYRRHA project as an accelerator driven system based on the lead-bismuth eutectic as a coolant of the reactor and a material for its spallation target. The nominal design power of the MYRRHA reactor is 100 MWth. It is driven in sub-critical mode (keff = 0.95) by a high power proton accelerator based on LINAC technology delivering a proton beam in Continuous Wave (CW) mode of 600 MeV proton energy and 4 mA intensity. The choice of LINAC technology is dictated by the unprecedented reliability level required by the ADS application. In the MYRRHA requirements the proton beam delivery should be guaranteed with a number of beam trips lasting more than 3 seconds limited to maximum 10 for a period of 3 months corresponding to the operating cycle of the MYRRHA facility. Since 2015, SCK•CEN and Belgium government decided to implement the MYRRHA facility in three phases to minimize the technical risks associated to the needed accelerator reliability.

On September 7, 2018 the Belgian federal government decided to build this large research infrastructure. In this lecture we will summarize 20 years of Design and R&D turned in a facility to be built.

Sustainability considerations of present and future accelerators and infrastructure at DESY

Wim Leemans, DESY

Reducing energy consumption of large scale infrastructure is an essential aspect of the operation of all modern facilities. We discuss the current approaches at DESY to become more and more energy efficient and achieve long term sustainability. This includes improvements on today's machines and concepts that are being explored for the planned upgrade of our flagship synchrotron facility PETRA-IV. We also present R&D and future plans for exploring plasma based advanced accelerators as foundation for future facilities and what needs to be explored and developed to ensure that they are more efficient than current day's technology.

PARALLEL SESSION: SUSTAINABLE TECHNOLOGY DEVELOPMENTS BY RI'S

Study of surface effects in s.c. accelerator cavities using muon spectroscopy

Andreas Suter, PSI

In the seminal paper of A. B. Pippard [1] where he proposed a second relevant length scale for superconductivity, the coherence length, he also calculated the modification of the electro-magnetic response of the superconductor due to the nonlocality. This leads to a modified Meissner screening profile which deviates from the text book exponential decay field profile $B(z)$, but he stated that "It is unlikely that any direct experimental demonstration of its existence can be devised". About 50 years later we could for the first time directly measure the nonlocal Meissner screening profile utilizing low-energy µSR [2]. This study shows that we have a tool to investigate subtle effects in magnetic depth profiles on the nm-scale with essentially no ab initio assumptions.
As a first example, I will present some recent results on Nb cavity cut-outs from "hot" regions of SRF cavities where we studied the Meissner screening by aim of low-energy µSR. It will be shown that the superconducting properties at the hot region are well described by the non-local Pippard/BCS model for niobium in the clean limit with a London penetration depth λ_L = 23±2 nm. In contrast, a cut-out sample from a 120 °C baked cavity shows a much larger λ_L > 100 nm and a depth dependent mean free path, likely due to gradient in vacancy concentration. This suggests that these vacancies can efficiently trap hydrogen and hence prevent the formation of hydrides responsible for rf losses in hot regions.

A route towards rf cavities which could be operated at higher temperature would be a change-over in material, as Nb_3Sn or NbTiN, or bi-layer systems like Nb_3Sn/Nb. I will present on-going studies on this subject, where direct measurements of the London penetration depth allow to determine the lower critical field and the superheating field. Bulk µSR studies (Triumf) allow to measure the field of first vortex penetration. The combined results confirm that Nb_3Sn cavities are indeed operated in a metastable state above the lower critical field.

[1] A. B. Pippard, Proc. R. Soc. London, Ser. A 216, 547 (1953).
[2] A. Suter, et al. Phys. Rev. Lett. 92, 087001 (2005).
[3] A. Romanenko, et al. Apply. Phys. Lett. 104, 072601 (2014).

Increasing the energy efficiency of particle accelerators by using superconducting radio frequency niobium-3 tin cavities

Ryan Porter, Cornell University

Particle accelerators are an important tool of modern natural sciences, contributing to almost every field, and becoming increasingly important in medicine and industry. These facilities are some of the largest tools used to pursue science and some of the most energy intensive. Most large-scale modern accelerators utilize superconducting radiofrequency (SRF) accelerating cavities made of niobium (Nb) that must be cooled to ~2 K. Cooling these cavities is one of the biggest energy consumers in these accelerators, requiring 10 – 20 kW of AC power per active cavity meter in continuous operation. For large facilities, the power consumption of the cooling plant can thus reach the 10 MW range. We are developing niobium-3 tin (Nb3Sn) as an alternative material to niobium for SRF accelerators. This material can be operated at 4.2 K where cooling efficiency drastically increases. At the current state of development, Nb3Sn is 3 times more efficient than clean Nb. Further development could push this to 5 – 10 times more efficient than Nb. This talk gives an over of Nb3Sn SRF development and discusses the implications on the energy sustainability of future accelerators.

Application of fuel cells for UPS

Felix Büchi, PSI

To secure the operation of important infrastructure, uninterruptible power supply (UPS) technology is used. Depending on requirements with respect to power and time duration to secure power, either batteries or a combination of batteries and diesel generators is used.

Fuel cell technology offers the possibility for longer duration power back-up based on renewable hydrogen as the fuel. The presentation discusses the boundary conditions, possibilities and limits of fuel cells in the UPS application.

Shining X-rays on a reactor: a necessary step to rationally design or optimize (electro-) catalysts

Maarten Nachtegaal, PSI

To rationally develop and improve catalysts and catalytic processes, insight in the reaction and deactivation mechanisms is essential. Thanks to their high penetration depth, hard X-ray based techniques, especially X-ray absorption and emission spectroscopies, are the method of choice to provide insight in the structure- activity relationship of catalysts and catalytic processes under realistic operating conditions. In this talk, I will show two recent examples where synchrotron studies were essential to to improve catalytic processes.

This first example comes from exhaust gas catalysis, where catalysts in Diesel fueled cars are needed to reduce nitrous oxide emissions. By combining transient experimentation with the latest development in time-resolved X-ray absorption spectroscopy[1], insight was obtained on the low and high temperature rate limiting steps of a commercial Cu-loaded zeolite catalyst. This knowledge was subsequently used to optimize the functioning of real catalytic converters[2].

The second example comes from the search for oxygen evolving electro-catalysts that are currently the rate-limiting step in electrolyzers. ELectrolyzers are devices that use an electric current to provide the energy that splits a water molecule into hydrogen and oxygen. By understanding the structure of the electrocatalyst[3] while it evolves water, better catalysts were designed that rival the activity and stability of state-of-the- art iridium oxides oxygen evolution catalysts, but are a factor 1000 cheaper[4].

[1] Quick-EXAFS setup at the SuperXAS beamline for in situ X-ray absorption spectroscopy with 10ms time resolution. 2016. O. Müller, M. Nachtegaal, J. Just, D. Lützenkirchen-Hecht, R. Frahm. *Journal of Synchrotron Radiation* 23, 260-266.

[2] Time-resolved copper speciation during selective catalytic reduction of NO on Cu-SSZ-13. 2018. A. Marberger, A.W. Petrov, P. Steiger, M. Elsener, O. Kröcher, M. Nachtegaal*, D. Ferri*. *Nature Catalysis* 1, 221-227.

[3] Superior bifunctional electrocatalytic activity of Ba0.5Sr0.5Co0.8Fe0.2O3-d/carbon composite electrodes: Insight into the local electronic structure. 2015. E. Fabbri, M. Nachtegaal, X. Cheng, T.J. Schmidt. *Advanced Energy Materials* 5, 1402033.

[4] Dynamic surface self-reconstruction is the key of highly active perovskite nano-electrocatalysts for water splitting. 2017. E. Fabbri, M. Nachtegaal, T. Binninger, X. Cheng, B.-J. Kim, J. Durst, F. Bozza, T. Graule, L. Wiles, M. Pertoso, N. Danilovic, K.E. Ayers, T.J.Schmidt. *Nature Material*, 16, 925-931.

PARALLEL SESSION: ENERGY MANAGEMENT AT RESEARCH INFRASTRUCTURES I

EC Energy policy and funding strategies of sustainable research

Anne Weidenbach,
European Commission

The European Union agreed a comprehensive update of its energy policy framework to facilitate the transition away from fossil fuels towards cleaner energy and to deliver on the European Union´s Paris Agreement commitments for reducing greenhouse gas emissions.

The completion of this new energy framework – called the ‘Clean Energy for All Europeans package’ – marks a significant step towards the imple-mentation of the Energy Union Strategy, adopted in 2015.

Putting energy efficiency first is a key objective in the package, as energy savings are the easiest way of saving money for consumers and of reducing greenhouse gas emissions. The European Union has therefore set binding targets of at least 32.5% energy efficiency by 2030, relative to a ‘business as usual’ scenario.

To boost energy efficiency, the Energy Efficiency Directive and the Energy Performance of Buildings Directive establish a set of binding measures to help the European Union reach its energy efficiency targets by 2020 and 2030. A number of measures adopted throughout the European Union are particularly important for universities and research institutes, like, for example, measures and longterm strategies targeting the renovation of public buildings or measures implemented for improving energy efficiency in the ICT sector.

The European Commission is working to make the energy efficiency first principle operational, so that it could be used across the board when investments, projects or legislation are planned. Moreover, the European Union has increased the amount of public funds available for improvements in energy efficiency. In this context, the European Commission has launched a number of programmes also available for universities and research institutes, e.g. the Smart Finance for Smart Buildings (SFSB) initiative, the European Structural and Investment Funds (ESIF), the European Fundfor Strategic Investments (EFSI) and Horizon 2020.

The SFSB initiative, for example, which is also part of the 'Clean Energy for All Europeans package', supports inter alia the use of Energy Performance Contracts in the public sector. These are a practical way of making public buildings and other public infrastructures more energy efficient.

Horizon 2020 is the biggest EU Research and Innovation programme removing barriers to innovation and making it easier for the public and private sectors to work together in delivering innovation.

ELENA (`European Local Energy Assistance'), a joint initiative of the European Commission and the European Investment Bank, supports private and public promoters to develop and launch large-scale bankable sustainable energy investments (above €30 million), including e.g. sustainability of campuses and research infrastructures, and covers up to 90% of project development costs.

The initiative PDA H2020 ('Project Development Assistance Horizon 2020'), complements ELENA and helps public and private promoters develop model sustainable energy projects, focusing on small and medium-sized energy investments of at least €7.5 million and up to €50 million, covering up to 100% of eligible project development costs.

Energy management for national high magnetic field facility in Grenoble

François Debray, LNCMI

The French High Magnetic Field Facility (LNCMI) is one of the 3 founding members of the European Magnetic Field Laboratory (EMFL) which offers to in-house and external researchers the highest possible magnetic fields to develop scientific researches and processes. The Grenoble Facility develops high field magnets and gives acess to DC magnetic fields much higher than those obtained using commercial low temperature superconducting electromagnets currently limited to 23 teslas. Consequently, a power of 30 MW (in 2021) is needed to reach magnetic fields in the range of 40 teslas leading to electricity costs as high as one third of the OPEX.

We present the different routes explored to ensure the long term sustainability of the high field facility in the context of the ongoing energy transition.

Energy consumption and sustainability of operations at the extreme light infrastructure

Allen Weeks, ELI

The Extreme Light Infrastructure (ELI) is transitioning from Construction to the Operations, marking an important milestone for laser-based research in Europe and researchers around the world. The overall status and objectives of the ELI-ALPS facility in Szeged, Hungary and ELI-Beamlines in Dolní Břežany in the Czech Republic are reviewed, with a focus on energy use the ELI-ALPS facility as it relates to operational aspects. The talk will present plans to supplement heating and cooling systems with state-of-the-art solar thermal systems. This is a particularly relevant opportunity for the Szeged facility as its location has some of the highest levels of solar isolation in Europe. The talk will also touch on the energy efficiency and potential of laser-driven systems.

Reducing energy costs and environmental impacts for research infrastructure – The SKA case Study

Adriaan Schutte, Jodrell Bank Observatory

The Square Kilometer Array (SKA) is developing the world's largest radio telescope. The SKA will consist of two telescope sites located in remote regions of Australia and South Africa, as well as supercomputing centres in Perth and Cape Town. Current estimates of the total SKA power consumption are in the 10-12MW range, and delivering low-cost, reliable and climate-friendly power to the four SKA telescope locations is a significant challenge. This is especially true given the mix of urban and very remote locations. In response to these challenges, the SKA Organisation (SKAO) has been centrally managing power as a core design activity that spans the entire system. By addressing holistically all aspects of power, including power supply, power distribution and power consumption, the SKAO has over the last four years been able to significantly reduce the power capex and opex cost forecasts. This was achieved by implementing a formal power budgeting process that consistently led to power reductions in most sub-systems, by optimising the distribution network to include local renewable generation where feasible, and by engaging with industry to investigate renewable energy sources as low-cost alternative to traditional networks. This work will not only lead to a decrease in overall costs, but also to a significant decrease in the CO_2 emissions from the observatory over its lifetime.

PARALLEL SESSION: ENERGY EFFICIENT TECHNOLOGIES I

Efficiency considerations of solid state pulse modulators

Jürgen Biela, ETHZ

Solid state pulse modulator systems supplying klystrons are a key element of modern accelerator systems. Due to the losses in the different power stages between the grid and the klystron as well as due to the non-ideal pulse shape, the modulator system has a significant impact on the overall accelerator efficiency. In the presentation, first typical topological concepts for solid state modulators for pulses in the micro- and millisecond range are presented. In a second step, the achievable efficiency limits for the different power stages as well as for the pulse/step-up transformer are evaluated. The evaluation is performed on the basis of the following three solid state modulator systems, which have been designed at HPE/ETH Zurich: 1) Swiss-FEL modulator: 370kV/3µs/127MW, 2) CLIC-modulator: 180kV/139µs/29MW, and 3) ESS long pulse modulator: 115kV/3.5ms/2.88MW.

Compact accelerator driven neutron source in the european landscape: efficiency and sustainability aspects

Fernando Sordo, ESS Bilbao

Neutrons are an essential tool in science and research for probing the structure and dynamics of matter from the mesoscale to the nanoscale and from seconds to nanoseconds. In Europe science, research and society benefit from a globally unique environment of various neutron sources with the flagship facilities ILL in Grenoble, France, and ESS in Lund, Sweden, which is currently under construction and will represent the world's most powerful neutron facility. More than 8000 users utilize the available neutron sources in Europe, requesting nearly twice the available capacity offered per year.

Neutrons can be produced by fission in nuclear reactors, by spallation using high-power proton accelerators, and by nuclear reactions with low-energy proton accelerators. The first two techniques are used very successfully in Europe and offer the highest neutron flux production with versatile options. In view of the continuously high demand for neutron experiments by science and industry and the phasing out of existing reactor-based neutron facilities in Europe in the near future, new solutions and strategies are required to provide sustainable and effective access to neutrons in Europe.

Compact Neutron Sources based on Low energy and hight current proton accelerators can provide a competitive solution compared with large scale facilities. The recent developments on target design, cold moderators and neutron transport optics allows to develop instrument-optimised target stations that maximise the efficiency of the complete system from source to the sample.

This concept, already demonstrate in Japanese Compact sources like RANS, can provide a competitive and efficient solution to compensate the research reactor phasing out in Europe.

Low loss s.c. cavities

Frank Gerigk, CERN

Many of today's and future particle accelerators use superconducting RF (SRF) cavities to transfer energy to particle beams. In the superconducting state surface losses on Niobium are ~6 orders of magnitude smaller than for normal conducting copper, which means that only a few Watts of heat are produced. However, each Watt deposited at cryogenic temperatures, "costs" up to 1 kW electrically due to the need of a refrigeration system. Hence the effort to further increase the efficiency of SRF systems, especially in view of future large-scale accelerators such as the International Linear Collider or Future Circular Colliders.

In this talk the SRF cavity losses are put into perspective to the overall RF system efficiency for various accelerator applications. The basic loss mechanisms are reviewed along with the R&D efforts to increase SRF efficiency. In particular we will cover bulk niobium and thin film cavities, the role of flux trapping and magnetic shielding, doped niobium and new materials with higher critical temperature, new coating techniques, and new tuning methods to reduce the RF power overhead.

MgB_2 based power transmission lines for the powering of the HL-LHC superconducting magnets

Amalia Ballarino, CERN

In the framework of the HL-LHC project, CERN has developed high-current power transmission lines based on MgB_2 superconductor. The lines, which are planned to be installed in the LHC underground areas in 2025, are more than 100 m long and transfer quasi-DC currents exceeding 110 kA – at temperatures of up to 25 K.

After an overview of the project, the main results from recent developments are presented, including the successful test at CERN of a 60 m long 2×20 kA demonstrator.

Future milestones as well as potential future applications of this innovative technology are also reported.

PARALLEL SESSION: ENERGY MANAGEMENT AT RESEARCH INFRASTRUCTURES II

District heating and use of waste heat recovery at the ESS

Sonny Strömberg, EON

One of the reasons ESS was placed in Lund was the ambitious sustainability goals. ESS aim to set a new standard for big science facilities concerning energy efficiency and sustainability, and a key to that is to recover the surplus heat. Together with energy partner E.ON an efficient solution is implemented which will provide the buildings in the surrounding area with thermal energy. The concept rests on two pillars: the high temperatures will be utilized in a conventional district heating system, whereas the low temperatures will be used as balance energy in a new heat- and cooling system called called ectogrid™.

Energy monitoring and heat recovery at DESY

Jens-Peter Jensen, DESY

The energy consumptions of high energy and synchrotron radiation facilities are one of the cost drivers, not only the electrical power but as well the costs for heating, cooling, ventilation, drinking water, nitrogen etc. Synchrotron radiation facilities like DESY are hosting a number of collaborations. Several new R&D LASER projects have been launched on the DESY campus. It is important to get a better understanding of the consumption of the accelerators, experimental areas, test stands, technical infrastructure and third consumer. A project team for energy monitoring was launched.

Since the last Sustainable Workshop 2017 in Bucharest the heat recuperation of the DESY helium cryogenic plant is in operation. It supplies about 50% of the heat consumption of the DESY premises.

The status of the automatic metering, the energy management software and the future ideas to use the water cooling systems for heating will be presented. In the next 20 years the City and University of Hamburg will build a new area called “Science City Bahrenfeld” adjacent to the DESY premises. This gives the chance to design the PETRA IV cooling systems in a way that the extracted heat can be used for medium and low temperature heating on the Science City Bahrenfeld premises.

Energy consumption considerations in the beam physics design and optimization of the ESS linac

Mamad Eshraqi, ESS

In recent years, increased global awareness on environmental impact, sustainability and higher energy costs, has required greater attention on the energy efficiency of high power accelerators. The ESS facility made it a commitment to respect these factors when Scandinavia submitted the application to host the ESS. The hardware used in the linear accelerator of the ESS has been designed with energy efficiency in mind. The beam physics design of the accelerator, how the transitions are handled and which types of structures are used does make an impact on the total energy consumption and the energy efficiency of the accelerator. This report focuses on the beam physics optimisation of the ESS linac with the aim of reducing the energy consumption of the linac.

Energy Management at ALBA

Joan Casas, ALBA

ALBA is the Spanish third-generation synchrotron light source located in Barcelona and constitutes the largest scientific infrastructure in Spain. Built 12 years ago in a green field, it was projected to be the center of gravity of a new hi-tech cluster and the justification for a different way to urbanize a new area. In addition to a very high electricity consumption (very demanding in terms of stability and availability), ALBA would have a relevant need for thermal energy (to cool down the accelerators) hence, would be the first and most important user of a new hot & cold district water infrastructure. This kind of infrastructure is not very common in Spain, and was seen at that time, as an incentive for the forthcoming research facilities, labs or factories to grow at the same location.

The relevance of the thermal energy term in the energy equation, and the general concern about sustainability and cost of energy (nowadays meaning 18% of the overall ALBA running cost) made sensible the option for building a new co-generation plant: ST4.

This paper will provide an updated view of the infrastructure and the process, and will briefly review the theoretical and real benefits of ST4, aimed to provide a 20% cost saving to the users. The main design trade-offs will be reviewed from real data after more than 10 years of operation, and some questions would be answered: ¿Do we have the promised cost saving? ¿What has been the overall investment? ¿How the existing approach compares to the self-generation of thermal energy from electricity purchased to the standard network? How sensitive is the cost saving to the balance between electricity and thermal energy? Do we have the required availability? Do we have the required stability?

ABSTRACTS
FRIDAY, 29 NOVEMBER 2019

PARALLEL SESSION
ENERGY EFFICIENT TECHNOLOGIES II

Status of high efficiency RF power sources - outcome of Uppsala workshop

Roger Ruber, Uppsala University

With the emergence of new accelerator projects always more demanding concerning the amount of energy drawn from the outlet by high power RF sources (FCC, ILC, CLIC), trying to improve energy efficiency of these sources has become a hot topic of recent R&D efforts to insure sustainability over the long term. In addition to simply reduce energy consumption, improving overall uptime of RF sources also helps in reducing accelerator downtime, and thus increasing efficiency in delivery of beam to users.

A workshop was organized in June 2019 to review the current status of innovative solutions to improve the efficiency and uptime of RF sources, and identify areas on which to focus to mature these new concepts, like improving simulation tools, R&D on solid state amplifiers, prototyping and long-term testing. New vacuum tube concepts based on multi-beam tubes, as well as on improved bunching techniques have been developed with the goal to gain at least 10% efficiency. Several ways have been identified that could push solid-state amplifier efficiencies for accelerator applications up to 80% and towards the GHz range.

Challenges of a megawatt CW class solid state power amplifier for the SPS at CERN

Eric Montesinos, CERN

Within the frame of our LHC Injector Upgrade programme, CERN decided to build two new amplifiers of 2 MW cw operating at 200 MHz. These amplifiers are based on Solid State technology, and use Cavity Combiner systems to reach the required power levels. A review of the challenges we had to face during the design phase of this new amplifiers will be presented. Complexity and advantages of the cavity combining systems will be presented, especially for the SSPA technology.

Permanent magnets for light sources

Joel Chavanne, ESRF

Since the 90's many 3rd generation light sources (3GLS) have been constructed and operated with a routine beam availability higher than 90 %. For all these facilities , a common denominator is the resistive magnet technology used for the accelerator complex. Depending on the size of the accelerators, the corresponding wall plug power is from a few hundreds of Kilowatts to a few Megawatts. 3GLS correspond also to the development of permanent magnet based Insertion Devices : a starting point for experiencing high performance permanent magnet materials in electron accelerators. More recently with the advent of ultra low emittance storage rings (4GLS), due to the resulting compactness of the magnet lattice and the need to reduce the electrical consumption of the facility, permanent accelerator magnets have been constructed or are considered in a number of upgrade projects. It includes primarily bending magnets and also potentially high gradient quadrupoles.

These important considerations are illustrated with ESRF EBS storage ring where permanent magnets dipoles based of Sm2C017 material have been constructed. Subjects like long term stability of these magnets are discussed.

High current pulsed magnets for energy efficient beam transport systems

Peter Spiller, GSI

For the transport of ion bunches, the guiding magnet field is only required for the duration of the beam pulse length.

Low inductance, high current magnetic lenses provide an energy efficient option for the transport of such ion bunches.

Furthermore, such lenses offer the possibility for generating high gradients similar to such of superconducting magnets. However, with much less demanding technical infrastructure.

In addition, by means of a parallel capacitance, a significant fraction of the electrical energy can be recovered and used for the subsequent pulse.

A comparison of magnet technologies in different applications will be presented in context with their energy efficiency.

PARALLEL SESSION: CRYOGENIC SYSTEMS AND CONVENTIONAL COOLING

Technology and economics of He refrigeration using the example of ESS

John G. Weisend, ESS

One of the principal values of the European Spallation Source, an accelerator driven neutron source currently under construction in Lund, Sweden is sustainability. This posed a challenge for the ESS Accelerator Cryoplant (ACCP) which provides up to 3 kW of cooling at 2 K for the superconducting radiofrequency (SRF) cavities in the accelerator. This plant must be able to adjust to dynamic changes in heat load due to changes in SRF and beam power as well as support two different accelerator configurations, one with forty-three SRF cryomodules and the other with fourteen additional cryomodules.

This talk describes how the design of the ACCP was adjusted to meet these goals while still operating efficiently in order to contribute to sustainability. Details on the selection criteria that optimized operating costs and capital costs are also given. The broader implications of the ACCP design and selection to sustainability goals of future large helium cryoplants is also discussed.

Energy efficient helium-neon refrigerator for FCC

Laurent Tavian, CERN

Following the update of the European strategy in particle physics, CERN has undertaken in 2014 an international study of possible future circular colliders beyond the LHC. The study considers an option for very high-energy (100 TeV) hadron-hadron collider, so called FCC-hh, located in a quasi-circular tunnel of 100-km circumference. One of the main source of heat loads is the synchrotron radiation, which is emitted by the high-energy beams and which is deposited on beam-screens. In total, 5.1 MW are deposited on the beam screens and must be extracted by the cryogenic system. Cooling these beam screens with operating conditions as applied to the LHC beam-screen cooling will require an electrical input power of 620 MW, which is definitely prohibitive. An exergy analysis has been performed to optimize the operating conditions of the FCC beam-screen cooling with as main outcome, a reduction of the corresponding entropic load by a factor ~5. In addition, by introducing new refrigeration cycles based on mixture of helium and neon, which have higher expected efficiency with respect to Carnot than pure helium refrigeration cycle, and by recovering the energy extracted by the large turbo-expanders, additional energy saving has been quantified.

After recalling the basic cryogenic design strategies, this presentation is focused on the optimization of the FCC beam-screen cooling in terms of operating conditions, distribution and refrigeration system, with emphasis on energy efficient helium-neon refrigeration.

Recent studies on water consumption and improvements on cooling towers effluents

Serge Deleval, CERN

Primary cooling of accelerators and experimental areas at CERN is achieved with open wet cooling towers. Over the past 20 years, CERN has been working on the rationalisation of its water consumption that has been reduced to 20% in the last 20 years while the overall cooling need has increased by 100% in the last 10 years, mainly related to the LHC operation. CERN has set up solutions to reduce the water consumption in the cooling towers, and also for environmental reasons, by reducing the quantity of blow-down or by recycling the water rejected. These solutions have been deployed on several cooling circuits for test and provided good results. CERN has therefore launched a project to install these solutions in all cooling towers. The author will present the main technical aspects of these solutions, the results achieved until now and the implementation planning for the coming years.

Efficiency versus sobriety: optimized cryogenic design of stand-alone superconducting magnets

Philippe Lebrun, ESI

A number of particle accelerator and transfer line projects make use of stand-alone superconducting magnets, i.e. magnets that have their individual cryostat, cryogenic feed and powering system. Typical examples are the retrofitting of superconducting magnets in a normal-conducting accelerator, large-aperture magnets used for high-resolution spectroscopy in a nuclear fragment separator, beam transport magnets in gantries for proton- or ion-therapy, or superconducting insertion devices in synchrotron light sources. When such magnets are optimized for cryogenic efficiency, cryogenic distribution to each of them is quite complex, usually requiring supply of liquid helium at around 4.2 K for the magnet bath or cooling circuit, recovery of helium vapour at 4.2 K sent to the refrigeration plant, supply of gaseous helium at around 60 K for the thermal shield, returned at around 80 K, as well as recovery of gaseous helium at room temperature coming out of the gas-cooled current leads. Moreover, this type of cooling scheme strongly links the operation of the refrigeration plant to that of the stand-alone magnets, thus imposing coupling between the operation modes of the different magnets. We present a much simpler scheme, based on the transfer of liquid helium to the stand-alone magnets and the recovery of gaseous helium at room temperature, the cryogenic plant then operating as a pure liquefier. We estimate the corresponding exergetic loss, to be balanced against the capital economy realized with a much simpler distribution scheme.

Lifecycle assessment: usefulness for and applicability to research infrastructures

Manuele Margni,
Polytechnique Montréal

The awareness of the need to transition to a carbon-neutral, socially responsible and fully circular society has increased substantially in the last few decades. Research and academia have played a key role in identifying the problem and proposing remedial strategies and solutions, but there is still progress to be made when it comes to defining approaches and best management practices research organisations themselves - and energy-intensive Research Infrastructures (RIs) in particular - should use to address their own environmental impact and sustainability.

This talk will introduce Life Cycle Assessment (LCA) as a holistic and quantified approach to evaluating environmental "hotspots" of products, services and technologies and discuss its usefulness for and applicability to RIs. We will show its relevance to RI stakeholders to support strategic decisions throughout the RI's lifecycle, but also to better inform operators in a wide range of management decisions. Using examples, the talk will illustrate that the energy footprint of RIs is more complex than traditional perceptions suggest and demonstrate the need for the development of good practices specific to RIs.

Ecological diversity

Therese Welander,
ESS

The ESS a source for biodiversity: The ESS sustainability goals go beyond limiting the environmental impact of the construction and the future operation of the facility. Instead of settling for turning Swedish class A farmland into an industry area, ESS is committed to have a positive impact on its close surroundings. Evolving the landscape from monoculture to biodiversity will directly support the vision of creating a sustainable research facility and an attractive working environment for ESS staff.

ORGANIZING INSTITUTIONS

CERN

CERN (www.cern.ch), the European Organization for Nuclear Research (Organization européenne pour la recherche nucléaire), is a European research organization that operates the largest particle physics laboratory in the world. Established in 1954, the organization is based in Geneva on the Franco–Swiss border, and has 23 member states and 8 associate member states.

CERN mission is to provide a unique range of particle accelerator facilities that enable research at the forefront of human knowledge, to perform world-class research in fundamental physics, to unite people from all over the world to push the frontiers of science and technology, for the benefit of all.

CERN is also the birthplace of the World Wide Web.

ERF-AISBL

ERF-AISBL (www.erf-aisbl.eu) has the not-for-profit purpose to promote the cooperation and the projects between Europeanlevel research infrastructures which are open, at international level, to external researchers. These Infrastructures include national infrastructures as well as European networks and consortia of research infrastructures. Since 2013 ERF has been recognized as an AISBL (Association Inter nationale Sans But Lucratif) according to the Belgian law, taking the place of the former ERF de facto association. In order to promote the cooperation and the projects between European-level research infrastructures the Association acts as a single voice, representing the Members with decision-makers, in particular at EU and international level; encourages the coordination, the development, the setting-up and the operation of high quality infrastructures, open at world level, contributing to the strength of the European Research Area, also through high level workshops and meetings; · helps in the creation of mechanisms and best practices for an appropriate allocation of funding and resources by the European States and the EU, to ensure the best response to international users requirements and to societal challenges; · facilitates the availability of resources (human, financial, instrumental) for high quality research infrastructures by encouraging the cooperation of the members, also through the initiation of specific joint initiatives, training courses or consortia; · facilitates and support the collection and the access to data relevant for users, policy makers and other stakeholders; · develops and implements specific projects of common interest, supported by the EU and/or international funding; · supports the development of strategic planning and forward looking at national and international level.

ESS

The European Spallation Source ESS (www.europeanspallationsource.se) is one of the largest science infrastructure projects being built in Europe today. ESS has the objective to be the world's leading research facility using neutrons, providing the tools for analysis that will enable the next important discoveries in nanotechnology, life science, pharmaceuticals, materials engineering, and experimental physics. It will also be the first large scale research facility that will be environmentally sustainable. Organized as a European Research Infrastructure Consortium, or ERIC, this next-generation research facility is being built through the collective global effort of hundreds of scientists and engineers from institutes and laboratories in the Member Countries throughout Europe. Located in Lund (Sweden), next to the world-leading synchrotron light source MAX IV, it will be an economic driver for all of Europe, serving up to three thousand guest researchers from universities, institutes and industry each year. ESS construction formally began with the Groundbreaking Ceremony on September 2, 2014. The first neutrons will be delivered by the end of the decade, with the user program to follow in 2023.

DESY

DESY is a national German research center and member of the Helmholtz Association. Researchers use the large-scale facilities at DESY to explore the microcosm in all its variety – from the interactions of tiny elementary particles and the behaviour of new types of nanomaterials to biomolecular processes that are essential to life. The accelerators and detectors that DESY develops and builds are unique research tools generating the world’s most intense X-ray light, accelerate particles to record energies and open completely new windows onto the universe. That makes DESY not only a magnet for more than 3000 guest researchers from over 40 countries every year, but also a coveted partner for national and international cooperation.

PSI

The Paul Scherrer Institute PSI is the largest research institute for natural and engineering sciences in Switzerland, conducting cutting-edge research in three main fields: matter and materials, energy and the environment and human health. PSI develops, builds and operates complex large research facilities. Every year, more than 2400 scientists from Switzerland and around the world come to PSI to use the unique facilities to carry out experiments that are not possible anywhere else. PSI is committed to the training of future generations. About one quarter of PSI’s staff are apprentices, post-graduates or post-docs.

ARIES

ARIES (https://aries.web.cern.ch/), the Accelerator Research and Innovation for European Science and Society, is an Integrating Activity project dedicated to the research, development and innovation of European particle accelerators and their related infrastructure and technology. The project will run for a duration of four years from May 2017 to April 2021 and is co-funded by the European commission under its Horizon 2020 programme. Future accelerators will need higher energy and luminosity to allow scientists to continue exploring the fundamental building blocks of the universe. To reach this goal new technologies and materials must first be developed so accelerator infrastructures can cope with the requirements of future research. Accelerators and their related technologies are used in a variety of different scientific disciplines and have broad applications in fields such as industry, healthcare, energy, environment, security and cultural heritage. Comprising 41 partners from academic and industry from 18 different European countries, including CERN, ARIES will combine an innovative programme of R&D with wider involvement and engagement from the scientific community to help ensure the future of accelerators is secured.

USEFUL INFORMATION

Registration

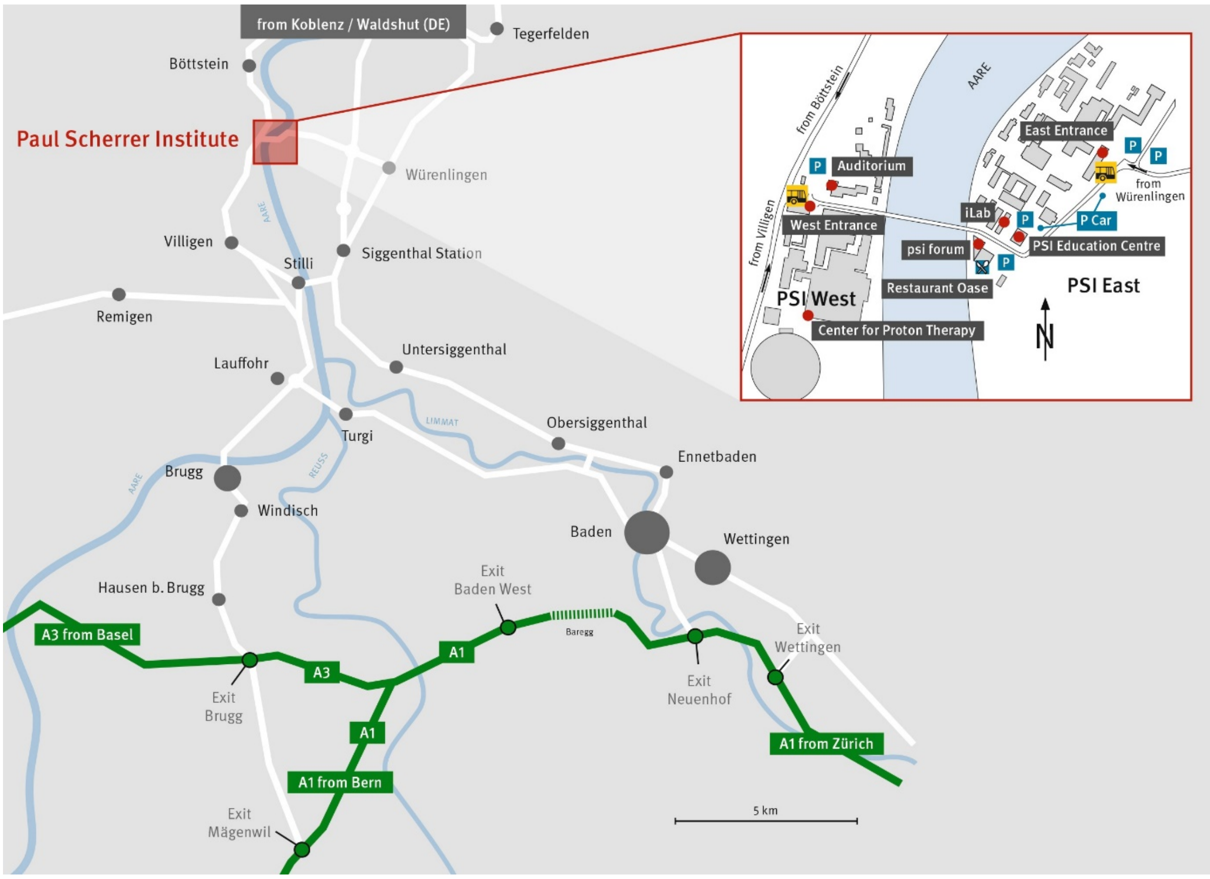
Thursday, 28 November 2019 | 8.00 – 9.00 h

Wireless on PSI Campus

- guest - Wireless Access to Guest Network
- eduroam - Wireless Access to Eduroam WLAN Access Community
- wlan-conf (password will be given at the workshop)

Workshop venue

- Auditorium PSI West
- PSI Education Center PSI East



Workshop Dinner at PSI Restaurant OASE

The Workshop Dinner will take place on Thursday evening, 28 November 2019, at 18.45 h at the PSI restaurant OASE.

Public Transport

Baden train station – Villigen PSI West | by train & bus

7.54 dept.	Baden | Train S27	8.24 dept.	Baden | Train S27
8.02 arriv	Siggenthal-Würenlingen	8.32 arriv.	Siggenthal-Würenlingen
8.04 dept.	Siggenthal-Würenlingen | Bus 357	8.34 dept.	Siggenthal-Würenlingen | Bus 357
8.12 arriv.	Villigen PSI West	8.42 arriv.	Villigen PSI West

Villigen PSI East - Baden | by train & bus | Thursday evening

20.46 dept.	Villigen PSI East | Bus 357	21.16 dept.	Villigen PSI East | Bus 357
20.51 arriv.	Siggenthal-Würenlingen	21.21 arriv.	Siggenthal-Würenlingen
20.53 dept.	Siggenthal-Würenlingen | Train S27	21.23 dept.	Siggenthal-Würenlingen | Train S27
21.03 arriv.	Baden	21.33 arriv.	Baden

Brugg train station– Villigen PSI West | by bus

8.04 dept.	Brugg | Bus 376	8.34 dept.	Brugg | Bus 376
8.15 arriv.	Villigen PSI West	8.45 arriv.	Villigen PSI West

PSI East – Brugg | by bus | Thursday evening

21.02 dept.	PSI East | Bus 376
21.24 arriv.	Brugg

Swiss Railway timetable: www.sbb.ch