Seventh CW and High Average Power RF Workshop

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Book of Abstracts

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Session 2 / **2**

The IPHI 352 MHz RF source at CEA/Saclay

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The IPHI (High Intensity Proton Injector) is a facility developed at CEA/Saclay in collaboration with CERN and IN2P3. The final step of this Low Energy accelerator prototype designed to accelerate beams up to 100 mA with energy up to 3 MeV is in progress. An overview of the main components is given, the RF source is described and last RF measurements are shown.

Session 4 - SSA / **4**

First Experience at ELBE with the new 1.3 GHz CW RF-System based on 10kW Solid State Amplifiers

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With the expansion of the radiation source ELBE, a centre for high power radiation sources is being built between 2009 and 2014 at the Helmholtz Zentrum Dresden Rossendorf. One part of this program is to increase the beam current of the ELBE LINAC. In January 2012 each of the 10kW CW klystrons used to operate the superconducting cavities of ELBE since 2001 had been replaced by a pair of 10kW solid state amplifiers.The talk gives an overview on the new RF-system of ELBE and its performance.

Session 7 / **5**

Performance and Upgrades of the Advanced Photon Source (APS) 352MHz / 1-MW Klystron Power Systems*

Author: Gian Trento[1]

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Essential for operation of the APS booster and storage ring are the high power radio frequency (rf) systems. The high-power rf system consists of five individual 100-kV, 20-A DC power systems each feeding its respective 1-MW continuous wave klystron. Each power system contains a medium voltage electrical substation, a 1400-V SCR gated voltage regulator, a 100-kV rectifier, an ignitron crowbar stack, and a hard tube modulator. Performance and upgrades to these klystron power systems will be discussed.

- Work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.

Session 1 / **6**

NSLS-II RF Systems: Status and Upgrade Plans

Author: James Rose[1]

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The NSLS-II is a third generation 3 GeV light source designed for 500mA of circulating current and up to 1.2 MW of installed RF power. The RF systems consist of a 200 MeV S-band pulsed LINAC, 90 kW IOT based transmitter powering a 7 cell cavity for the booster and up to four 500 MHz SRF systems and two 1500MHz SRF passive cavities in the storage ring distributed equally in two RF straight sections. Only one of the storage ring RF straights are funded in the project baseline (two 500 MHz and one 1500 MHz systems). The project has taken the conservative approach of two 300 kW klystron transmitters powering CESR 500 MHz SRF cavities for the project baseline, along with a passive SRF 1500 MHz cavity for bunch lengthening. An R&D program is looking at competing technologies for the second two 500 MHz RF systems including combined solid state transistor amplifiers at ≥ 400 kW each and new cavity coupler designs. Status of the LINAC, booster and SR systems will be given as well as an overview of the R&D program will be presented.

Session 7 / **7**

Status of the Advanced Photon Source (APS) 352-MHz Radio Frequency Test Stand (RFTS)*

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The APS 352MHz radio frequency test stand (RFTS) was constructed in 2002 primarily to test and condition storage ring and booster rf cavity components. Since the rf test stand's inception, modifications have been made to increase the RFTS's testing capabilities. These modifications include: the installation of a solid state switch / mod-anode regulator, a high-voltage switch tank, access to the klystron garage, and addition of waveguide components to connect a klystron under test to a 1-MW rf load. These recent improvements and the overall performance of the RFTS will be discussed.

- Work supported by the U.S. Department of Energy, Office of Science, Office of Science, under Contract No. DE-AC02-06CH11357.

Session 2 / **8**

The Advanced Photon Source 352-MHz RF Systems – A Case for Solid State?

Author: Douglas Horan[1]

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The Advanced Photon Source (APS) booster and storage ring rf systems utilize 352-MHz, 1.2 MW klystrons as final rf amplifier devices. After seventeen years of APS operation, optimized system designs and detailed preventative maintenance activities have resulted in rf system reliability statistics that have exceeded the wildest expectations hoped for at the start of APS operations. How we learned to bullet-proof rf systems and tame skittish klystrons will be discussed. The conceptual design for a solid state conversion at APS will also be discussed with a focus on the daunting challenge of matching the reliability of our existing klystron-based rf systems.

Session 7 / **9**

New HOM damped cavities at the ESRF

Author: Jorn Jacob[1]

Co-authors: Bernard Ogier [1]; Loys Goirand [1]; Vincent Serriere [1]

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New HOM damped cavities have been developed at the ESRF on the basis of the BESSY/ALBA cavity. Three prototypes have been built by three companies RI, SDMS and CINEL following different manufacturing procedures. The first one is under test on the storage ring, the second one is ready for tests to be started next summer and the last one is to be delivered in the coming weeks. Design features, manufacturing processes and first tests will be reported.

- This work has received support from the EU in the framework of the FP7/ESFRI/ESRFUP project

Session 4 - SSA / **10**

Development at the ESRF of advanced solid state amplifiers for accelerators

Author: Jorn Jacob[1]

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The ESRF has ordered seven 150 kW solid state amplifiers (SSA) from ELTA. In parallel, the ESRF has started an R&D program for mroe compact and less costly SSA using planar balun circuits and cavity combiners. The status of the project will be reported.

- This work receives supported from the EU in the framework of the FP7/ESFRI/CRISP program.

Session 2 / **11**

Operation status and commissioning of four 150 kW SSA on the ESRF booster

Author: Jean-Maurice Mercier[1]

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The operation performance of the ESRF RF system will be presented, followed by a detailed report on the procurement, installation, test and commissioning of four 150 kW solid state amplifiers on the booster.

Session 1 / **12**

NSLS I : Challenges and upgrades on a 30 year old high power RF systems

Author: Aditya Goel[1]

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The National Synchrotron Light Source consists of an x-ray ring operating with 300mA stored beam at 2.8 GeV and a UV ring with 1 ampere of stored beam at 800 MeV and a shared injector linac and booster. It has been in operation since 1979. The RF systems at this facility cover a wide variety of RF technologies from high power tetrode tube based systems to moderate power solid state devices. Over the 33 years of operation the system has seen some upgrades but the amplification and control chain has remained relatively static. This presentation describes some of the upgrades and challenges that are faced in trying to maintain and extract maximum reliability and performance out of these systems. The challenges are unique mainly because of the age of the systems involved and the fast changes the RF industry has seen in the recent years with the advent of solid state devices and decline in the tube based device market.

Session 7 / **13**

Design, simulations and conditioning of 500kW CW FPCs for the ERL SRF gun at BNL

Author: Wencan Xu[1]

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BNL 704MHz SRF gun for ERL uses two high power fundamental power couplers (FPCs) to deliever 1MW CW RF power to gun cavity. Prior to install the FPCs to the cavity, we used the 1MW klystron to condition the two couplers. This paper will address design of the high power couplers, conditioning test of the FPCs. Multipacting simulation using Track3P and comparison with conditioning will be pesented as well.

Session 8 / **14**

Status of the the S-band RF Power System for the FERMI@Elettra Linac

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FERMI@Elettra is a single-pass linac-based FEL user-facility covering the wavelength range from 100 nm (12 eV) to 4 nm (310 eV) and is located next to the third generation synchrotron radiation facility Elettra in Trieste, Italy. The machine is presently under commissioning and the first FEL line (FEL-1) will be opened to the users by the end of 2012. The 1.5 GeV linac is based on S-band technology. The S-band system is composed of fifteen 3 GHz 45 MW peak RF power plants powering the gun, eighteen accelerating structures and the RF deflectors. This presentation provides a summary of the FERMI linac and reviews the S-band RF power plants and the performances results of the main subassemblies during the commissioning of the accelerator.

Session 1 / **15**

RF POWER UPGRADE AT JEFFERSON LAB

Author: Richard Nelson[1]

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Eighty RF positions are being added to the existing 340 as part of an energy doubling upgrade at Jefferson Lab. Built around a newly designed and higher efficiency 13 kW klystron developed for JLab by L-3 Communications, each new RF chain is completely revamped because of increased power capabilities, yet needed to fit into an existing footprint. This paper will discuss the main components of the new systems including the 13 kW klystron, waveguide isolator, and switch-mode HV power supply, plus installation and operational results so far

Session 3, hot topic, SSA / **16**

Evolution of High Power LDMOS Transistors at NXP

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This presentation will discuss the evolution of high power transistors at NXP Semiconductors. It will focus on the technology specific to the frequency bands most utilized by the accelerator community. It will show the improvements in performance, and what those improvements can bring to the design community. Finally, future roadmaps will be shown. This will be a platform to start discussions with

the design community about what trends can most help them leverage solid state technology for their amplifier needs in the future.

Session 3, hot topic, SSA / **17**

150kW SSA for ESRF Booster Upgrade

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In the frame of ESRF Booster Upgrade, ELTA-AREVA has designed and provided four 150kW Amplifier at 352 MHz, based on Solid State Amplifier technology.
The presentation describes main features and performances of the 150 kW SSA that have been qualified on fictive terminations and have been recently connected to Booster cavities.
The SSA is based on 650W LDMOS Power Amplifier Modules, optimized in terms of efficiency. Power coupling, control and monitoring units, thermal management and mechanical structure have been specifically designed for this application.

Session 8 / **18**

A new generation of arc detectors for the LHC and Linac4 high power RF system

Author: Daniel Valuch[1]

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During operation, the LHC high power RF equipment has to be protected from damage caused by electromagnetic discharges (arcs). The LHC waveguide arc detector system is based on the optical detection of the discharge through small apertures in the waveguide walls, optical fibres and very sensitive photo detectors.
Experience shows that some of the currently used optical fibres suffer from x-ray induced opacity. The sensors are also exposed to the radiation produced by secondary showers coming from the high intensity beams which, if not treated properly, can cause frequent spurious trips.
Therefore a new generation of arc detectors with number of improvements has been developed. New fiberless design, based on measurements with optical parameters from real arcs with redundant detectors for critical environments will be presented.

Session 7 / **19**

RF fundamental power coupler news

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Recent fundamental power coupler designs and tests for various projects such as SPL, Linac4, ESRF, SOLEIL, APS, HIE-Isolde.

Session 2 / **20**

RF power source and distribution at 352 MHz for spoke cavities for ESS and at FREIA

Author: Rutambhara Yogi[1]

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European Spallation Source (ESS) is one of the world's most powerful neutron sources. The ESS linac will accelerate 50mA of protons to 2.5GeV in 2.86ms long pulses at a repetition rate of 14 Hz. It produces beam with 5MW average power and 125MW peak power. There are 36 superconducting spoke resonators, which provide a power of 0.5MW to the beam.
FREIA (Facility for Research Instrumentation and Accelerator Development) in Uppsala University will develop one prototype amplifier chain.
The baseline for the RF system in ESS is a point-to-point generation and distribution of the RF power from a single source to a single accelerating cavity. The capital and running cost of an accelerator is strongly affected by the r.f. power amplifiers in a number of ways. The capital cost of the amplifiers (including replacement tubes) is an appreciable part of the total capital cost of the accelerator. Their efficiency determines the electricity required and, therefore, the running cost. The gain of the final power amplifier determines the number of stages required in the r.f. amplifier chain. The size and weight of the amplifiers determines the space required and can, therefore, have an influence on the size and cost of the tunnel in which the accelerator is installed. Hence selection of power source is very important.
Selection and the criteria used for selection is dealt in the present paper. Typical power sources used at 352MHz at high power are tetrodes, klystrons, IOTs, solid state amplifiers and diacrodes.
The paper discusses all these topologies based on capital cost, size, efficiency, gain, power supplies and stringent requirements on specifications of power supplies, replacibility, life time and their running cost. Considering all these parameters, the tetrode has been selected as driver amplifier. The tetrode gain is relatively low, around 20 dB, and a pre-amplifier stage is required. The possible pre-amplifier topologies are solid state amplifier and triode. Both the topologies are compared based on various parameters as discussed above for the amplifier and solid state amplifiers are selected as pre-amplifier. The paper also discusses the RF distribution scheme between power source and spoke resonator.

Session 2 / **21**

The European Spallation Source RF System Design

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The European Spallation Source Linac reaches an energy of 2.5GeV within 350 meters. The linac delivers an average power of 5 MW with a 4% duty factor (2.9 mSec pulse at a rate of 14Hz). The peak power of the linac is over 123 MW. This averages to a peak power density that must be supplied to the beam of over 350kW/meter. Because of the large power density, 98% of the linac consists of superconducting radio frequency (RF) resonators that are used to transfer power to the beam. Before the superconducting part of the linac is a normal conducting drift-tube linac operating at 352 MHz. The normal conducting linac will be powered by four 2.0 MW power sources. There are three types

of superconducting resonators. The first 28 resonators are spoke resonators operating at 352 MHz. The remaining 184 resonators are elliptical cavities operating at 704 MHz. The peak power level covers a range from 50kW to 850 kW. The RF system for the ESS linac is defined as the system that converts AC line power to RF power at either 352 or 704 MHz to be supplied to the RF accelerating cavity couplers. This paper will give an overview of the low-level RF control, the RF power sources, and the RF distribution for the ESS RF system.

Session 7 / **22**

The cavity for RF input coupler conditioning at SPring-8

Author: Hiroyasu Ego[1]

Co-authors: Hiroshi Saeki [1]; Hiroto Yonehara [1]; Shigeki Sasaki [1]; Takahiro Watanabe [1]; Yoshitaka Kawashima [2]; Yuji Ohashi [1]

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We have developed a cavity specifically used for the coupler conditioning. For the booster synchrotron, 5-cell cavities are used and maximum 300-kW RF power must be fed through the couplers, whereas for the storage ring single cell cavities are used and the power fed through the coupler is 150 kW at maximum. Each coupler should be conditioned before the installation to the actual machine. We used the prototype 5-cell cavity for acceptance tests when we purchase additional couplers as spare parts. However, a vacuum leak occurred on the 5-cell cavity, in addition, the 5-cell cavity was heavy, large and not easy to handle. We decided to make a new cavity used only for conditioning the couplers. Two couplers were connected face to face, in-between the coupler-conditioning cavity was located. For the conditioning, one of the couplers was connected to the output of a 1-MW klystron, and the other coupler was connected to a dummy load. During the conditioning, RF power passed through the couplers and the cavity, and was absorbed in the dummy load. The coupler-conditioning cavity is small, light and easy to handle. The efficiency of the conditioning work was significantly improved.

Session 5, hot topic, IOT / **23**

90 kW CW IOT Development at L-3 Communications Electron Devices

Author: Michael Boyle[1]

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L-3 Communications Electron Devices has developed a 90 kW CW 500 MHz IOT for the BNL NSLS-II Booster RF Transmitter System. L-3 has been manufacturing IOTs for use in UHF terrestrial broadcast applications since 1998. Details regarding design modifications to our standard broadcast IOT along with performance data will be presented.

Session 7 / **24**

High Voltage Power Supply for the ALS Storage Ring RF system-Disconnect Switch status.

Author: Slawomir Kwiatkowski[1]

Co-authors: James Julian [1]; Kenneth Baptiste [2]

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The new ALS Main Ring 500MHz RF system will require significant modification of the existing HV power supply in which classical ignitron based crow-bar system will be replaced with house made solid state disconnect switch which is undergoing final high power test. The principle of the operation and the status of the testing will be presented.

Session 6 / **25**

Testing & Commissioning a New Klystron at the ALS - Lessons Learned

Author: Kenneth Baptiste[1]

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I will present the the issues that we encountered and ultimately overcame while testing and commissioning our new 300kW class klystron. Issues such as unexpected mod-anode PS ripple frequencies, HV electro-static shielding, correct biasing of the mod-anode electrode during a fast HV fault, HV turn-on transients, filament resistance changes, etc.

Session 3, hot topic, SSA / **26**

High power RF amplifiers using LDMOS technology

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This presentation will cover Freescale high power RF amplifiers using LDMOS technology, and some its advantage it brings over traditional technologies. It will also cover topics regarding design support, thermal characterization and ruggedness/reliability. Presentation will conclude with an outlook on future trends of LDMOS RF amplifiers.

Session 7 / **27**

Short Circuit Energy

Author: Andre Spichiger[1]

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Short circuit energy considerations using the example of a pulse step modulator based HVPS.

Session 5, hot topic, IOT / **28**

The Diamond Storage Ring IOT Based High Power Amplifier

Author: Morten Jensen[1]

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Diamond currently operates its storage ring with two high power IOT based amplifiers. Each amplifier combines the output of up to four 80 kW IOTs. We present here the outline design of the amplifier and operational parameters.

Session 1 / **29**

Upgrades, operational experience and EM simulations of the Diamond SR High Power Amplifiers

Author: Morten Jensen[1]

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We present here a selection of results and some of the major upgrades specific to the high power amplifiers.

Session 2 / **30**

The SNS MEBT RF Power Amplifier Solid State Upgrade

Author: Mark E. Middendorf[1]

Co-authors: Michael E. Clemmer [2]; Thomas Hardek [2]

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The original vacuum-tube-based rf power amplifiers (four online, two spare) that drove the four rebunching cavities on the Spallation Neutron Source (SNS) Medium Energy Beam Transport (MEBT)

structure have been replaced with commercially available 25-kW solid state amplifiers (4 online, one spare). A 4+1 switch matrix permits remote switching of the spare amplifier into any one of the four MEBT rebunching cavities. The fifth and final solid state amplifier was installed in September, 2011, and the system has operated without fault since that time. We describe the integration and operation of the system upgrade.

*Work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.

Session 5, hot topic, IOT / 31

Inductive Output Tube (IOT) Development at CPI

Author: Edward L. Eisen[1]

[1] *CPI, Palo Alto*

The Inductive Output Tube (IOT) has played a major role in in the broadcast television industry for many years, due to the IOTs improved efficiency, linearity and reduced footprint compared to the klystron. In the past decade this electron device has found expanded use in both RF accelerator systems and military defense applications. The IOT can provide continuous wave power up to hundreds of kilowatts and pulsed power up to a megawatt, at frequencies ranging from approximately 300 MHz to 1500 MHz. A brief history of the IOT and its development at CPI will be presented followed by a discussion of some IOT development efforts currently underway at CPI. Some of the major design/technology issues that must be overcome to achieve successful performance will also be discussed.

Session 1 / 32

Elettra 500 MHz RF Power Plants

Author: Cristina Pasotti[1]

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A review of the ELETTRA Storage Ring and Full Energy Injector 500 MHz RF power plants (klystron and IOT sources) is described as well as their performances and maintenance procedure. An introduction on RF power projects and future installations is given

Session 6 / 33

10 years of klystron operation and improvement in Swiss Light Source

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Last year we celebrated the 10th anniversary of commissioning the Swiss Light Source. The heaters of all klystrons collected about 255'000 hours during this time and the overall operation was extremely successful. Nevertheless several issues, like reinforcing the HV cabinet, coincident arc detection and cooling air interlock had to be improved. These klystrons are not any longer produced by EEV or E2V and we therefore bought two spare klystrons from Thales and started together with CPI a refurbishment program.

Session 8 / **34**

SRF Cryomodule Construction and Photocathode Prototyping at AES

Author: David Meidlinger[1]

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Current activities by AES in the construction of single-cell 500 MHz SRF cryomodules for NSLS-II will be discussed as well as aspects of the protyping of a BNL/AES SRF electron gun designed for 500 mA average beam current.

Session 8 / **35**

Standing Wave Issue in Waveguide Directional Coupler Calibration Process

Author: Nikolai Schwerg[1]

[1] *CERN*

The low-level RF system for LHC and Linac4 relies on the accurate readings of waveguide directional couplers as well as the cavity antenna measurements. A good calibration of both is crucial for an effective regulation.

We briefly revise the working principle of waveguide directional couplers and illustrate the coupler calibration process. Inevitable standing waves in the calibration setup limit the accuracy for the directivity. We will discuss this effect and a technique to compensate this imperfection of the directional coupler mathematically in the low level RF system.

Session 6 / **36**

LHC RF power system. Status, experience with nominal beam, upgrades during the long technical stop.

Authors: Erk Jensen[1]; Olivier Brunner[1]

Co-authors: Daniel Valuch [1]; Nikolai Schwerg [1]

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placeholder for the CERN colleagues

Session 4 - SSA / **37**

Developments of high CW RF power solid state amplifiers at SOLEIL

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At SOLEIL, 5 Solid State Amplifiers (SSA) are providing the required 352 MHz CW power : 1 x 35 kW in the Booster (BO) cavity and 4 x 180 kW on the 4 superconducting cavities of the Storage Ring (SR). Based on a design fully developed in house, they consist in a combination of a large number of 320 W elementary modules (1 x 147 in the BO and 4 x 724 in the SR) with MOSFET transistors, integrated circulators and individual power supplies.
After 6 years of operation, this innovative design has proved itself and demonstrated that it is an attractive alternative to the vacuum tube amplifiers, featuring an outstanding reliability and a MTBF > 1 year.
In the meantime, thanks to the acquired expertise and the arrival of the 6th generation LDMOS, SOLEIL has carried out developments which led to doubling the power of the elementary module (650 W @ 352 MHz) while improving the performance in terms of gain, linearity, efficiency and thermal stress. Four 150 kW SSA, relying on such modules, were recently commissioned in the ESRF Booster.
Now, 500 MHz amplifiers, based on this technology, are being built for ThomX (50 kW) and SESAME (140 kW) projects. All key parts have been validated.

Session 2 / **38**

Current activities on the rf-system for the proton accelerator facility at PSI

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At PSI, protons are accelerated up to an energy of 590 MeV by two separated sector cyclotrons, the Injector 2 and the Ring. Since 2008 the Ring cyclotron is running with 4 copper cavities. By increasing the cavity voltage to 850 kVp the number of turns was reduced and the beam current is increased up to 2.4 mA, which results in a beam power of 1.4 MW.
In 2010 the regular operation suffered from arcing and plasma in the Ring cyclotron. The story ended up in cleaning of cavity surfaces and differential tuning systems for cavity number 3 and flattop cavity to reduce the radiated rf power. The cleaning and results of the new tuning systems will be shown.
An upgrade program of the Injector 2 rf-system will replace the flattop cavities (150 MHz) by accelerating cavities (50 MHz). The new cavities are manufactured and the first one was tested under power. Issues such as cavity power test, tuners, and finger contact tests will be presented.

Session 2 / **39**

CW RF Systems at the CLS

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The Canadian Light Source is a third generation 2.9 GeV synchrotron light source which has been operational since 2003. This talk will discuss the booster ring and storage ring RF system architecture, performance, reliability and improvements made since commissioning.

Session 8 / **40**

High Power RF Distribution with Vector Control for Multicavity Cryomodule Test

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A four-way waveguide RF power distribution system for testing the SNS multi-cavity cryomodule to investigate the collective behavior has been developed. A single klystron operating at 805MHz in 60Hz 8% duty cycle powers the 4-way waveguide splitter to deliver up to 600 kW to Individual cavities. Each cavity is fed through a waveguide vector modulator at each splitter output with magnitude and phase control. A vector modulator consists of two quadrature hybrids and two motorized mechanical waveguide phase shifters. The phase shifters and the assembled waveguide vector modulators were individually tested and characterized for low power and high pulsed RF power in the SNS RF test facility. Precise calibrations of magnitude and phase are done to generate the look up tables (LUTs) to provide operation references during the cryomodule test. An IQ demodulator board was developed and utilized to generate 2-port magnitude and phase LUTs. PLC units were developed for mechanical control of the phase shifters. Labview software was programmed for the measurements and the system operation. LUT based operation algorithm was implemented into EPICS control for the cryomodule test stand.

Session 3, hot topic, SSA / **42**

reserve for discussion

Session 5, hot topic, IOT / **43**

reserve for discussion

Greetings / **44**

Greetings

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Agenda and overview