10th Anniversary of CWRF
Looking Back and to the Future

A. Nassiri on behalf of Organizing and Program Committees
June 29, 2018
The goal of this workshop is to share the experience and ideas on applications which utilize high-power klystrons, gridded tubes, combined solid-state architectures, high-voltage power supplies, high-voltage modulators, high-power combiners, circulators, cavities, power couplers and tuners. New ideas on upgrading the high-power RF systems and novel ways of the RF power generation and distribution will also be discussed.
Venues

ALBA - 2010

BNL - 2012

Elettra - 2014
### Highlights - Numbers speak for themselves

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<tr>
<th>Year</th>
<th>Host</th>
<th>No. of Attendees</th>
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<td>2000</td>
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<td>2018</td>
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Welcome to the 1st Annual Meeting of Argonne National Laboratory's CW RF Users Group Meeting. The event took place from March 1 to March 3, 2000.

Highlights - ANL, 2000 (Inaugural)
Highlights - ANL, 2000 (Inaugural)

17 talks

Wednesday, March 1, 2000
9 AM Welcome and Introduction -- Doug Horan - ANL
9:15 – 9:45 Conception of the 500 MHz RF Systems and Operational Experience at DESY-2, DORIS, PETRA-e and HERA-e Michael Ebert - DESY
9:45 – 10:15 10 Years of Operational Experiences with the LEP RF High-Power Systems -- Hans Frischholz - CERN
10:15 – 10:30 Break
10:30 – 11:00 Transmitter Operation at ESRF -- Christian David - ESRF
11:00 – 11:30 ESRF RF System Arc Detector Design and Operation Jean Maurice Mercier - ESRF
11:30 – 12:00 Advanced Photon Source Klystron Operational History Doug Horan -- ANL
12:00 – 13:30 Lunch
13:30 – 14:00 Overview and Operation of the RF System for the LEDA Accelerator and Future Applications -- Mike Lynch -- LANL
14:00 – 14:30 Cathode Follower RF System for High-Intensity Proton Synchrotron Yoshiro Irie - KEK
14:30 – 14:45 Break
14:45 – 15:15 Operating Experience with Klystrons and Cavities Jim Judkins - SLAC

Thursday, March 2, 2000
9:00 – 9:30 Automatic Phasing of the Eight RF Systems at HERA-e Michael Ebert - DESY
9:30 – 10:00 Low-level RF Experience with PEP-II Paul Corredouera - SLAC
10:00 – 10:15 Break
10:15 – 10:45 Parallel Klystron Operation at APS -- Doug Horan - ANL
10:45 – 11:15 Klystron Collector Failure at LEDA, Symptoms and Cause Dan Rees - LANL
12:00 – 13:30 Lunch
13:30 – 14:00 Reliability of the UVC DC Power Supplies -- Alex Cours - ANL
14:00 – 14:30 Initial Performance Challenges, Solutions and Reliability Results of the First Two Continental SSM IGBT Power Supplies Joe Bradley - LANL
14:30 – 14:45 Break
14:45 – 15:15 +AC1 - SPEAR 2/3 RF + AC1 – Sam Park - SLAC/SSRL
19:00 – No-Host Dinner

Friday, March 3, 2000
9:00 – 9:30 High-Power Test Results for RF Components at 352 MHz and 700 MHz -- William Roybal - LANL
9:30 – 10:00 APS Storage-Ring Cavity Components -- Justin Jones - ANL
10:00 – 10:15 Break
10:15 – 11:00 Analog Gap Voltage Regulation System in the APS Storage-Ring Doug Horan - ANL
12:00 – 13:30 Lunch
13:30 – 15:00 Tour of APS RF Systems
15:00 – Meeting Adjourned
Highlights - ANL, 2002

- Operating the PSI RF Systems at 1MW CW Beam Power - Peter Sigg, PSI
- SNS RF System Design - Dan Rees, LANL
- The Doris HOM-Coupler Story - Michael Ebert, DESY
- Performance of the APS 350MHz RF Systems - Doug Horan, ANL
- Measurement of Harmonics for LHC Klystrons - Daniel Valuch, CERN
- Operation of the RF at the ESRF - Jean Maurice Mercier, ESRF
- Fast RF Phase Shifter for High Power Application - Yoon Kang, SNS
- OPEN DISCUSSION - Methodology for RF System Personnel Safety Shutdown
Highlights - PSI, 2004

- Operating Experience with the SLS RF-Systems - Marco Pedrozzi, PSI
- ESRF RF System: Status and Developments - Jorn Jacob, ESRF
- The RF System of PETRA-III - Michael Ebert, DESY
- ELETTRA RF plants: Present Status and Upgrade to Higher Power - Alessandro Fabris, ELETTRA
- Spear3 RF System and Operation - Sam Park, SLAC
- High Power 352 MHz Solid State Amplifiers for the SOLEIL Synchrotron Light Source - Ti Ruan, SOLEIL
- Installation and Operation of IOTs for RF Separation in Jefferson Lab's Main Accelerator - R. Nelson, JLAB
- 350MHz Fast Ferrite Tuner Testing at APS - Doug Horan, ANL
- 352MHz High Power, Fast Ferrite Phase Shifter - Daniel Valuch, CERN

27 talks
Highlights - PSI, 2004

Dinner at Habsburg Castle
Highlights - PSI, 2004

Dinner at Habsburg Castle
### Highlights - ANL, 2006

#### FORTH CW AND HIGH AVERAGE POWER RF WORKSHOP  Argonne National Laboratory

**AGENDA**

**SUNDAY April 23rd**
- Reception 1830
- Building 301 5th Floor

**Monday May 1st**
- Building 360- Room A224
- 090 Welcome and Introduction
- 1030 The Spallation Neutron Source Accumulator Ring RF System
- 1230 Lunch
- 1310 Period with a Tahoe or latest developments of PSI
- 1350 Status of the SPS RF System
- 1430 Coffee Break
- 1510 Modern and Costless DC Power Supplies for CE Applications
- 1600 Performance report on the 20kV/25A Anode Power Supply System Built for the KEKAN,RIS

**Tuesday May 2nd**
- Building 360- Room A224
- 090 50kW Power Plant for the Sirena RF System Upgrade Project
- 1010 TRIUMF Cyclotron 23 MHz RF System
- 1230 LUNCH
- 1550 Coffee Break
- 1640 LUNCH

**Wednesday May 3rd**
- Building 360- Room A224
- 090 Design and Applications of Polysilicon Resonant Converter-Modulator
- 1010 TRIUMF Cyclotron 75 MHz RF System
- 1230 LUNCH
- 1400 Experience with the Klystron Procurement and Testing for the SNS Accelerator
- 1540 Bunch-by-Bunch Feedback and NOXON Damplified Cavities for Current Increase at the SRF
- 1620 APS Particle Accumulator Ring Upgrades in Supporting of Progress in Bunch Purity and A. Greck

**Thursday May 4th**
- Building 360- Room A224
- 090 Feasibility of Short Pulses at the ESRF
- 1010 Coffee Break
- 1200 LINCH 1
- 1330 Tour of APS RF Systems

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**FORTH CW and High Average Power RF Workshop**

**Advanced Photon Source, Argonne National Laboratory**

**April 17th – 20th 2006**

The 4th CW and High Average Power RF Workshop will be held at the Advanced Photon Source, Argonne National Laboratory April 17th-20th 2006.

The goal of this workshop is to share experience with synchrotron facilities and high average power linac rf systems including high-power klystons, high voltage power supply, power coupler and tuner and discuss new ideas for high power rf system upgrade.

**Workshop Chair:** D. Horan (ANL)

**Workshop Co-Chair:** D. Rees (LANL)

**Scientific Program Committee**
- M. Elbert (DESY)
- J. Jacob (ESRF)
- Y. Kang (ORNL)
- M. Middendorf (ANL)
- A. Nassiri (ANL) - Chair
- P. Sigg (PSI)

**Local Organizing Committee**
- R. Brzowski (Workshop Secretary)
- C. Eybeger (Chair)
- D. Horan
- K. Jage
- M. Middendorf
- A. Nassiri

WORKSHOP INFORMATION IS AVAILABLE AT:
http://www.aps.anl.gov/CWHARP06.html
Highlights - ANL, 2006

Fourth CW and High Average Power RF Workshop
Argonne National Laboratory
Argonne, Illinois, USA
May 1-4, 2006
Highlights – ANL, 2006
Dinner at 5 Seasons Country Club
Highlights – ANL, 2006
• To allow our US colleagues who can not participate personally to attend the workshop whole event will be transmitted by a video link to the Argonne National Laboratory near Chicago, US.
• It seems the era of monster multi-megawatt CW klystrons for large next generation accelerators is over. There are only few customers left
• Demands for high power pulsed klystrons for e.g. medical applications and new linacs are rising
• Many new light sources are being built around the world. More than single high power station many ~100kW stations are required. But... “clean” RF power
• New devices like IOTs, diacrodes or solid state devices can do the job
• The solid state segment is rising. More and more labs are working on high power (~100kW) amplifiers
• We do not yet have enough experience with solid state amps. ~5000 hours running time of one amplifier is not sufficient to compare with the tube technology.

Will be a very good subject for the 2010 meeting as more operation hours and experience will be available.
Highlights - CERN, 2008

Underground Tour of Accelerator/RF
Highlights - CERN, 2008

On the bus to Thonon

Visit to Thales ED Facility - Thonon, France
Hot topic – IOT vs. Klystron vs. Solid State – Paco Sanchez

### Output Power, Efficiency and Gain:

<table>
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<tr>
<th>Klystron</th>
<th>IOT</th>
<th>SSA</th>
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<tr>
<td>60 - 1000 kW</td>
<td>80 kW</td>
<td>700 W</td>
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<tr>
<td>62 %</td>
<td>71 %</td>
<td>70 %</td>
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<td>40 dB</td>
<td>25 dB</td>
<td>20 dB</td>
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(module) (Tower)
Highlights – ALBA, 2010

Hot topic – IOT vs. Klystron vs. Solid State – Paco Sanchez

**Purchase Cost** in kEuro/ kW:

**Klystrons** 400 MHz / 250 kW → ~ 230 k€ → ~ 0.9 k€ / kW

**IOTs** 500 MHz / 80 kW → ~ 50 - 70 k€ → ~ 0.6 - 0.9 k€ / kW

**SSA** 352 MHz / 200 kW → ~ 740 k€ → ~ 3.7 k€/ kW (300W)

~ 2.8 k€/ kW (700W)

*N.B:* SSA from SOLEIL data (4 “towers” of 200 kW). The complete transmitter includes transformer + HV rectifier + control system, …), but SOLEIL manpower is not included. All components were built in the industry according to the SOLEIL specifications)
Highlights - ALBA, 2010
Highlights – BNL 2012
Shark Dive

- 10+ volunteers have signed up for the shark swim— they have shark logos on their name tags to identify them—greet them during the breaks.
- We will choose 2 of these brave souls to swim with the sharks after the Banquet (their last meal?)
- There is a sign-up sheet for those who wish to add their name to the list of volunteers— it is not too late!
- We will vote for the two swimmers during this afternoon’s coffee break: Put an X next to two of the volunteers’ names and those with the most votes will swim!

Congratulations to our shark divers Rocio Santiago-Kern and Mark Middendorf
IOT Hot Topic Summary

Availability/Obsolescence time of IOT's
Not much said about the topic. Slow rate of development was evident

Capital and Operational costs

Technical Considerations (power, reliability, footprint, ops and maintenance)
Although acknowledged there was not a good discussion about the arcing problem in IOT's causing constant trips. It was my impression that these arcs were more common than in klystrons- is this a limiting factor in ultra-high reliability?

1) Linear in power with lots of headroom great for feedback systems seems to be a strong point for IOT's

Long term trends in cost, power per device
Development costs are high- vendors burned in development of 1.3GHz 13kW tubes- not likely to pony up $ or euros again
Estimate given of ~1M$ per year for 3 years to develop ~500kW IOT for ESS
Highlights – Elettra 2014
Highlights - Elettra 2014

Robert Lopes’ tribute to Ti Ruan

"Dear madams, dear sirs,

In the name of our family I sincerely thank you all for your condolences and memory to my father. My father lived for science, it was his dream and pleasure. I am sure that he would be very happy in his last rituals and that his contribution is inherited in the scientific world."

Jean, the daughter of Ti Ruan

Do not forget who was THE pioneer in the domain of high power solid state RF amplifiers

Ti RUAN, 1936 - 2014

SOLEIL R&D with 352 MHz SSPA’s

Development of new RF modules, based on 6th generation LDMOS (Vd = 50V)

P_{com} ~ 700 W, G ~ 20 dB, η ~ 70 % at 352 MHz

[ With original LRD01 (20V), P_{com} = 315 W, G = 13 dB, η = 62 % @ 352 MHz ]

Huge improvement: P_{com} x 2.2, better performance (G, η, linearity) & thermal stress strongly reduced (ΔT: -60 °C) ⇒ longer lifetime

ESRF upgrade ⇒ Replace 1 MW klystrons by 150 kW SSPA’s (1 per cavity)
⇒ 2009, SOLEIL transfer of technology with ELTA-AREVA
⇒ 7 SSPA’s of 150 kW, built by ELTA under SOLEIL license

BO: 4 x 150 kW SSPA’s in use since January 2012
2 trips in ~ 5 years of operation ⇒ refill postponed

SR: 3 x 150 kW SSPA’s in use since October 2013
2 trips in ~ 3 years of operation ⇒ beam loss
Trip due to youth problems, which are now fixed

BO + SR: ~ 1800 transistors ⇒ not a single failure!

Efficiency (dc to RF): 58% (dc-dc converters)
With new ac-dc converters ⇒ η (overall ac to RF) > 60%

ESRF 150 kW 352 MHz SSPA from ELTA/SOLEIL
Jim Rose – BNL

• Early commissioning results of the NSLS-II high power rf systems
  o SR commissioning started Feb. 2014 using PETRA cavity
  o Beam current limited to 25 mA (no active beam interlocks)
  o Single and coupled bunch instabilities seen, not limiting progress
  o Booster RF system tested to 90 kW, ramps from 600 W to 60kW at 1 Hz. Petra cavity temperature adjustable +/- 5°C to move HOM’s -not required yet..
  o System has been very reliable-No problems with Thomson Comark/Ampegon) transmitter, L3 IOT, Ferrite Inc. circulator, AFT loads

Nashat Sawai – SESAME (Jordan)

• A 2.5 GeV synchrotron radiation facility, under construction near Amman, Jordan.
  • The members are Bahrain, Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, Palestinian Authority and Turkey.
  • Observers: Brazil, China, France, Germany, Greece, Italy, Japan, Kuwait, Portugal, Russia, Sweden, Switzerland, UK and USA.
  • 500 MHz 80 kW SSA (x 4)
Highlights - Elettra 2014
Eric Montesinos – CERN
20 years of high average fundamental power coupler designs at CER

Design from scratch
4-8 years

Modification of existing
3-5 years


Conclusion
• Be careful of the lifetime of Fundamental Power Couplers!
• Start the next design as soon as possible (as you complete one)
• As always, the Devil is in details, that is particularly true with Fundamental Power Couplers, so do not forget to keep a careful eye on everything!
Highlights – Elettra 2014

Michel Langlois - ESRF
SSA using a cavity combiner
• 5 ideas could make it happen
  o Make use of a cavity combiner to provide compactness
  o Use of-the-shelf power supplies
  o RF modules feature planar baluns, no chock and no trimming
  o RF and DC distribution use the same support as the rf modules
  o The modules are not individually shielded

Morten Jensen – ESS
The ESS RF systems and the plan for new developments
Highlights – Elettra 2014
Erk Jensen – CERN
Recent developments towards very high efficiency klystrons

Motivation

- Future large scale accelerators
  - FCC – CW 800 MHz, 110 MW
  - ILC, pulsed, 1.3 GHz, 88 MW
  - CLIC, pulsed, 1.0 GHz 180 MW

- Combination of three methods promises a significant increase in klystron efficiency (approaching 90%)
  - Congregated bunch
  - Bunch core oscillations
  - BAC (Bunch, Align velocities, Collect outsiders)

- HEIKA collaboration (High Efficiency International Klystron Activity)

- A prototype 40-beam MBK allowed to validate the approach. An old tube ($\eta = 42\%$) was refurbished, implementing the new methods, and reached 66% with 52 kV.
"Château de Vizille" from the 17th century. It now houses the museum dedicated to the French revolution in 1789.
Highlights - ESRF 2016

AT Hôtel Restaurant Chavant - Bresson
Highlights - ESRF 2016
All-in-One
Looking to future

- This workshop serves the accelerator community well by bringing together RF experts from users facilities, research institutes, and industries to discuss high power rf systems.
- We certainly will be very busy at least for a decade AND more!
  - Exciting times, a number of ongoing and new accelerators on the horizon.
  - Light Sources - Sirius (Brazil), ESRF-EBS (France), APS-U (USA), SPring8-II (Japan), LCLS-II-HE (USA), ALS-U (USA), ALBA-U (? Spain), ILSF (Iran)
  - High Energy – PIP-II (USA), LBNF (USA), HiLUMI/HL-LHC (Switzerland), FCC (Switzerland)
  - Nuclear Physics – ARIEL-II (Canada), eRHIC – EIC (USA), FRIB (USA), HIAF (China), RAON (Korea), FAIR (Germany), Cyclotron (Italy)
  - Spallation Sources – ESS (Sweden), PPU (USA)
- We should advance rf performance limits as technology evolves (clean rf power, higher power density, higher efficiency – 80% or better, compactness, power-on-demand, ....) while maintaining high reliability and availability/uptime
- RF performance and functional requirements drive the choice of high-power rf sources and auxiliary components. The “one size fits all” approach will not work. Different applications – different technologies.
Foremost to all 570 participants since 2000
Also, our deepest thanks, sincere gratitude and appreciation to all Local Organizing Committee members.
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<td>Ming-Chyuan Lin</td>
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Let’s not forget our International Organizing and Program Committee Members! A special shout-out to Daniel, workshop indicoido grandmaster!
Finally, we want to sincerely thank NSRRC Local Organizing Committee, staff and particularly Ming-Chyuan for all their hard work. Congratulations on putting together an impressive workshop.

We all had a BEARY good time!

Thank you for your warm and kind hospitality! 

Thank you!