RFTECH REPORT ON CAVITY DESIGN, LLRF & HPRF SYSTEMS AND DESIGN INTEGRATION, & COSTING

De Conto, J M (UJF) *et al*

12 June 2014

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project EuCARD, grant agreement no. 227579.

This work is part of EuCARD Work Package **4: AccNet: Accelerator Science Networks**.

Grant Agreement No: 227579

EuCARD

European Coordination for Accelerator Research and Development

Seventh Framework Programme, Capacities Specific Programme, Research Infrastructures,
Combination of Collaborative Project and Coordination and Support Action

DELIVERABLE REPORT

RFTECH REPORT ON CAVITY DESIGN, LLRF & HPRF SYSTEMS AND DESIGN INTEGRATION, & COSTING

DELIVERABLE: D4.3.3

Document identifier:	EuCARD-Del-D4-3-3-Template-edmsid-v0.1
Due date of deliverable:	End of Month 52
Report release date:	23/07/2013
Work package:	WP4: AccNet
Lead beneficiary:	CERN
Document status:	Final

Abstract:

This report highlights results from the EuCARD WP4.3 RFTech network, which was active from April 2009 to July 2013. The objective of RFTech was bringing together RF experts from different laboratories and communities, e.g. proton & electron accelerators, or storage rings & linacs, to exchange ideas and to promote innovation on all aspects of RF technology. RFTech organized 4 primary annual workshops and the organized or co-organized several topical workshops or dedicated sessions in larger conferences, like MIXDES, ICAP 12 etc. The present document highlights the main topics covered during this networking activity. The RFTech activities related to superconducting RF infrastructures are described in the EuCARD report “European Infrastructures for R&D and Test of Superconducting Radio-Frequency Cavities and Cryo-modules” (Wolfgang Weingarten, ISBN 978-83-7207-952-7).

The European Coordination for Accelerator Research and Development (EuCARD) is a project co-funded by the European Commission in its 7th Framework Programme under the Grant Agreement no 227579. EuCARD began in April 2009 and will run for 4 years.

Delivery Slip

	Name	**Partner**	**Date**
Authored by	J.-M. De Conto, M. Grecki, F. Zimmermann	UJF, DESY, CERN	18/07/2013
Contributors	Speakers at RFTech Annual Meetings		
Reviewed by	F. Zimmermann	CERN	20/07/2013
Approved by WP Coordinator	Frank Zimmermann	CERN	20/07/13
Approved by Project coordinator	Jean-Pierre Koutchouk		23/07/13

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1. EXECUTIVE SUMMARY

RF for accelerators is a wide domain encompassing theory and models, simulation, experimentation, a wide panel of technologies and large scale constructions. It is a dynamical activity, driven by the continuous need for more powerful accelerators.

From 2009 to 2013 the EuCARD WP4.3 RFTech networking organized or co-organized a series of 20 workshops with the goal of bringing together RF experts from different laboratories and communities, e.g. proton & electron accelerators, or storage rings & linacs, in order to exchange ideas and to promote innovation on all aspects of RF technology.

The following conclusions emerged from these RFTech workshops.

Theory and models are required for a good understanding of the fundamental RF aspects. They are the key for more powerful numerical codes.

High power RF is a challenging part of the activity, related both to economic aspects and to reliability and maintainability aspects. New technologies are arising, such as solid state amplifiers, with on-line maintenance, high reliability and low-cost repair.

The new communication technologies of xTCA are very useful to guarantee modularity, flexibility and upgradeability. Their reliability is also very high. These technologies are not motivated by the accelerator field. The new standard (MTCA.4) tries to fill the gap between telecommunication hardware products and the instrumentation needs for high energy physics. It is important to keep the accelerator community in close contact with this development.

Cavity design is an active field of activity. The development of high power proton/ion linacs is motivating the development of new kinds of superconducting cavities (QWR, HWR, spoke), while the planned luminosity upgrade of the LHC has led to a worldwide effort for novel compact crab-cavities. The intensity upgrade of linear or circular machines is driving the design of HOM-free or damped structures. For all these kinds of cavities, there is a significant progress in the associated technologies: cavities proper, cryostat, cavity processing, materials…

Low Level RF lays the foundation for high performance machines, with ever more demanding performance requirements for amplitude and phase control. In order to assure best performance (especially reliability and maintainability) the RF control must be based on the most powerful new technologies.

Reliability improvements can be realized by increasing component MTBF, but also via a better modularity or maintainability, as well as by new RF operating modes, e.g linac-cavity failure recovery. For high power klystrons special systems are being developed to extend the device life-time (Klystron Life-time Management System).

The ambitious development programs of advanced RF technology are crucial for future high-performance accelerators and, therefore, need a strong support. Among this support, exchanges between specialists are an essential ingredient, to share experience and solutions. Another essential point is the training of young persons, including participation in conferences and workshops. Providing this needed support was the prime motivation for launching the RFTech network.

2. INTRODUCTION, SCOPE OF THE DOCUMENT

The objective of RFTech was bringing together RF experts from different laboratories, proton & electron accelerators, ILC, CLIC, FAIR, etc. to exchange ideas and to promote innovation on all aspects of RF technology, e.g. klystron development, RF power distribution system, cavity design, and low-level RF system, for linear accelerators, storage rings, and associated research infrastructures, including transversely deflecting (crab) cavities and financial aspects such as costing tools.

The RFTech contribution has been the organization of 4 dedicated workshops and the support for participation to several workshops and conferences, like LLRF workshop, MIXDES conferences, ICAP 12 conference etc. A list of all workshops and conference organized or co-organized by RFTech is included at the end of this report. The present document highlights the main topics covered during this networking activity. It does not cover all the presentations done during this period. We arbitrarily decided to group them in the following chapters:

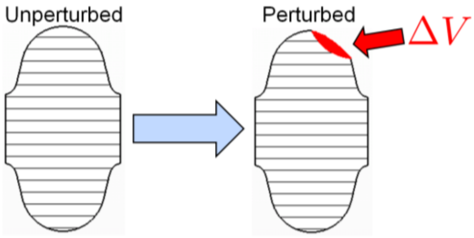
- RF field models and computing
- High Power RF
- Components, xTCAs
- RF cavities
- Low level RF
- Costing

The RFTech activities related to superconducting RF infrastructures led to the EuCARD report “European Infrastructures for R&D and Test of Superconducting Radio-Frequency Cavities and Cryo-modules” (Wolfgang Weingarten, ISBN 978-83-7207-952-7), the contents of which is not repeated here.

3. RF FIELD MODELS AND COMPUTING

3.1. FIELD CALCULATION

In addition to the classical finite element (FE) computing, the computation of RF fields can be done using the Slater’s theorem. Starting from a basic design obtained with FE techniques, small modifications can thereby be studied in a faster and simpler way. These modifications occur during the optimization process of the cavity. They can also be used to study the effect of machining imperfections, for example. During the design phase, the eigenmodes from the new structures can be derived from those of the basic one.

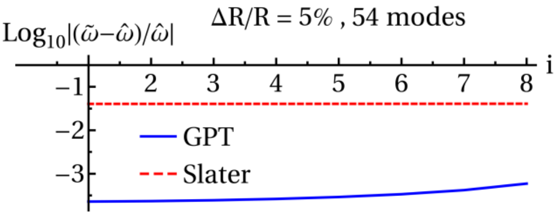


The Slater theorem gives the frequency of the perturbed eigenmode.

$$\tilde{\omega}_{\mathrm{i}} - \omega_{\mathrm{i}} = \frac{\iiint\limits_{\Delta V} \left(\omega_{\mathrm{i}} \mu \cdot |\vec{H}_{\mathrm{i}}(\vec{r})|^2 - \omega_{\mathrm{i}} \epsilon \cdot |\vec{E}_{\mathrm{i}}(\vec{r})|^2 \right) \, \mathrm{d}V}{U_{\mathrm{i}}}$$

This formula can be extended towards a more general form, leading to the so called General Perturbation Theory (GPT), used to compute the new RF fields:

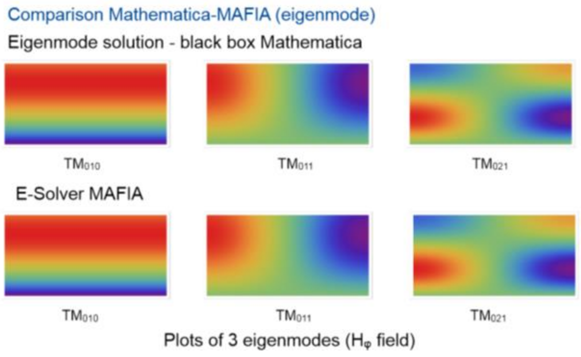
$$s_{\mathrm{ik}} = \frac{\iiint\limits_{\Delta V} \left(\omega_{\mathrm{i}} \mu \cdot \vec{H}_{\mathrm{i}}(\vec{r}) \cdot \vec{H}_{\mathrm{k}}(\vec{r}) - \omega_{\mathrm{k}} \epsilon \cdot \vec{E}_{\mathrm{i}}(\vec{r}) \cdot \vec{E}_{\mathrm{k}}(\vec{r}) \right) \mathrm{d}V}{2U_{\mathrm{i}}}$$



Eigenfrequencies of a cylindrical cavity

This method has proven to be an efficient and fast approach to compute perturbed eigenmodes. It permits the calculation of both resonant frequencies and stationary fields, with significantly more accurate results than the older Slater's theorem. A limitation arises due to the finite number of computable eigenmodes.

Other methods can be considered for field calculation. One is the development of Finite Integration Maxwell solvers, based on the integral form of the Maxwell's equations over the domain boundaries. The picture illustrates the comparison between this method and a Finite Element method:



The problem of local thin meshes in Finite Element methods leads to a strong increase in computing time. Methods are investigated using the Discontinuous Galerkin technique to overcome this difficulty, by using local stepping schemes. In addition, the use of Adams-Bashforth (instead of Runge Kutta) integration methods leads to a significant reduction of computing time.

Concerning the computational platform, the parallel computing using GPUs is gaining in importance. Computer clusters equipped with GPUs are much more powerful for RF field simulations. These computer platforms can be programmed not only in C/C++ language using GPU manufacturer extensions and libraries, but they also support the Matlab program, which significantly simplifies the writing and debugging of the parallel simulation software.

References:

D. Meidlinger, *A General Perturbation Theory for Cavity Mode Field Pattern*, Proceedings of SRF2009, Berlin, Germany, THPPO005, 2009.

Korinna Brackebusch: Computation of RF Fields in Resonant Cavities based on Perturbation Theory. Third RFTech worshop.

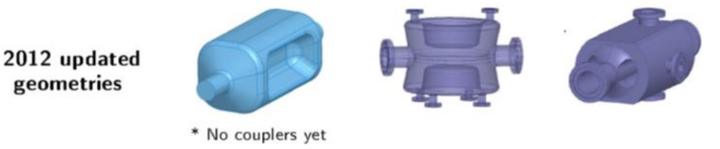
Mirjana Holst: Application of 2D Finite Integration Maxwell Solvers on Time Dependent and Eigenmode Problems. Third RFTech worshop.

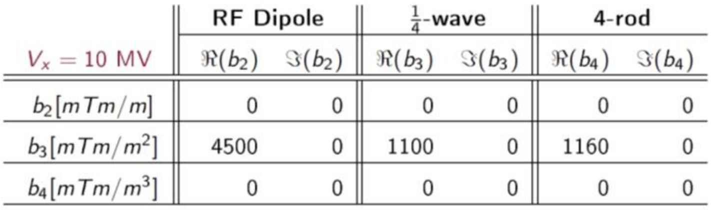
Kai Papke: Implementation and Investigation of a Local Time Stepping Scheme Based on DG-FEM. Third RFTech worshop.

Link to 3rd RFTech workshop: http://lpsc.in2p3.fr/Indico/conferenceDisplay.py?ovw=True&confId=646

3.2. RADIOFREQUENCY MULTIPOLES FOR CRAB CAVITIES

Three kinds of crab cavities have been studied with regard to the multipole field contents, including the effect of manufacturing imperfections and modeling multipole measurement techniques based on the bead pull method. The multipole expansion is performed in the vicinity of the beam by a finite element method. The bead pull method has to be executed in a new way: instead of only determining the main on-axis field, off-axis measurements are also needed.





$V_x = 10$ MV	RF Dipole		$\frac{1}{4}$-wave		4-rod	
	$\Re(b_2)$	$\Im(b_2)$	$\Re(b_3)$	$\Im(b_3)$	$\Re(b_4)$	$\Im(b_4)$
$b_2[mTm/m]$	0	0	0	0	0	0
$b_3[mTm/m^2]$	4500	0	1100	0	1160	0
$b_4[mTm/m^3]$	0	0	0	0	0	0

Multipole coefficents for three kinds of crab cavities

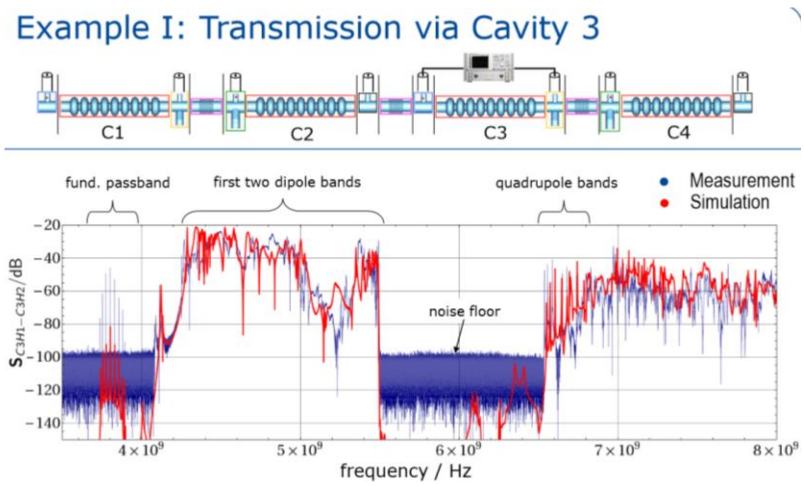
Reference:

Maria Navarro-Tapia: RF multipoles in LHC crab cavities, 4th RFTech workshop.

Link to the 4th RFTech workshop:https://lpsc.in2p3.fr/Indico/conferenceDisplay.py?confId=862

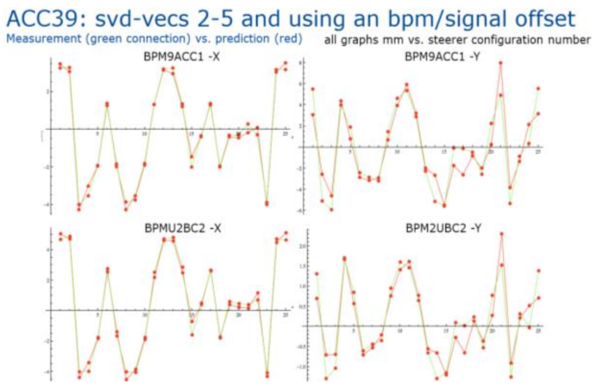
3.3. COMPUTATION OF BEAM EXCITED HOM PORT SIGNALS

A beam on axis induces monopole modes, while an off-axis beam can also excite dipole modes. HOM couplers signal can then be used as a diagnostic, if the *S* parameters of the cavity are known from measurements on the HOM ports. Whereas the simulation of the whole structures requires several days computing time, the concatenation (“CSC”) of *S* parameters needs only a couple of minutes, with a good agreement between calculation and measurement.



Example: ACC39 for FLASH. Comparison between measurement and CSC. No beam

Beam induced signals of complex structures can be computed using concatenation schemes of individual elements (and by using RF computation codes). The following picture demonstrates the excellent agreement between this method and a BPM measurement.



References:

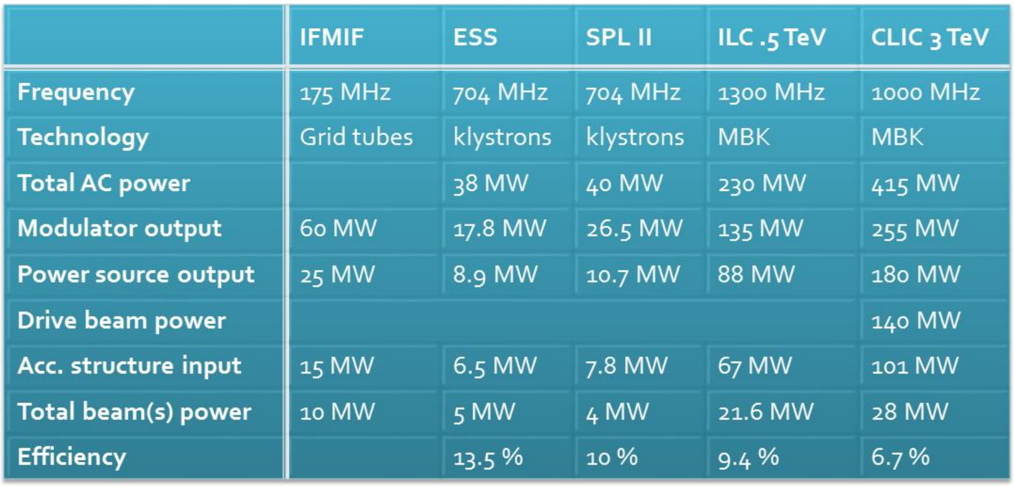
T. Flisgen et al.: “A Concatenation Scheme for the Computation of Beam Excited Higher Order Mode Port Signals”, Proceedings of IPAC2011, San Sebastián, Spain

Thomas Flisgen, Hans-Walter Glock and Ursula van Rienen: A Coupling Formalism for the Computation of Beam Excited HOM Port Signals. Third RFTech workshop.
Link: http://lpsc.in2p3.fr/Indico/conferenceDisplay.py?confId=646

4. HIGH POWER RF

4.1. HIGH POWER ISSUES

High power issues can be summarized by 5 keywords: Power, Efficiency. Complexity, Reliability, Cost.



	IFMIF	ESS	SPL II	ILC .5 TeV	CLIC 3 TeV
Frequency	175 MHz	704 MHz	704 MHz	1300 MHz	1000 MHz
Technology	Grid tubes	klystrons	klystrons	MBK	MBK
Total AC power		38 MW	40 MW	230 MW	415 MW
Modulator output	60 MW	17.8 MW	26.5 MW	135 MW	255 MW
Power source output	25 MW	8.9 MW	10.7 MW	88 MW	180 MW
Drive beam power					140 MW
Acc. structure input	15 MW	6.5 MW	7.8 MW	67 MW	101 MW
Total beam(s) power	10 MW	5 MW	4 MW	21.6 MW	28 MW
Efficiency		13.5 %	10 %	9.4 %	6.7 %

Present needs for RF Power (true for both peak and average)

The overall AC to beam efficiency is about 10%. An increased efficiency would reduce the environmental impact, reduce the size of the installed power, reduce the size of the necessary cooling, and decrease the electricity bill. For example, for CLIC @ 3 TeV, with 415 MW AC consumption and 5000 h operation per year, the annual electricity bill is estimated at 69 M€. Assuming a klystron efficiency of 65 %, a 1% (up to 66%) efficiency increase would save 1.1 M€ every year in electricity alone.

1. Toshiba: E3736 (6 beam): 1.3 GHz, 10.4 MW, 10 Hz, 66 %, 49 dB gain
2. Thales: TH 1801 (7 beam): 1.3 GHz, 10.1 MW, 10 Hz, 63 %, 48 dB gain
3. CPI: VKL-8301B (6 beam): 1.3 GHz, 10.2 MW, 10 Hz, 66.3 %, 49.3 dB gain

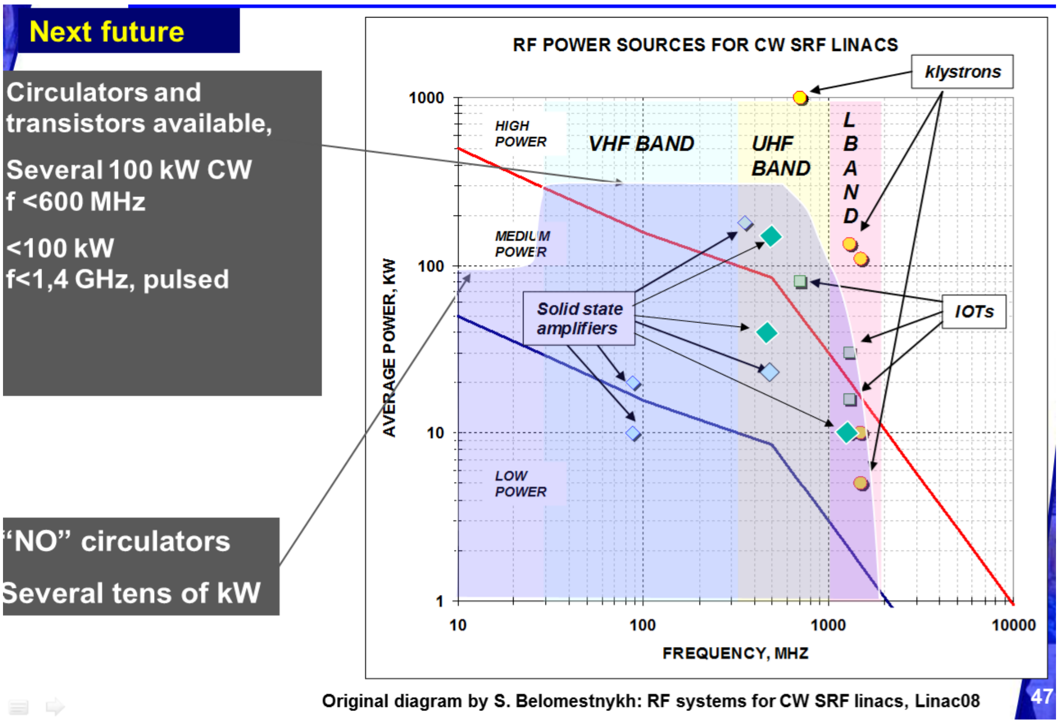
1.

2.

3.

2-Dec-2010 RFTech Workshop, PSI E. Jensen, RF Power Sources and Related Issues

Examples of state-of-the-art klystrons



Next future

Circulators and transistors available,

Several 100 kW CW
f <600 MHz

<100 kW
f<1,4 GHz, pulsed

"NO" circulators

Several tens of kW

Original diagram by S. Belomestnykh: RF systems for CW SRF linacs, Linac08

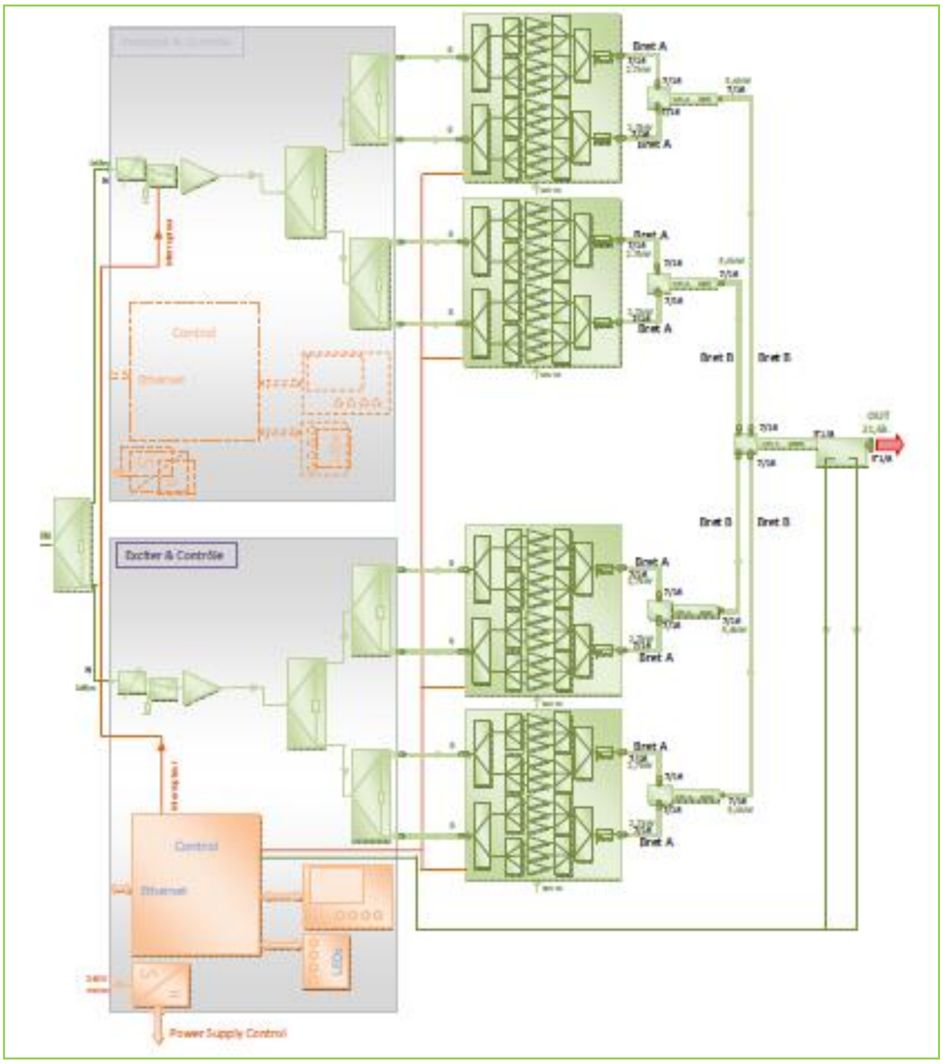
Overview of RF amplifier working ranges, comparing klystrons, IOTs and SSAs.

4.2. SOLID STATE AMPLIFIERS

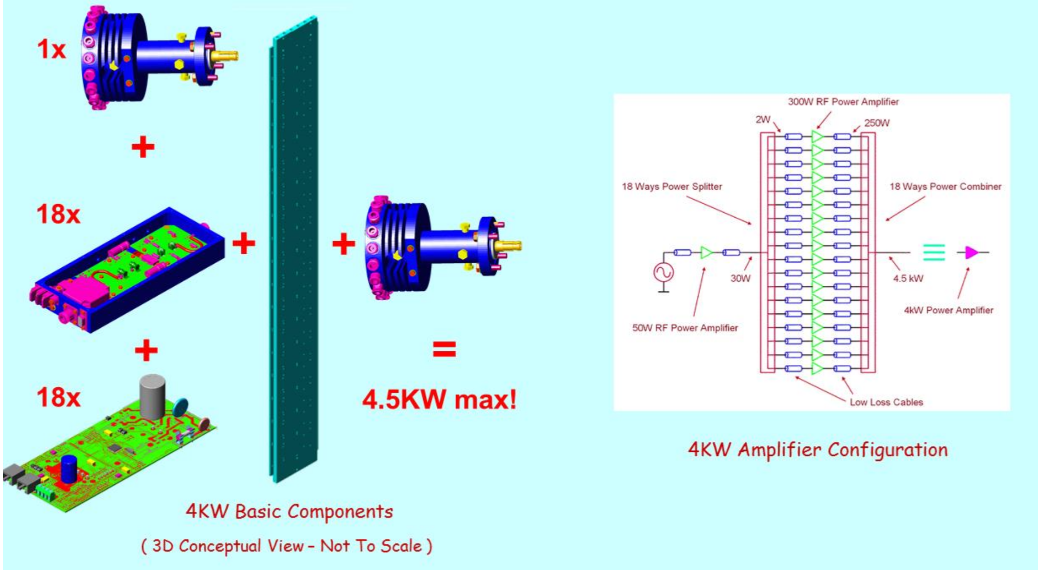
Solid state amplifiers (SSAs) are based on transistors instead of vacuum electron tubes as active device. The key point is the progress done in the MOSFET domain since the 90's. The architecture is based on individual pallets (one MOSFET each) combined together to obtain the required high power. Arrangement depends on application to fit the required amount of RF power. N-way splitters and combiners are required. Circulators can also be added to decouple each amplifier, making it unconditionally stable, and in this case non isolated splitter/combiners can be used (case 1). Isolated dividers and combiners (case 2) can be used to avoid oscillations or other phenomena which could lead to the transistor destruction. Most accelerator applications require reflected power management. In case 2 an external circulator is added. Some examples (components, architectures) are presented below (cf, mainly, RFTech 2nd workshop).

Pallet

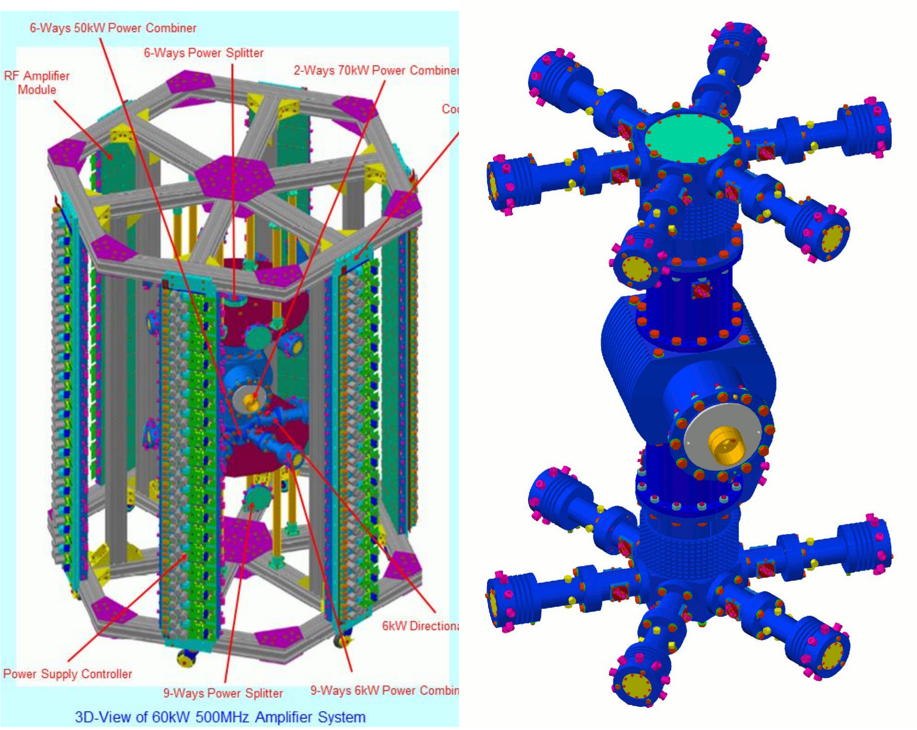
Example (SOLEIL) of a 330 W module, 352 (or 500 MHz but different devices)
1 transistor/pallet, 1 circulator/transistor. © Synchrotron SOLEIL - Ti Ruan



General structure (SPIRAL2) – 88 MHz, 21 kW

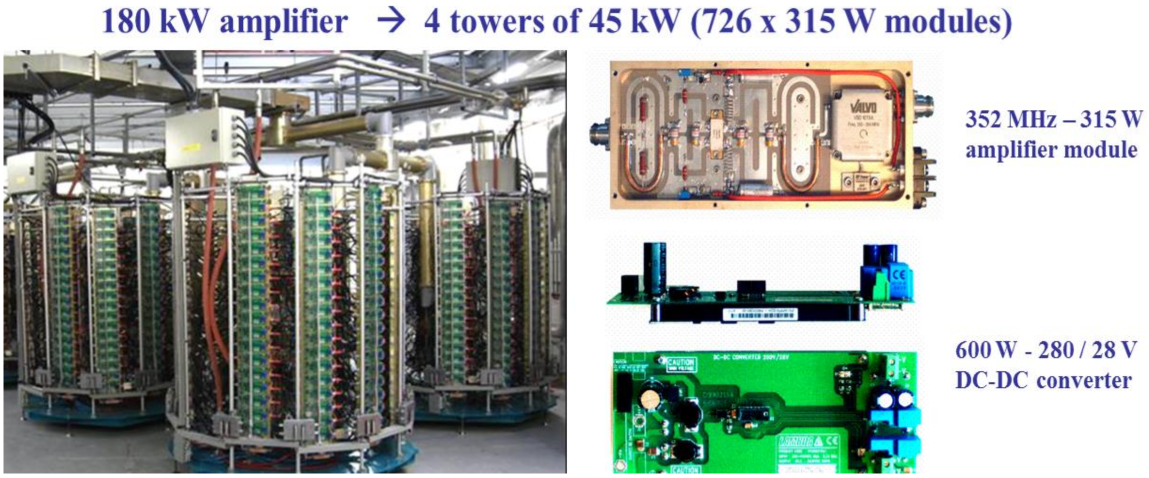


4kW amplifier for PSI (validation prototype)



Example of the 60kW 500MHz PSI Amplifier System. General view (left), power output power recombiner (right)

The example of SOLEIL: The SOLEIL RF system (4 cavities) requires 16 amplifiers (180 kW towers) and around 3000 modules. After 25000 running hours (~5 years), only 3 short dead times occurred. The module failure rate is ~4% per year with no impact on the operation. The maintenance cost is ~5k€ per year.



SOLEIL solid state amplifiers

References:

Erk Jensen: RF Power Sources and Related Issues. RFTech 2nd workshop

S. Belomestnykh: RF systems for CW SRF linacs, Linac08

Marco di Giacomo: Solid State Amplifiers. RFTech 2nd workshop.

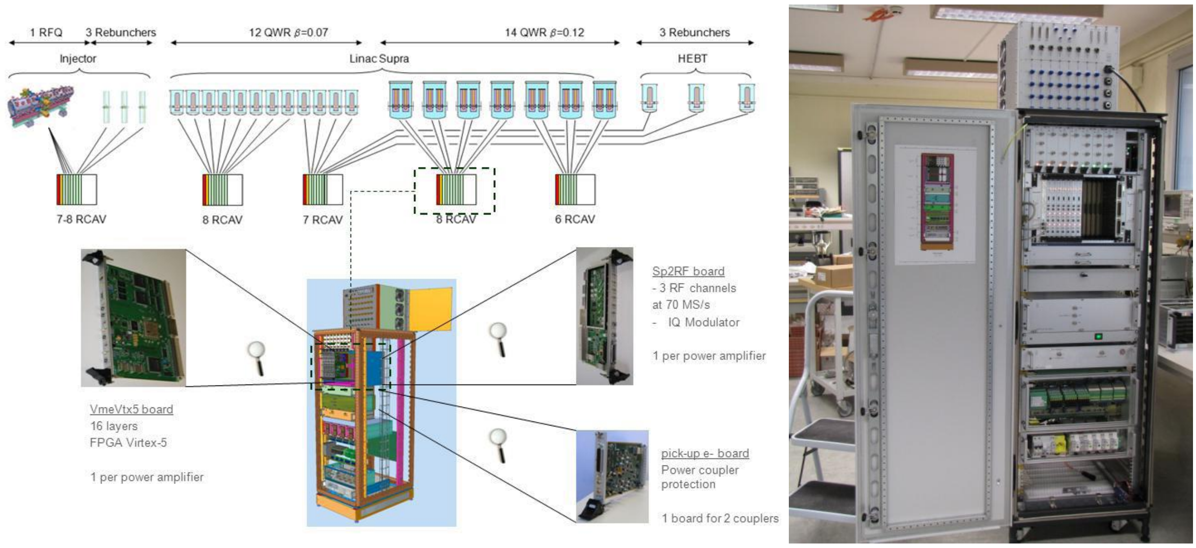
Marcos Gaspar Solid State Amplifier development at PSI. RFTech 2nd workshop.

Jorn Jacob: SOLEIL Experience with High Power Solid State Amplifiers (on behalf of P. Marchand, SOLEIL). RFTech 2nd workshop.

Link: http://lpsc.in2p3.fr/Indico/conferenceDisplay.py?confId=530

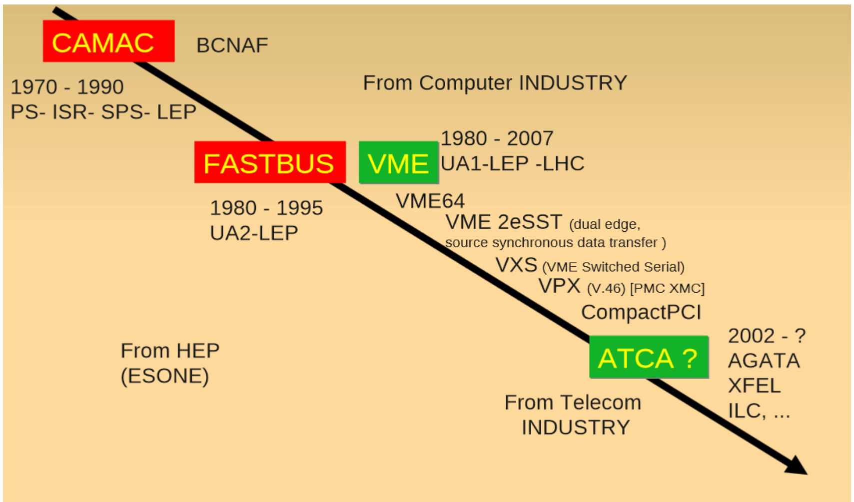
5. COMPONENTS, XTCAS

Specific components are needed for beam instrumentation, Data Acquisition, triggering etc. The needs are: Modularity, Scalability, Robustness, Serviceability (avoid front panel connection), easy upgrade path, flexibility and availability in the next 20 years. The former standard VME while still alive and widely distributed is clearly being pushed out by new technologies.



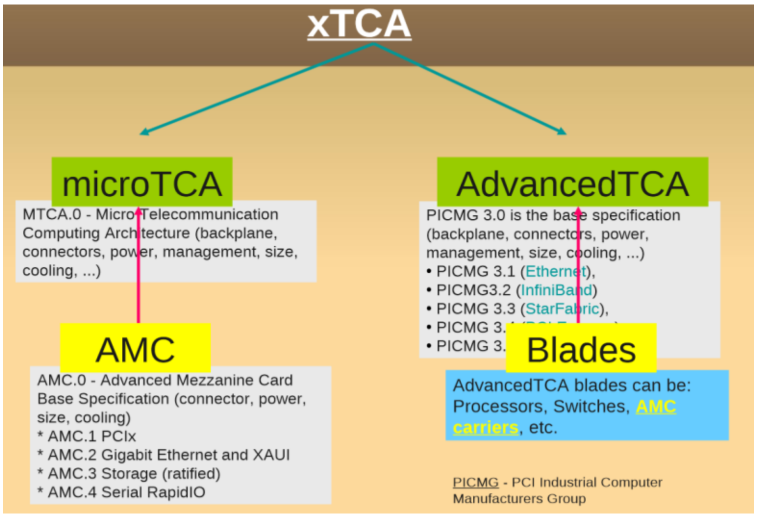
VME based digital LLRF for SPIRAL2 accelerator

While the VME extensions and upgrades (VPX, VXS) exist and attempt to overcome the VME limitations there are new technologies (ATCA) coming from telecommunication industry with new highly scalable architecture and much better performance. The advantages of the ATCA (Advanced Telecommunication Computing Architecture) technology is mainly: A scalable shelf capacity up to 2.5Tb/s, a reliability up to 99.999%, a redundant power supply (48V@200 W/slot with adequate cooling), a high speed point-to-point serial connectivity via Full Mesh Backplane, the modularity, scalability and robustness, as well as a flexible configuration of processing topology according to algorithm within shelf and shelf management for remote configuration and monitoring. Since the original ATCA was not designed for instrumentation there was a need to develop a new standard especially designed for this purpose. That goal was achieved in MTCA.4 (MicroTCA for Physics) which is a new standard for instrumentation, for which there are more and more components produced by industry, allowing cost reduction.



CAMAC
BCNAF
1970 - 1990
PS- ISR- SPS- LEP
From Computer INDUSTRY
FASTBUS
VME
1980 - 2007
UA1-LEP -LHC
1980 - 1995
UA2-LEP
VME64
VME 2eSST (dual edge, source synchronous data transfer)
VXS (VME Switched Serial)
VPX (V.46) [PMC XMC]
CompactPCI
From HEP
(ESONE)
ATCA ?
2002 - ?
AGATA
XFEL
ILC, ...
From Telecom
INDUSTRY

Evolution of standards



xTCA

microTCA

MTCA.0 - Micro Telecommunication Computing Architecture (backplane, connectors, power, management, size, cooling, ...)

AMC

AMC.0 - Advanced Mezzanine Card Base Specification (connector, power, size, cooling)
* AMC.1 PCIx
* AMC.2 Gigabit Ethernet and XAUI
* AMC.3 Storage (ratified)
* AMC.4 Serial RapidIO

AdvancedTCA

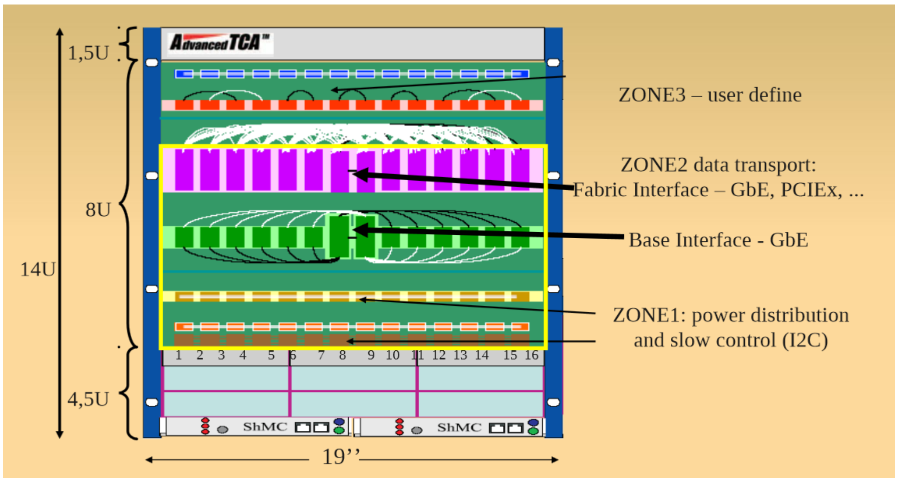
PICMG 3.0 is the base specification (backplane, connectors, power, management, size, cooling, ...)
- PICMG 3.1 (Ethernet),
- PICMG3.2 (InfiniBand)
- PICMG 3.3 (StarFabric),
- PICMG 3.
- PICMG 3.

Blades

AdvancedTCA blades can be: Processors, Switches, AMC carriers, etc.

PICMG - PCI Industrial Computer Manufacturers Group

xTCA panorama

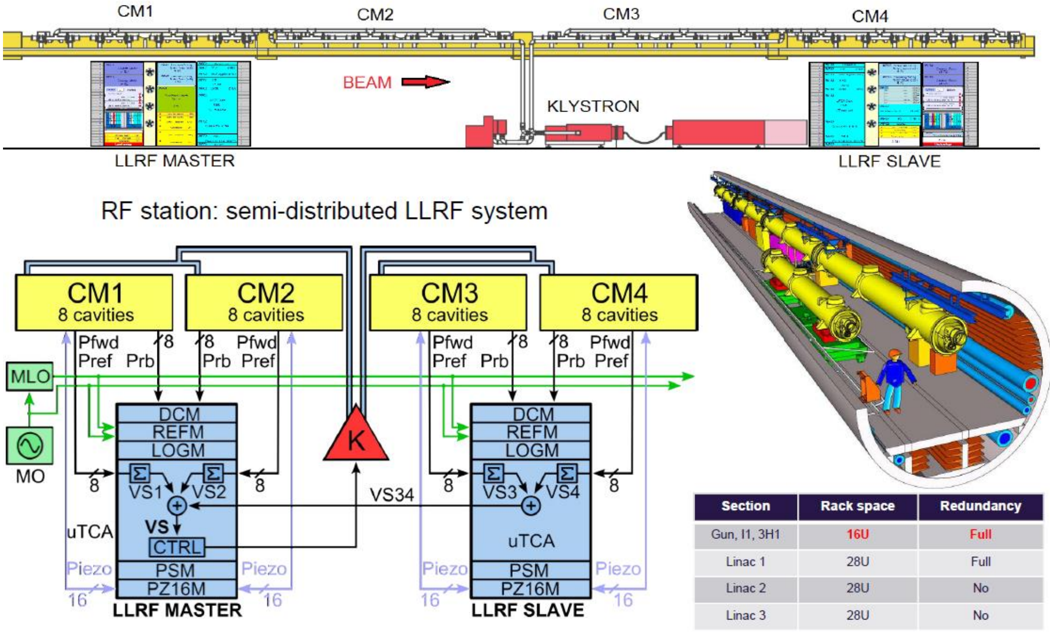


Overview of an ACTA crate

Examples of xTCA components for evaluation at SLAC.

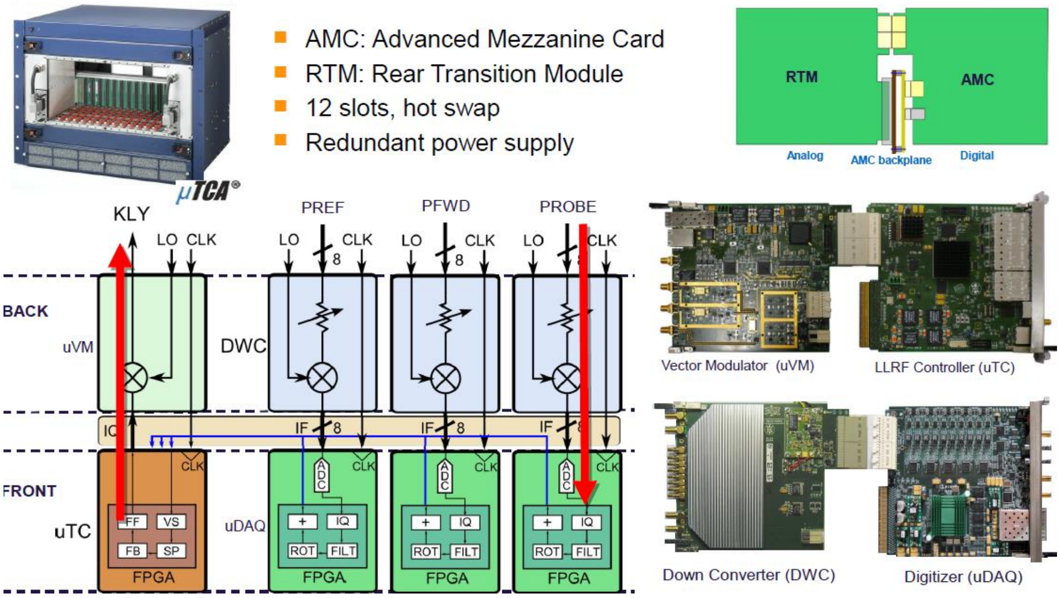
RFTech participated and sponsored a special session in the MIXDES conferences during the four years, with several contributions from the RFTech community (7-10 papers every year) and also sponsored participation of the MTCA Workshop.

The example of XFEL/FLASH: the pictures below illustrate the Low-Level RF system. For FLASH a new LLRF system has been developed using the MTCA.4 architecture. A prototype system has been tested at FLASH and CMTB with very good results and the permanent FLASH installation is in progress.



Section	Rack space	Redundancy
Gun, I1, 3H1	16U	Full
Linac 1	28U	Full
Linac 2	28U	No
Linac 3	28U	No

LLRF at XFEL: general view



MTCA LLRF system at XFEL

References:

Marco Di Giacomo: Status of the RF Systems of the SPIRAL2 accelerator

Tomasz Jezynski : xTCA for Instrumentation. First RFTech workshop

Link to the 1st RFTech workshop: https://indico.desy.de/internalPage.py?pageId=3&confId=2831

MIXDES 2013: http://www.mixdes.org/Mixdes3/

MIXDES 2012 Conference proceedings:

http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=6218252

MIXDES 2011 Conference proceedings:

http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=6006988

MIXDES 2010 Conference proceedings:

http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=5543946

Mariusz Grecki: uTCA architecture for HEP instrumentation. Fourth RFTech workshop.

Link to the 4th RFTech workshop: https://lpsc.in2p3.fr/Indico/conferenceDisplay.py?confId=862

6. RF CAVITIES

The development of cavities is a regular theme for RFTech. Beside the development of “classical” cavities, several works have been presented on HOM damped cavities and crab cavities.

6.1. QUARTERWAVE RESONATORS

Quarterwave resonators (88 MHz) have been developed for the SPIRAL2 project, as well as for HIE-ISOLDE project (@ 101MHz, and similar other specification). These cavities are well adapted to beams with low β - Lorentz factor (0.06-0.1 range). SPIRAL2 cavities are made from pure Niobium, HIE-ISOLDE are made from copper with Niobium sputtering.

Copper cavity substrate

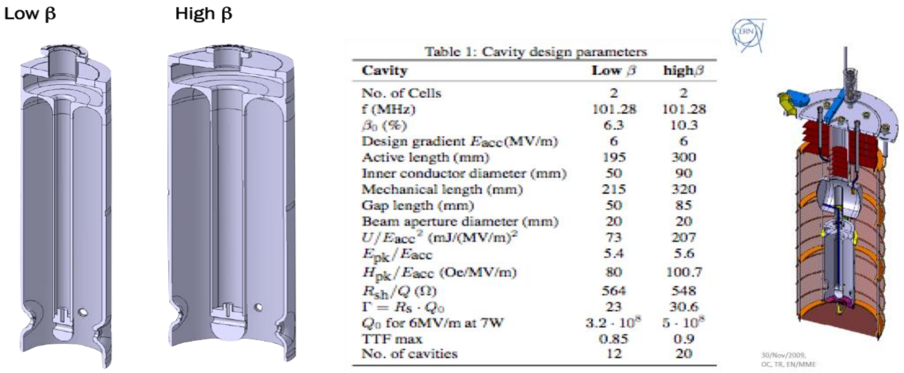


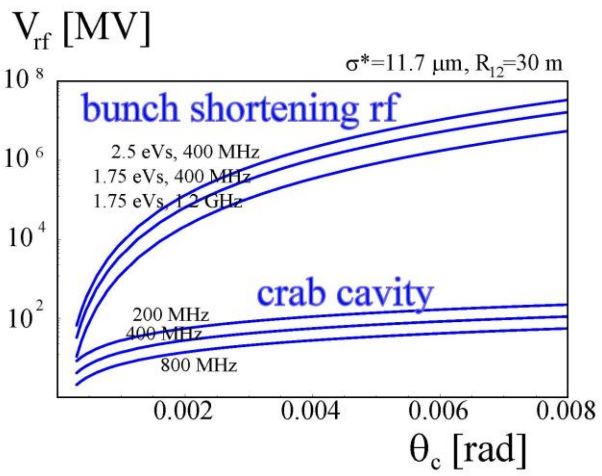
Table 1: Cavity design parameters

Cavity	Low β	highβ
No. of Cells	2	2
f (MHz)	101.28	101.28
β_0 (%)	6.3	10.3
Design gradient E_{acc}(MV/m)	6	6
Active length (mm)	195	300
Inner conductor diameter (mm)	50	90
Mechanical length (mm)	215	320
Gap length (mm)	50	85
Beam aperture diameter (mm)	20	20
$U/E_{acc}{}^2$ (mJ/(MV/m)^2	73	207
E_{pk}/E_{acc}	5.4	5.6
H_{pk}/E_{acc} (Oe/MV/m)	80	100.7
R_{sh}/Q (Ω)	564	548
$\Gamma = R_S \cdot Q_0$	23	30.6
Q_0 for 6MV/m at 7W	$3.2 \cdot 10^8$	$5 \cdot 10^8$
TTF max	0.85	0.9
No. of cavities	12	20

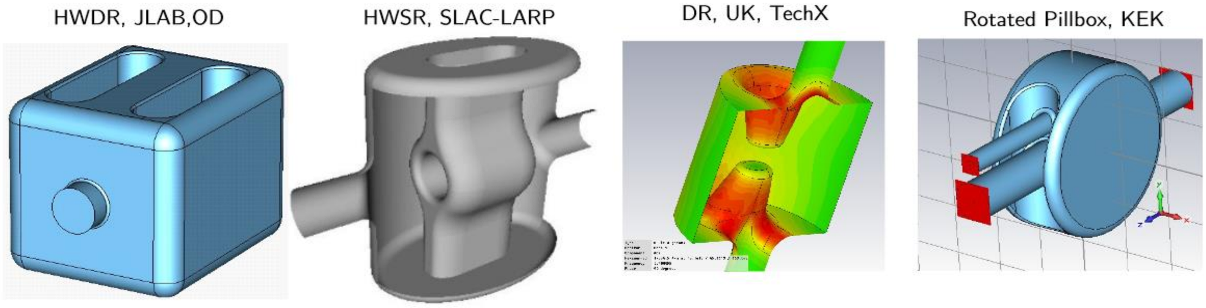
Cavity specifications and cryostat overview

6.2. CRAB CAVITIES

A worldwide effort is undertaken for the development of crab cavities, in particular for the LHC, but also for light source applications and for CLIC, with specific working groups, networks and workshops. At the LHC they are essential for realizing a quasi head-on collision with maximum luminosity in the presence of a large crossing angle. They are much more efficient than the conventional RF required for an “equivalent” bunch shortening, as illustrated in the following figure.

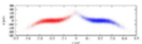


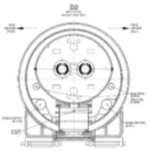
Comparison of RF voltages required for bunch shortening and crab cavities



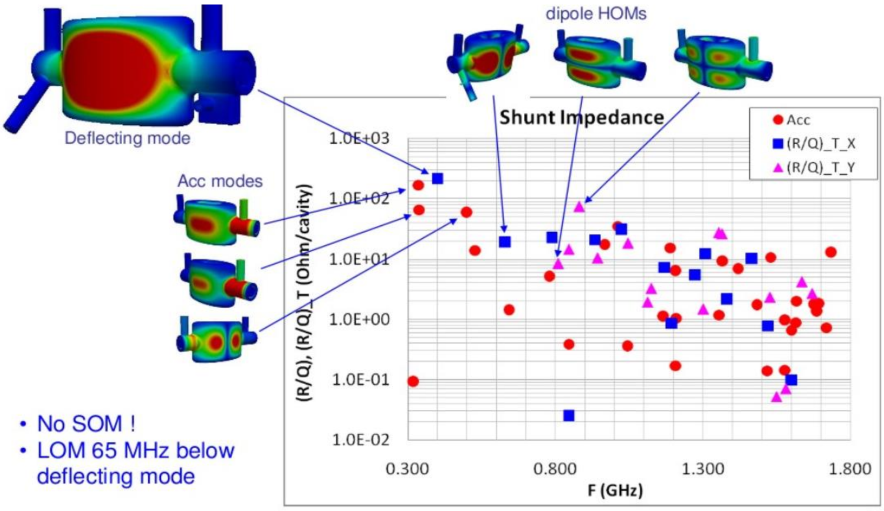
Compact cavities with small footprint (400 mm) 5-10 MV/cavity

	Baseline	Unit	LHC
RF	Frequency	MHz	400 (800)
	Deflecting Voltage	MV/Cav	3
	Peak E-field	MV/m	< 50
	Peak B-field	mT	< 100 mT
Geometrical	Aperture (diameter)	mm	84
	Cav Outer Envelope	mm	< 150
	Module length	m	~ 1m
	HV crossing	-	Desirable
Optics	β* (IR1/IR5)	cm	15-25
	β crab	km	~ 5
	Non-linear harmonics	Units [10^-4]	2-3
	Impedance Budget/cav	Longitudinal, Transverse	300kΩ, 187kΩ/m

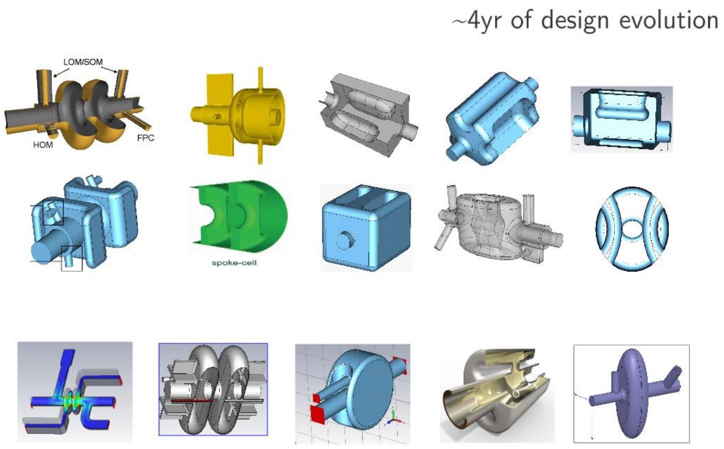

σ_z = 7.55 cm


Beam-beam separation

Cavity specification for LHC



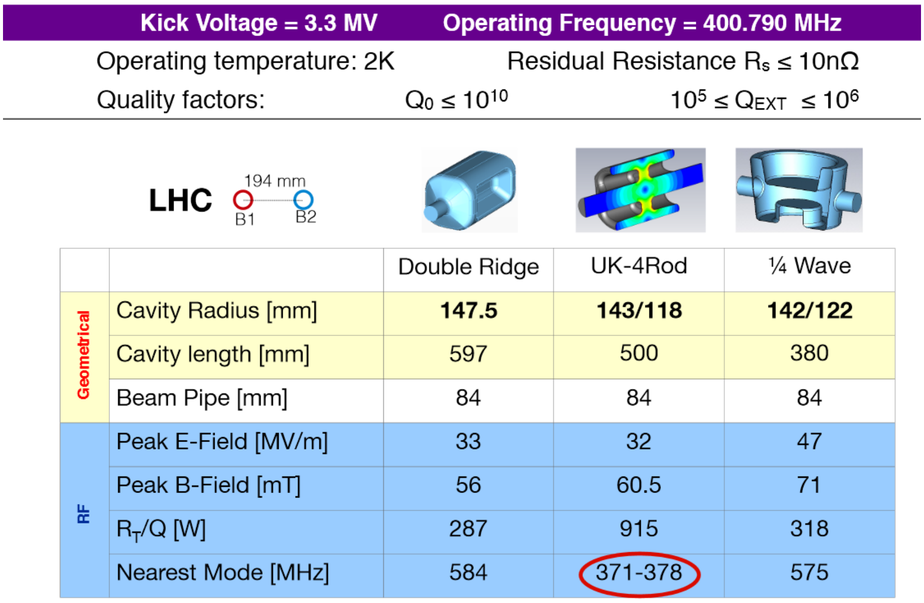
Calculated shunt impedances of the SLAC-LARP cavities



Crab-cavities: a worldwide design effort

Tests at CERN- SPS: Tests of crab-cavities are foreseen at CERN-SPS (2016) with the following objectives: (1) to validate the crab cavity design for proton beams, e.g. with regard to emittance growth due to crab RF noise, and (2) to validate the operational functionality & machine protection mechanisms. Testing prototypes with beam at the CERN is considered essential to finalize design & operational scenarios.

The SPS Crab Cavity Validation Program requires a full characterization of cryomodule & cavities prior to the installation of a prototype in the SPS. The crab cavities must be transparent to operation when detuned. The SPS tests with beam will include measurements of cavity response, heat loads, RF noise etc. These tests will also aim at the validation of crabbing and at a performance analysis vs. beam parameters, e.g. in view of beam-loading effects. Machine protection aspects will be considered along with the detection of failure modes and mitigations/interlocks associated with LLRF.



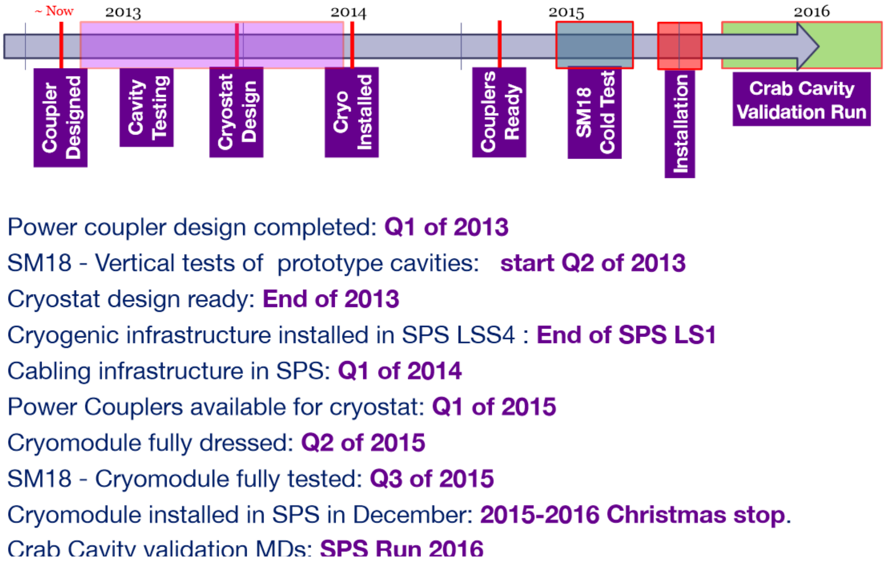
Kick Voltage = 3.3 MV Operating Frequency = 400.790 MHz

Operating temperature: 2K Residual Resistance $R_s \leq 10n\Omega$

Quality factors: $Q_0 \leq 10^{10}$ $10^5 \leq Q_{EXT} \leq 10^6$

		Double Ridge	UK-4Rod	¼ Wave
Geometrical	Cavity Radius [mm]	**147.5**	**143/118**	**142/122**
	Cavity length [mm]	597	500	380
	Beam Pipe [mm]	84	84	84
RF	Peak E-Field [MV/m]	33	32	47
	Peak B-Field [mT]	56	60.5	71
	R_T/Q [W]	287	915	318
	Nearest Mode [MHz]	584	371-378	575

Compact crab cavities: Three candidates



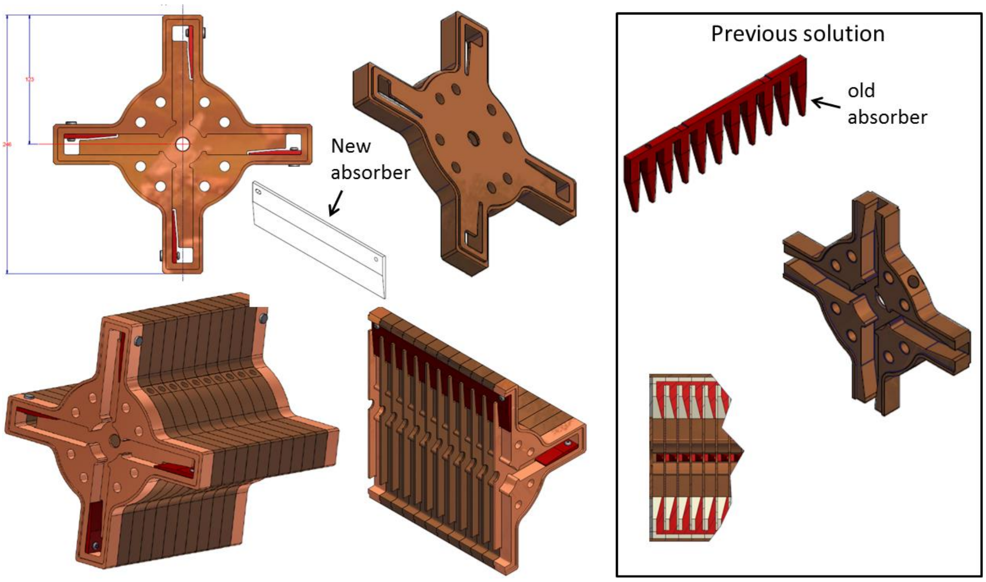
- Power coupler design completed: **Q1 of 2013**
- SM18 - Vertical tests of prototype cavities: **start Q2 of 2013**
- Cryostat design ready: **End of 2013**
- Cryogenic infrastructure installed in SPS LSS4 : **End of SPS LS1**
- Cabling infrastructure in SPS: **Q1 of 2014**
- Power Couplers available for cryostat: **Q1 of 2015**
- Cryomodule fully dressed: **Q2 of 2015**
- SM18 - Cryomodule fully tested: **Q3 of 2015**
- Cryomodule installed in SPS in December: **2015-2016 Christmas stop**.
- Crab Cavity validation MDs: **SPS Run 2016**

Schedule up to installation in the SPS

6.3. OTHERS

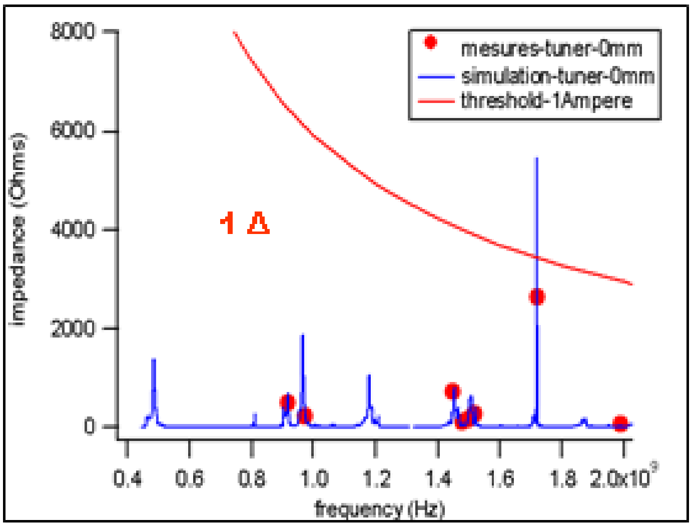
Damped cavities are under development for reducing beam instabilities. We can highlight the development of HOM free cavities at ESRF, as well as damped structures for LNF-SPARC energy upgrade and ELI-NP project.

For ELI, the power released by the beam on the dipole modes is dissipated into SiC absorbers. Several different solutions are possible for the absorber design. The final geometry has been optimized to simplify the manufacturing procedure and the overall cost of the structures. From the e.m. point of view this is not the «ideal» solution but it is still very good from the point of view of HOM damping.

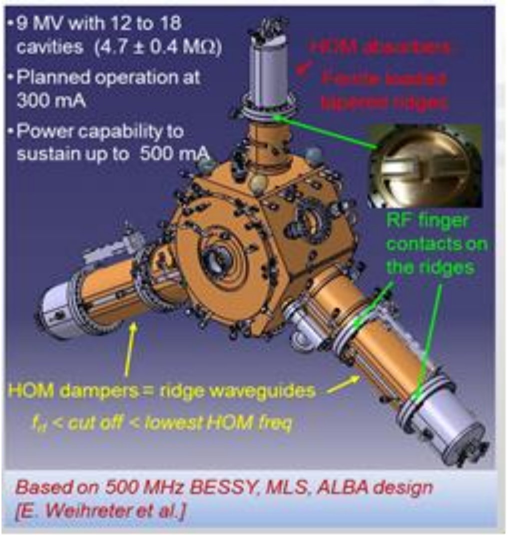


ELI-NP damping system design

For its intensity upgrade strategy, up to 300 mA, ESRF has developed HOM free cavities, normal conducting cavities with 3 asymmetric HOM dampers.



HOM-free ESRF cavity impedance



ESRF HOM-free cavity

References:

Wolfgang Weingarten : HIE-ISOLDE cavity and test cryostat*. First RF Tech workshop*

Frank Zimmermann: LHC Crab Cavities. First RF Tech workshop

Rama Calaga: LHC Crab Cavities. Second RFTech workshop

Rama Calaga: LHC Crab Cavities. Third RFTech workshop

Alick McPherson: Crab Cavity Plans in the SPS. Fourth RFTech workshop

David Alesini: Damped C-Band RF structures for the European ELI-NP proposal. Fourth RFTech workshop

Jorn Jacob: RF Developments at ESRF: HOM damped Cu cavities & Solid State Amplifiers. Second RFTech workshop

Link to the 1st RFTech workshop: https://indico.desy.de/internalPage.py?pageId=3&confId=2831

Link to the 2nd RFTech workshop: http://lpsc.in2p3.fr/Indico/conferenceDisplay.py?confId=530

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Link to the 4th RFTech workshop: https://lpsc.in2p3.fr/Indico/conferenceDisplay.py?confId=862

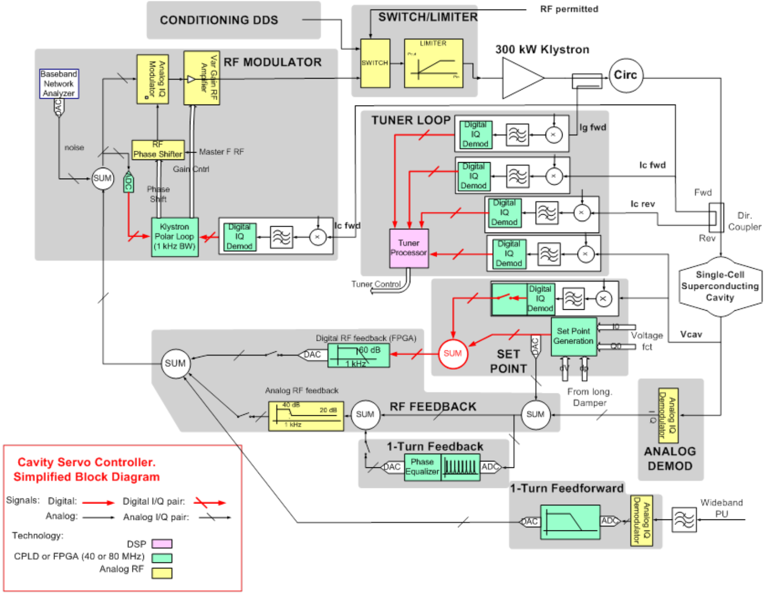
7. LOW LEVEL RF

The RF control system must guarantee a high performance. For example, for the XFEL, the RF amplitude must be controlled at the 0.01% level and the phase to about 0.01 degree. The RF system must be reproducible, reliable and operable. As was mentioned earlier, at present the hardware platform for LLRF control systems is slowly moving towards the xTCA technology, but designs using VME extensions (like VXS) are still present and cannot be ignored. Other hardware platforms (e.g. Compact PCI, customized designs, etc.) are rarely encountered. Independently of the platform the digital signal processing is usually handled by FPGA(s) and communication between system components is realized through fast serial links. Analog signal acquisition is done by fast (sampling rate ~100MHz) ADCs with resolution up to 16b. Much effort is spent on designs with direct RF signal processing based on very fast ADCs and DACs (Gigahertz sampling rate) – this allows getting rid of signal down-conversion and up-conversion, and all the associated problems (noise and nonlinearity introduced by frequency conversion).

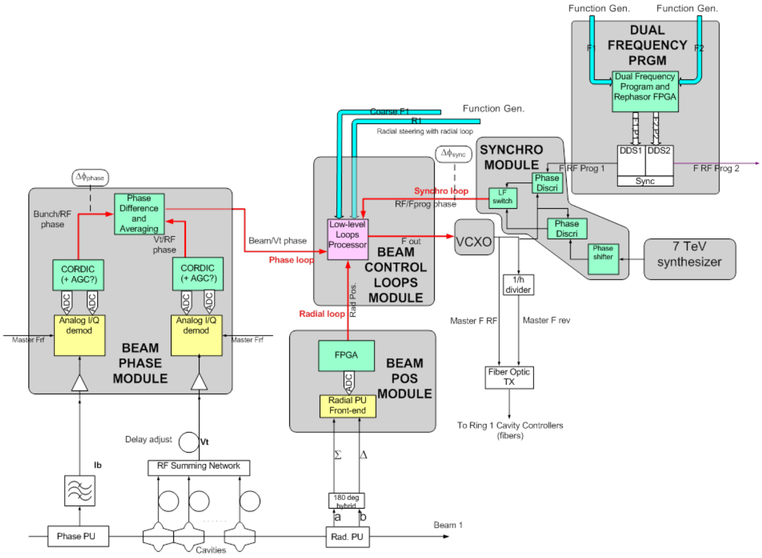
RFTech workshops provided an opportunity to share experience between various laboratories and machines. In particular, RFTech sponsored or co-sponsored a series of LLRF-related workshops such as the “LLRF workshop 2011” in Hamburg.

Among all the systems reviewed during RFTech, we can highlight the LHC LLRF system. This system has to deal with the transient beam loading during filling. The RF voltage must be kept constant over one turn. This means, in particular, cavity detuning and moving couplers. The LLRF is made of 4 subsystems:

- Beam Control: Slow loops (clocked at revolution frequency) using beam-based measurements. They control the average energy of the beam via the RF frequency, and the phase of the average voltage. They include a phase loop, a radial loop and a synchro loop.
- Cavity controller: Potentially fast loops (clocked at 40 MHz bunch frequency) using cavity or waveguide measurements, for individual control of the field in each cavity, its tune and the klystron gain/phase shift.
- Longitudinal damper: During the sequence of injections, this damps the phase and energy error (dipole oscillation) and the bucket mismatch (quadrupole) by modulating the field in the cavities. Used only at injection.
- RF Synchronization: Pilots the bunch into bucket transfer from SPS to LHC.

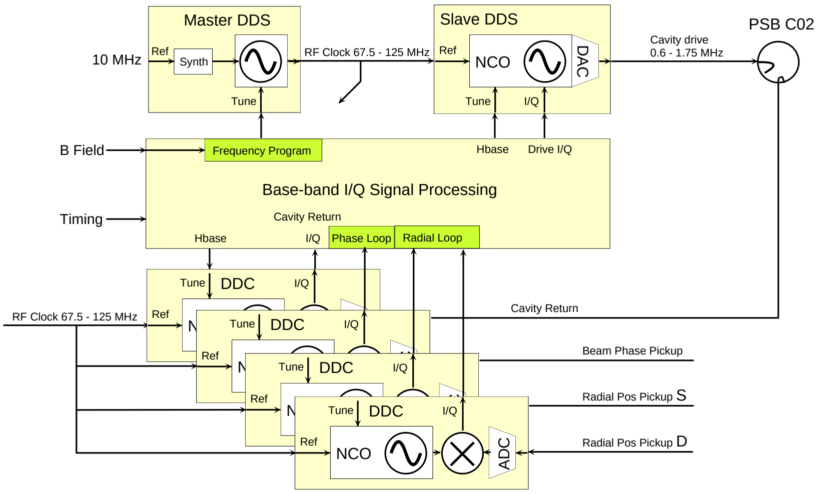


Cavity control loop for LHC

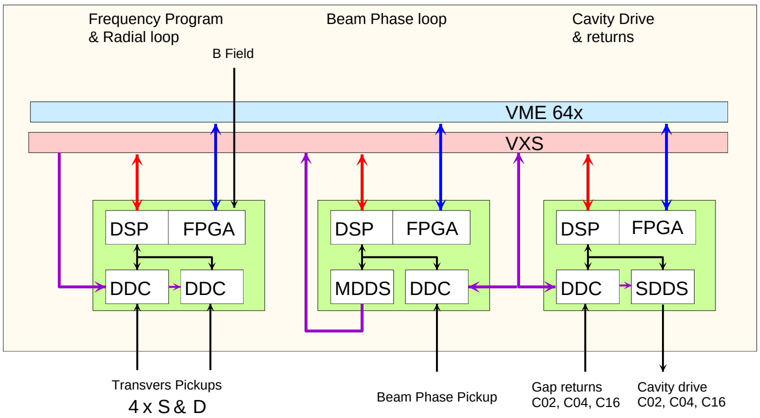


Beam control loop for LHC

We can also summarize the RF Low-level Beam Control system for PS Booster built in VME VXS using FMC mezzanines.



General structure of the system



Hardware structure

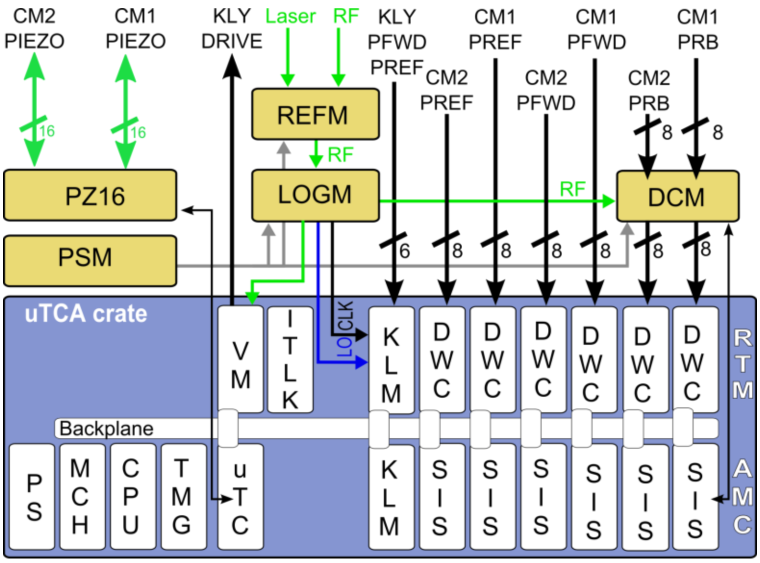
Status for PS booster LLRF:

Hardware: Laboratory and successive tests on CERN PSB Ring 4 with a 2 board system, built in V1 hardware (VXS-DSP-FMC Carrier and VXS-Switch) have successfully demonstrated the feasibility of the new digital Low-level RF system. The 2-board system has been transferred to a MedAustron test stand for specific MedAustron software developments. A pre-series of V2 hardware is under production.

Firmware: The developed FPGA firmware has now reached a workable state; much work is left in the details. The remote updating of FPGA firmware and DSP has to be added. IPMI for FMC developments has started.

Software: Test DSP code has been demonstrated successfully. Much more code needs to be developed for the full PSB system. The device drivers and test FESA classes generated with help from the Cheburashka memory map tool work nicely in synchronism with the firmware. A control room application will be created in 2013.

Other LLRF presented at RFTech meetings was LLRF system for XFEL and FLASH designed using the new MTCA.4 standard. Its components were already presented in this report in the chapter “Components, xTCAs”. The system for 2 SRF accelerating modules consist of uTCA crate equipped with electronic boards (uTC, VM, DWCs, SIS and others) communicating (including RF signals) through the backplane (no front panel connections) and external modules for specific purposes (piezo control, signal reference, drift calibration, LO generation).



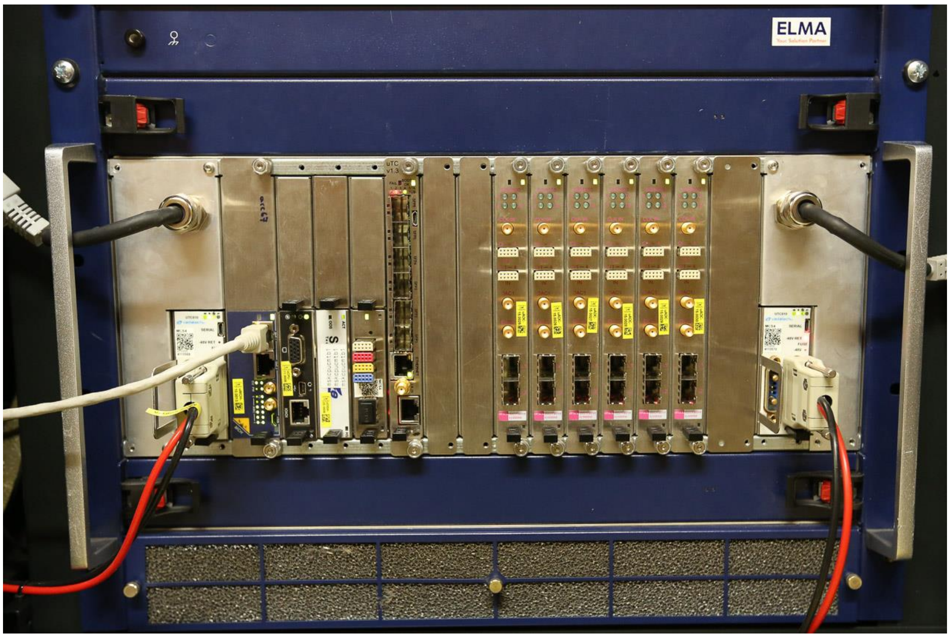
LLRF system for XFEL/FLASH (for 2 SRF accelerating modules)

The boards are placed both at the front (AMC) and back side (RTM - Rear Transition Modules) of the crate. The communication between the boards is provided through backplane. There are 2 kinds of backplanes: one for digital signals and the other to carry RF reference signals, high precision clocks and timing signals. Majority of system components is integrated in MTCA crate. The properties of some external modules prevented their integration with the main part of the system.

The system components are as follows:

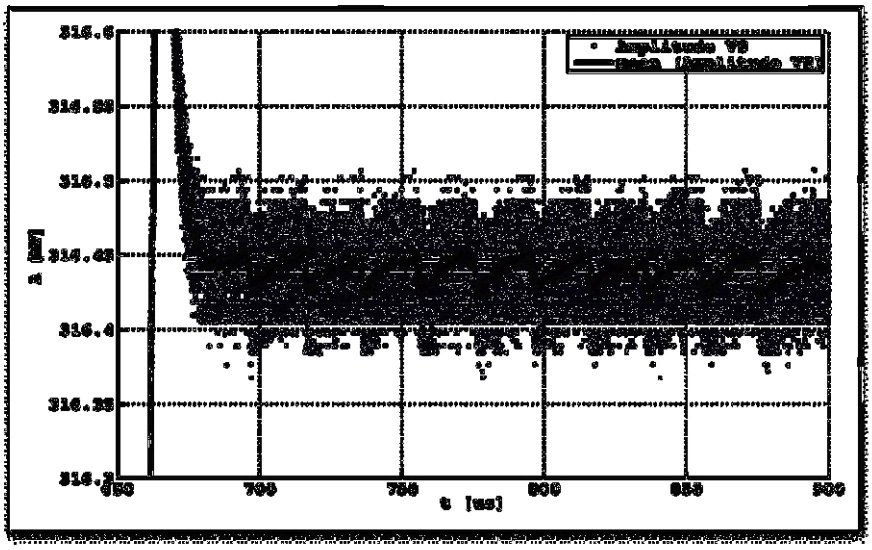
- PS – Power Supply (for uTCA crate)
- MCH – MicroTCA Carrier Hub (management unit for uTCA crate)
- CPU – microprocessor board
- TMG – timing AMC module
- uTC – Controller (signal processing unit)
- VM – Vector Modulator

- ITLK – Interlock interface (RTM module)
- KLM – Klystron Management Unit (front and RTM modules)
- SIS – SIS8300 digitizer board (10 channels, 16 bits resolution, 125MHz ADCs board from Struck)
- DWC – downconverters RTM board (10 channels)



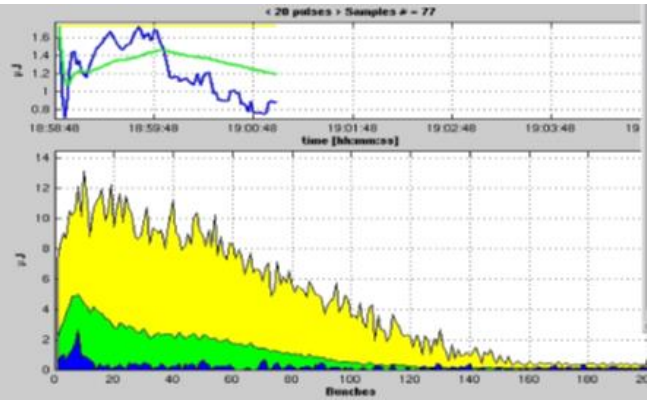
LLRF system installed at FLASH ACC23

The best regulation precision achieved with a new system so far was dA/A<9x10^{-5} for amplitude and dPh<0.008 deg. for phase. Certainly precise tuning and system calibration can further improve these numbers.

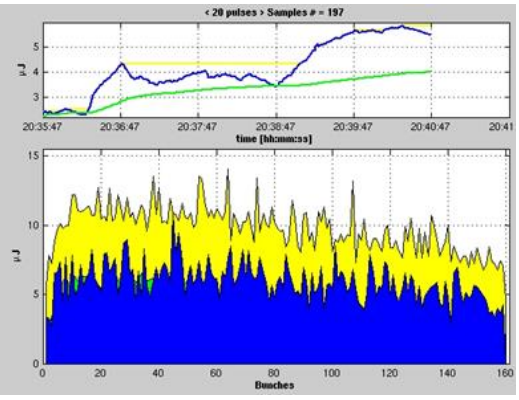


Vector sum regulation performance

The beam energy can be also stabilized by directly using the beam parameters. At FLASH, beam-based feedbacks have helped significantly to stabilize the long train beams. Decrease of the energy spread by a reduced arrival time jitter, has a significant influence on the SASE radiation generated in the undulator. For the SASE operation without beam feedback in the best case (yellow color), the radiation in the undulator has the highest intensity at the beginning of the bunch train, and then this intensity decreases about linearly in time due to energy variations. Around the 150th bunch it is close to zero. With beam-based feedback applied the SASE process lasts up to 160 bunches with uniform intensity.



SASE without beam feedback



SASE with beam feedback

References:

Mariusz Grecki: Report from LLRF Workshop. Third RFTech workshop.

Philippe Baudrenghien: The LHC LLRF. First RFTech workshop

Maria Elena Angoletta : CERN's PS complex LLRF renovation: beam results and plans. Second RFTech workshop.

J. Molendijk: An RF Low-level Beam Control system for PS Booster built in VME VXS using FMC mezzanines. Fourth RFTech workshop.

Link to the 1st RFTech workshop: https://indico.desy.de/internalPage.py?pageId=3&confId=2831

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8. COSTING

Accelerator design requires estimation of the facility costs at all stages of the design. Most of the costs are for the hardware (tunnel, accelerating modules, RF sources, control system), but software costs also play a role due to increasing software complexity, in particular in certain parts of the machine (e.g. LLRF control).

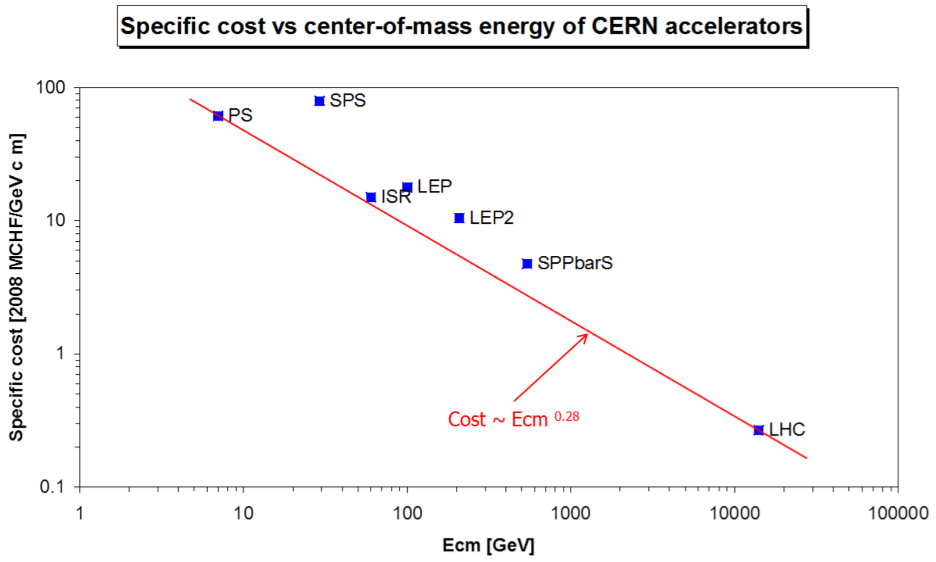
Concerning the hardware cost estimation the main contribution was made by Philippe Lebrun during the 4th RFTech workshop. We here report some highlights.

Cost estimate methods: They are either analytical or empirical.

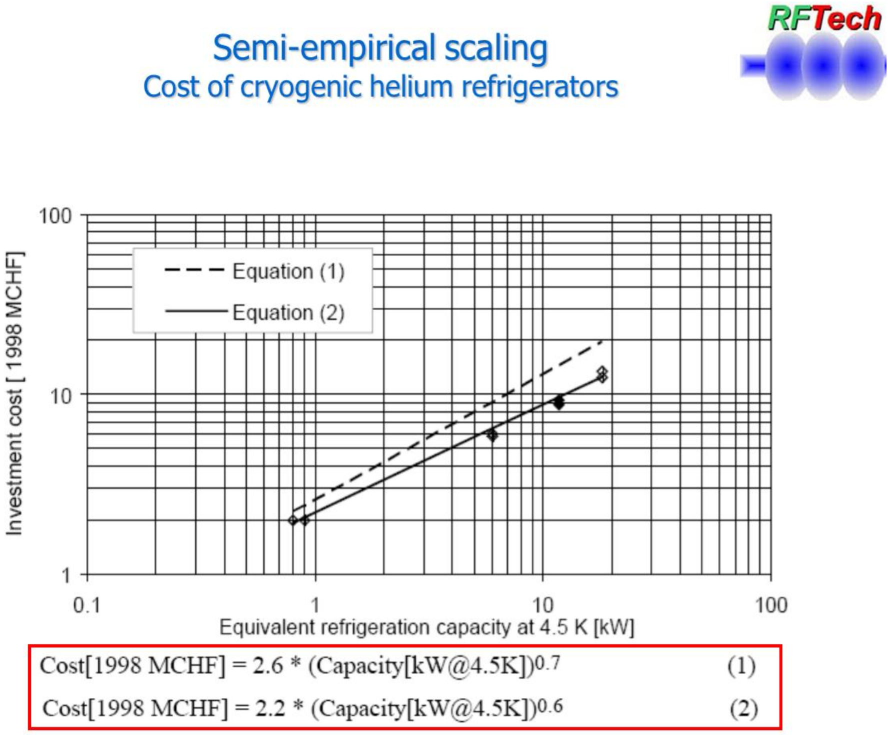
Analytical methods are based on project/work breakdown structure. They define the production techniques, estimate the fixed costs, establish unit costs & quantities (including production yield and rejection / reprocessing rates). In case of large series, a learning curve has to be introduced.

Scaling methods must establish scaling estimator(s) and scaling law(s), including conditions & range of application. The scaling laws can either be based on *first principles* or be *empirical*.

In most cases, the method is a hybrid between these methods.



Specific cost of CERN accelerators reflecting progress in technology

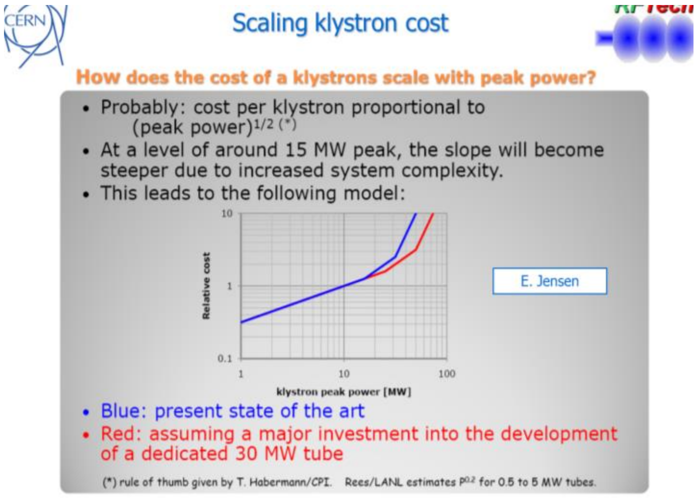


Semi-empirical scaling
Cost of cryogenic helium refrigerators

Cost[1998 MCHF] = 2.6 * (Capacity[kW@4.5K])$^{0.7}$ (1)

Cost[1998 MCHF] = 2.2 * (Capacity[kW@4.5K])$^{0.6}$ (2)

A semi-empirical example



Scaling klystron cost

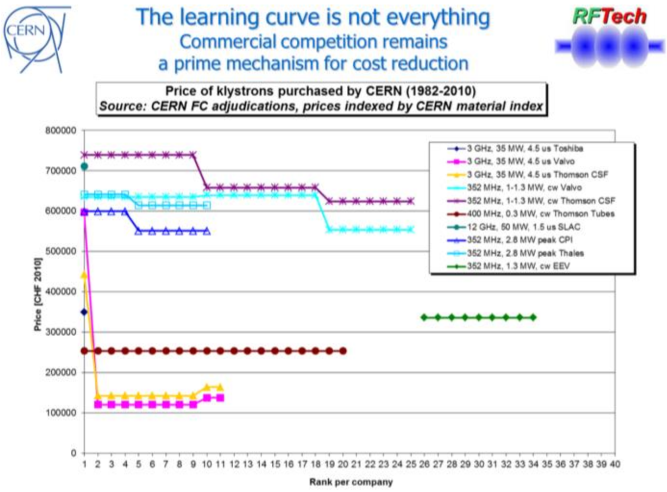
How does the cost of a klystrons scale with peak power?

- Probably: cost per klystron proportional to (peak power)$^{1/2}$ (*)
- At a level of around 15 MW peak, the slope will become steeper due to increased system complexity.
- This leads to the following model:

- Blue: present state of the art
- Red: assuming a major investment into the development of a dedicated 30 MW tube

(*) rule of thumb given by T. Habermann/CPI. Rees/LANL estimates $P^{0.2}$ for 0.5 to 5 MW tubes.

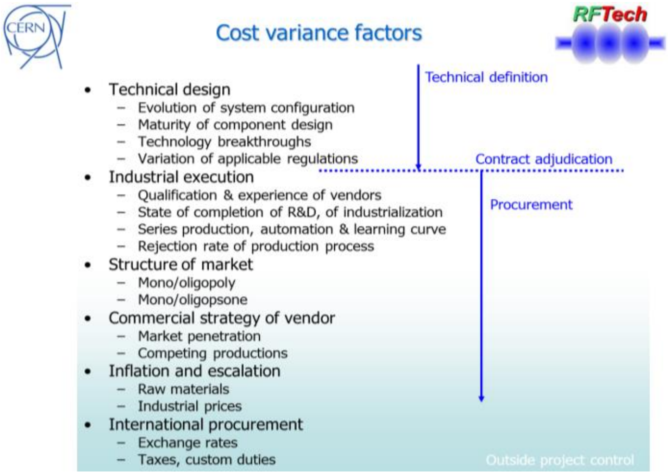
Another example of scaling law



The learning curve is not everything
Commercial competition remains
a prime mechanism for cost reduction

Price of klystrons purchased by CERN (1982-2010)
Source: CERN FC adjudications, prices indexed by CERN material index

Use and limitation of learning curves



Cost variance factors

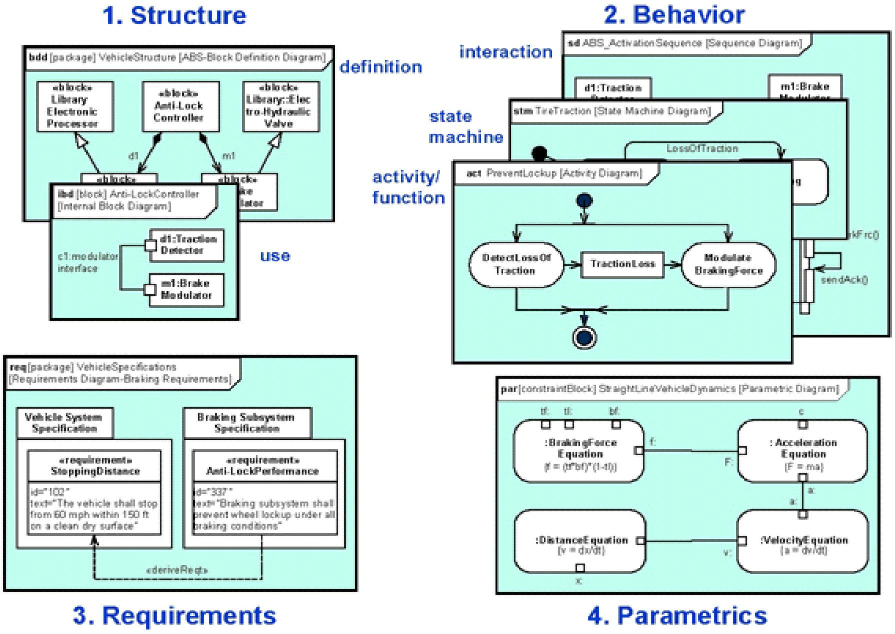
- Technical design
  - Evolution of system configuration
  - Maturity of component design
  - Technology breakthroughs
  - Variation of applicable regulations
- Industrial execution
  - Qualification & experience of vendors
  - State of completion of R&D, of industrialization
  - Series production, automation & learning curve
  - Rejection rate of production process
- Structure of market
  - Mono/oligopoly
  - Mono/oligopsone
- Commercial strategy of vendor
  - Market penetration
  - Competing productions
- Inflation and escalation
  - Raw materials
  - Industrial prices
- International procurement
  - Exchange rates
  - Taxes, custom duties

Cost variance factors

The estimation of the software costs is greatly developed by software industry. Industry uses a software model (usually described in UML language), on the basis of which the software development cost is evaluated. This procedure is currently very common in all software-design related tasks in industry.

However at the design stage of the complex control system it is not yet clear how the system will finally be implemented. Some parts can be finally designed as hardware components, while some of the others may be implemented in software. In order to enable modeling of the system as a unity independently of the final way of implementation the SysML language has been developed.

The SysML is a graphical language based on UML. The system model consists of several types of diagrams describing the system structure and behavior. In spite of the graphical form of the description it is formal and features quite complex a language. As has been witnessed during the design of the LLRF for XFEL, the system description is not as easy as it appears at first sight. Nevertheless, SysML as a formal way to describe the whole system is used in various industries and is gaining popularity and importance.



SysML diagrams

The UCP (Use Case Points) method uses SysML diagrams to estimate complexity of the system behavior. It takes into account the number of steps to complete the use case, the number and complexity of the actors, the technical requirements of the use case such as concurrency, security and performance, and various environmental factors such as the development teams, experience and knowledge. Using several factors (that must be calibrated for a given system and developer team) it provides a numerical value reflecting the cost of the system implementation.

References:

Philippe Lebrun. Costing high-energy accelerator systems. Fourth RFTech workshop.

Mariusz Grecki: Application of SysML to LLRF system design. First RFTech workshop

Link to the 4th RFTech workshop:https://lpsc.in2p3.fr/Indico/conferenceDisplay.py?confId=862

9. CONCLUSIONS

RF for accelerators is a very large domain including theory and models, simulation, experimentation, a wide panel of technologies and large scale constructions. It is a dynamical activity, driven by the continuous need for more powerful accelerators.

Theory and models are required for a good understanding of the fundamental aspects of the domain. They are the key for more powerful numerical codes. We presented some examples to illustrate this point, such as more efficient cavity optimization, modeling of large scale coupled systems or faster computing.

High power RF is a challenging part of the activity, related both to economic aspects and to reliability and maintainability aspects. New technologies are arising, such as solid state amplifiers, with on-line maintenance, high reliability and low-cost repair.

The new communication technologies of xTCA are very useful to guarantee modularity, flexibility and upgradeability. The reliability is also very high. These technologies are not motivated by the accelerator field. The new standard (MTCA.4) tries to fill the gap between telecommunication hardware products and the instrumentation needs for high energy physics. It is important to keep the accelerator community in close contact with this development and to have a visible participation in pertinent conferences like, for example, MIXDES.

Cavity design is a very active field of activity. The development of high power proton/ion linacs is motivating the development of new kinds of superconducting cavities (QWR, HWR, spoke), while the planned luminosity upgrade of the LHC has led to a worldwide effort for novel compact crab-cavities. The intensity upgrade of linear or circular machines is driving the design of HOM-free or damped structures. For all these kinds of cavities, there is a significant progress in the associated technologies: cavities proper, cryostat, cavity processing, materials…

Low Level RF lays the foundation for high performance machines, with ever more demanding performance requirements for amplitude and phase control. In order to assure performance (especially reliability and maintainability) it must be based on the most powerful new technologies. Scientific exchange between specialists is of paramount importance, and is achieved via regular meetings and workshops. RFTech was glad to support some (or parts of these) workshops.

All the aforementioned domains require a strong improvement in reliability. This can be realized by increasing component MTBF, but also via a better modularity or maintainability (see for example Solid State Amplifiers). This can also be achieved by new running schemes (for example: cavity failure recovery by adjacent cavities in high power linacs). For high power klystrons special systems are being developed to help extend the device life-time (Klystron Life-time Management System). For details see the 4th workshop.

The very ambitious development programs of advanced RF technology are crucial for future high-performance accelerators and, therefore, need a strong support. Among this support, exchanges between specialists are an essential ingredient, to share experience and solutions. Another essential point is the training of young persons, including participation in conferences and workshops. Providing this needed support was the prime motivation for launching RFTech.

The present report aimed at illustrating all the relevant points.

10. WORKSHOPS ORGANIZED OR CO-ORGANIZED BY WP4.3 EUCARD-RFTECH

Table: Workshops and mini-workshops held in the frame of RFTech, showing the topic, partner organizers (if any), date, location, and the number and origin of registered participants.

#	Topic	Organizers	Time	Place	Registrants
1	LHC Crab cavities “LHCC09”	EuroLumi, RFTech, CERN, KEK, US-LARP	16-18 Sep 2009	CERN	54 from EU, USA, Japan
2	Low Level RF	KEK, RFTech	19-22. Oct. 2009	KEK	~100 from Japan, USA, EU, China
3	1st RFTech Annual Meeting	RFTech	29 Mar. 2010	DESY	17 from EU
4	Integrated Circuits for Low Level RF	MixDes, RFTech	24-27 June 2010	Wroclaw / Poland	~300 from EU
5	2nd RFTech Annual Meeting	RFTech	02-03 Dec. 2010	PSI	30 from EU
6	LHC Crab cavities “LHCC10”	EuroLumi, CERN, KEK, US-LARP	15-17 Dec. 2010	CERN	50 from EU, US, Japan
7	Advanced Low Level RF Control	RFTech	18-20 April 2011	Krakow	38 from EU
8	Linac Operation with Long Bunch Trains	DESY, RFTech	6-8 June 2011	DESY	40 from EU. US. Japan
9	Integrated Circuits for Low Level RF	MixDes, RFTech	16-18 June 2011	Gliwice / Poland	~300 from EU
10	MulCoPim’11	ESA & U. Valencia EuroLumi	21-23 Sep. 2011	Valencia	~120 from EU, US
11	Low Level RF	DESY, RFTech	17-21 Oct. 2011	DESY	~100 from EU, US, Japan
12	LHC Crab Cavities, “LHC-CC11”	EuroLumi, KEK, US-LARP, UK	14-15 Nov. 2011	CERN	52 from EU, USA, Japan

		CI/DL			
13	3rd Annual RFTech Meeting	RFTech	12-13. Dec. 2011	Warnemünde / Rostock / Germany	17 from EU
14	Low Level RF System Integration	RFTech	14-16 Dec 2011	Warsaw	36 from EU
15	Integrated Circuits for Low Level RF	RFTech	24-26 May 2012	Warsaw / Poland	~300 from EU
16	Higher Order Modes in SC RF	CI, ICFA, ASTeC, IoP, RFTech	25-27 Jun 2012	Daresbury / UK	59 from EU, US
17	Advanced Low Level RF Control	RFtech	6-8 Aug 2012	Lodz / Poland	43 from EU
18	Computing in Accelerator Physics	U. Rostock, EuroLumi, RFTech, CST	19-25 Sep 2012	Warnemünde, Germany	about 100 from EU, US, Russia, and Japan
19	Low Level RF for XFEL	RFTech	19-21 Feb 2013	Swierk / Poland	55 from EU
20	4th Annual RFTech Meeting	RFTech	24-26 Feb 2013	Annecy / France	33 from EU

11. PUBLICATIONS AND EUCARD DOCUMENTS OF WP4.2 ACCNET-RFTECH

1.	E. Koukovini-Platia, G. De Michele, G. Rumolo, C. Zannini, *Electromagnetic Characterization of Materials for the CLIC Damping Rings*, Proc. ICAP'12 Warnemünde, 19-24 August 2012, p. 198, EuCARD-CON-2012-018
2.	U. Niedermayer, O. Boine-Frankenheim, *Numerical Calculation of Beam Coupling Impedances in the Frequency Domain using FIT*, Proc. ICAP'12 Warnemünde, 19-24 August 2012, p.193, EuCARD-CON-2012-017
3.	C. Zannini, G. Rumolo, *EM Simulations in Beam Coupling Impedance Studies: Some Examples of Application*, Proc. ICAP'12 Warnemünde, 19-24 August 2012, p. 190,): EuCARD-CON-2012-016
4.	T. Kozak, D. Makowski, A. Napieralski, *FMC-based Neutron and Gamma Radiation Monitoring Module for xTCA Applications*, MixDes2012 Conference, Warsaw, 24-26 May 2012, EuCARD-CON-2012-022
5.	A. Mielczarek, D. Makowski, G. Jabłoński, P. Perek, A. Napieralski, *Image Acquisition Module for uTCA Systems*, MixDes2012 Conference, Warsaw 24-26 May 2012, EuCARD-CON-2012-023
6.	P. Perek, J. Wychowaniak, D. Makowski, M. Orlikowski, A. Napieralski, *Image Visualisation and Processing in DOOCS and EPICS*, MixDes2012 conference, Warsaw 24-26 May 2012, EuCARD-CON-2012-024
7.	M. Grecki, *Joint Highlight Talk of WPs 4&10: Overview of the LLRF Developments for FLASH*, 3rd EuCARD Annual Meeting, WUT, Warsaw, Poland, 27 April 2012
8.	G. Burt, *Joint Highlight Talk of WPs 4&10: Compact Crab Cavities for LHC*, 3rd EuCARD Annual Meeting, WUT, Warsaw, Poland, 25 April 2012
9.	W. Weingarten, *European Infrastructures for R&D and Test of Superconducting Radio-Frequency Cavities and Cryo-Modules*, EuCARD Monograph Series, Vol. 10, EuCARD-BOO-2011-002
10.	V. Khan, *A Damped and Detuned Accelerating Structure for the Main Linacs of the Compact Linear Collider*, PhD Thesis, U. Manchester, September 2011, EucARD-BOO-2011-001
11.	W. Weingarten, *Strategy/Result for SRF Test Infrastructures*, EuCARD-MIS-2011-003
12.	W. Weingarten, *Is there a need for a 'European Infrastructure for R&D and Test of SRF cavities and cryomodules?* 2 November 2010, EuCARD-PRE-2010-030
13.	W. Weingarten, *European Infrastructures for R&D and Test of Superconducting Radio-Frequency Cavities and Cryo-Modules*, EuCARD Monograph Series, Vol. 10, EuCARD-BOO-2011-002
14.	M. Grecki, *Sub-LSB DAC resolution enhancement applied to LLRF control*, Proceedings of MIXDES 2010 Conference, page 157.
15.	K. Prygoda, T. Pozniak, D. Makowski, T. Kozak, M. Wisniewski, A. Napieralski, M. Grecki, *Power supply unit for ATCA-based piezo compensation system*, Proceedings of MIXDES 2010 Conference, pages 152-156
16.	A. Piotrowski, D. Makowski, *pciexpress hot-plug mechanism in linux-based ATCA control systems*. Proceedings of MIXDES 2010 Conference, pages 148-151
17.	S. Bou Habid, K. Czuba, W. Jalmuna, T. Jezynski, *Design of eight channel ADC card for ghz signal conversion*, Proceedings of MIXDES 2010 Conference, pages 144-147
18.	P. Perek, D. Makowski, P. Predki, A. Napieralski, *ATCA carrier board with dedicated IPMI controller*, Proceedings of MIXDES 2010 Conference, pages 139-143.
19.	J. Wychowaniak, D. Makowski, P. Predki, A. Napieralski, *Application for management and monitoring of xtcs software*, Proceedings of MIXDES 2010 Conference, pages 133-138.
20.	K. Czuba, M. Ladno, *AMC Timing receiver and clock synthesizer module for the LLRF system*, Proceedings of MIXDES 2010 Conference, pages 129-132.

21.	T. Kozak, D. Makowski, *AMC radiation monitoring module for ATCA, μTCA based Low Level RF Control System*, Proceedings of MIXDES 2010 Conference, pages 125-128
22.	J. Glowka, M. Macias, K. Czuba,K. Pozniak, R. Romaniuk, *Stanowisko testowe z miedzianą strukturą typu TESLA (Test stand with copper TESLA structure)*
23.	T. Stanislawksi, T. Czarski, K. Pozniak, R. Romaniuk, *Conditioning of complex envelope signal from FLASH accelerator cavities* (Kondycjonowanie sygnału obwiedni zespolonej z wnęk akceleratora FLASH)
24.	K. Pozniak, T. Stanislawski, W. Zabolotny, W. Koehler, F. Stephan, S. Simrock, *Indirect method of measuring changes of EM field in RF-gun cavity for XFEL accelerator* (Pośrednia metoda pomiaru zmian pola we wnęce działa elektronowego akceleratora XFEL)
25.	L. Dymanowski, K. Lewandowksi, M. Linczuk, A *project of universal computing platform - cluster of floating point DSP processors* (Projekt uniwersalnej platformy obliczeniowej - klastra zmiennoprzecinkowych procesorów DSP)
26.	P. Drabik, K. Pozniak, *Object oriented programming environment for reconfigurable applications implemented in FPGA chips*
27.	R. Romaniuk, *Photonics and Web Engineering: WILGA 2009*
28.	W. Koprek, *ACTA-based LLRF System for XFEL - Demonstration at FLASH*, LLRF09, Tsukuba, 19-22 October 2009
29.	M. Grecki, *Piezo Control for LFD Compensation*, LLRF09, Tsukuba, 19-22 October 2009
30.	K. Czuba, *Timing and Synchronization (Tutorial/Overview)*, LLRF09, Tsukuba, 19-22 October 2009