ESS-Bilbao Contribution to ESS Warm LINAC High Power RF Systems

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RF Group

www.essbilbao.org

On behalf of:

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Ibon Bustinduy	**MEBT Project Leader**

ESS-Bilbao RF Group:

- **Nagore Garmendia**
- **Tomasso Poggi**
- **Leire Muguira**
- **Oscar Gonzalez**
- **Arash Kaftoosian**

And with sincere thanks to the ESS colleagues

ESS - BILBAO

“International Centre of Excellence for Neutron Science and Technologies”

Public Consortium: Funded by Spanish and Basque Country Governments (50/50)

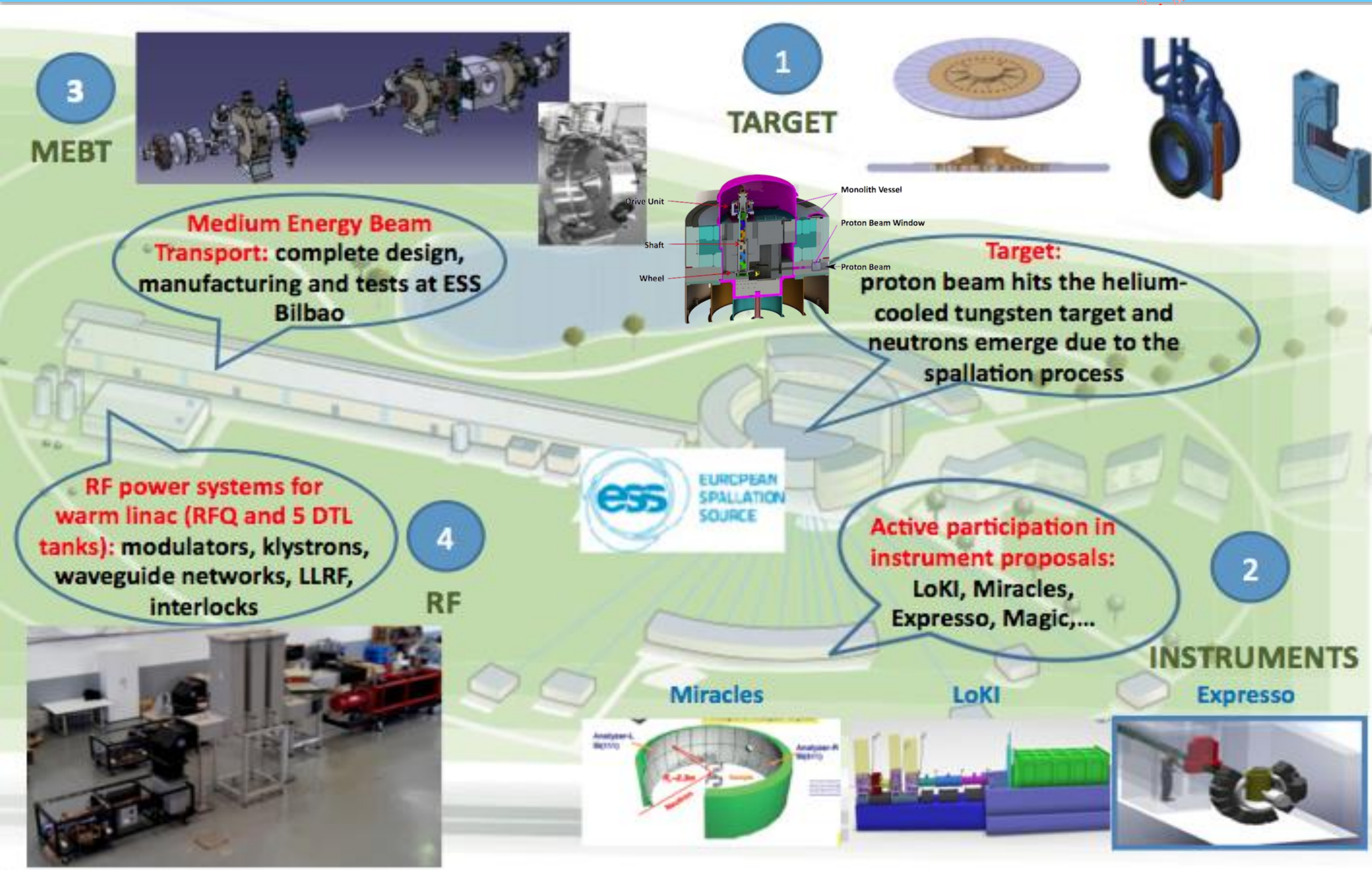
Main Objective: In kind Contribution to ESS (Lund, Sweden)

Spain participation in ESS: **5%**

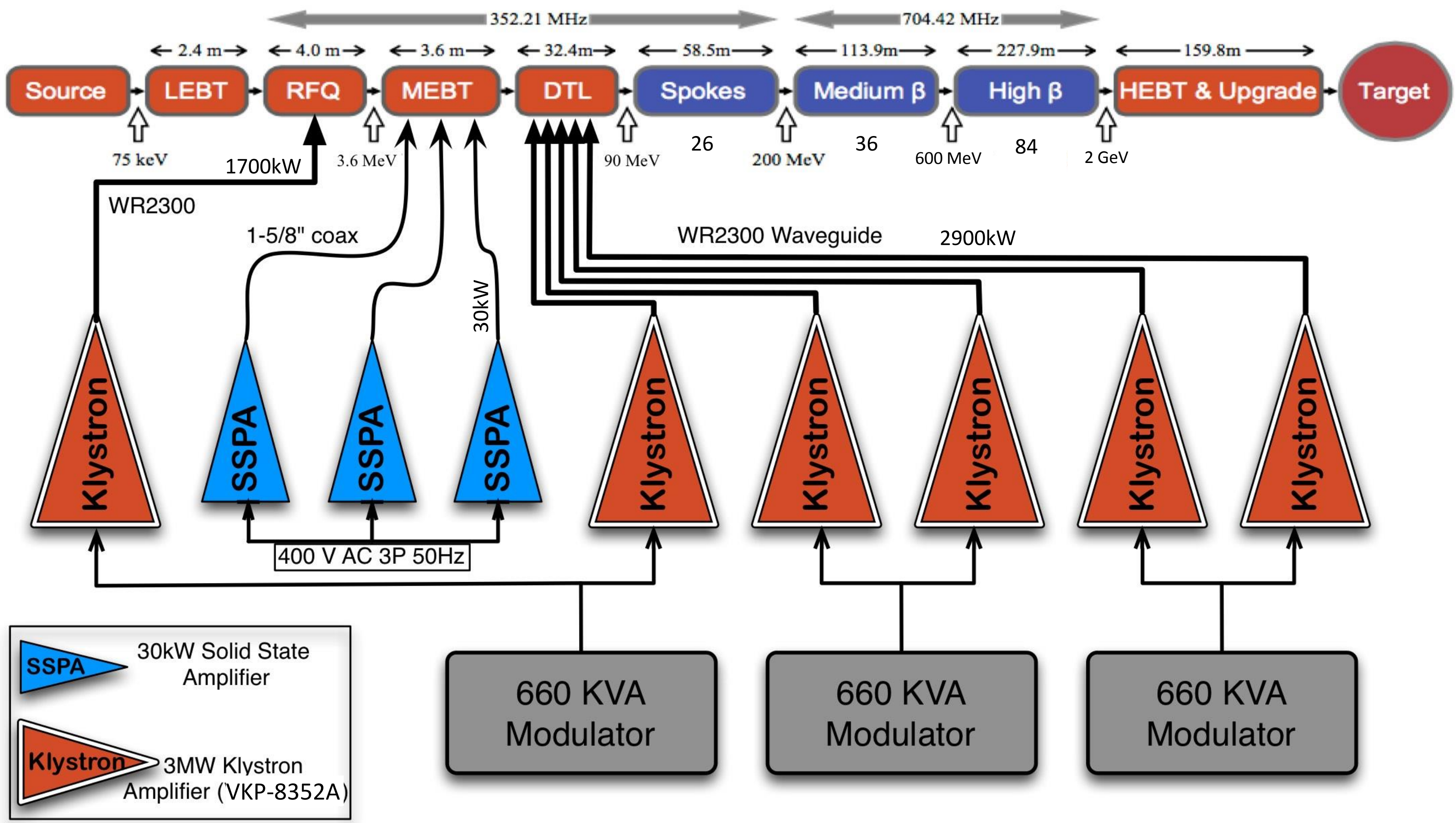
In-kind: Some 70 M€ (50% Accelerator/Target and 50% Neutron Instr.)

Staff: ~60 people (researchers, technicians, support)

Spanish Contribution to ESS



ESS Warm LINAC RF Power System



ESS-Bilbao RF Contribution

- **Klystrons:** 6x 2.9MW 352MHz Pulsed 3.5ms/14Hz
- **Modulators:** 3x 660 KVA, 120kV, 110A, long pulse (3.5ms)
- **Solid-State Power Amplifiers:** 3x 30 kW for MEBT Buncher Cavities
- **LLRF:** 9+26 DLLRF based on µTCA4
- **RF Interlock System:** Fast and Slow interlock modules (FIM: <10 µs and SIM:<50ms)
- **RF Distribution System:** Circulators, Loads, Directional Couplers, Power Detectors, Splitters, Waveguide components

Klystrons

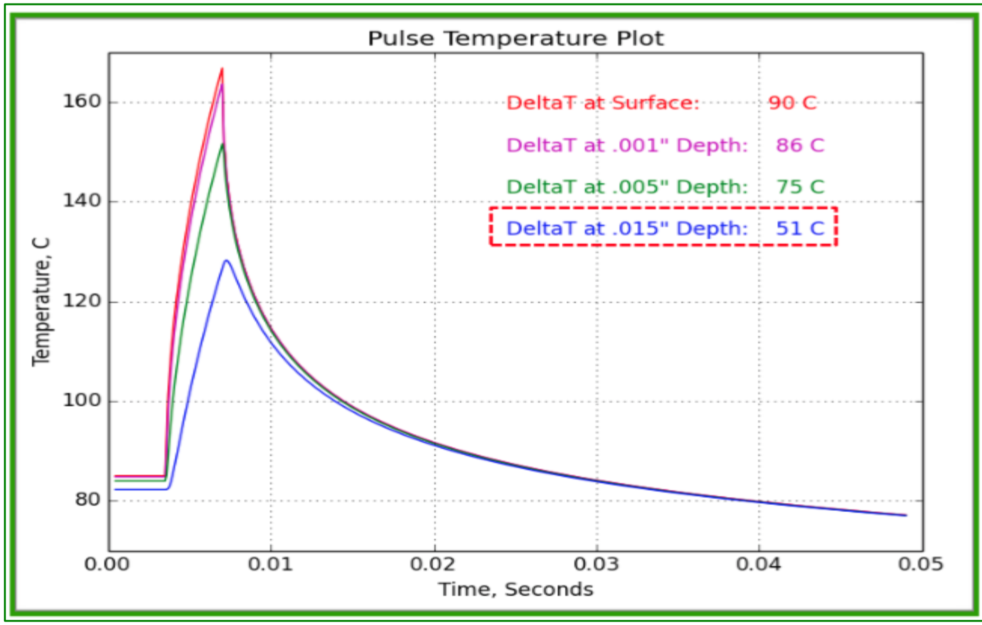
Module	Frequency (MHz)	Peak Power (kW)	Qty.	Amplifier	Transmission Line
RFQ	352.21	1700	1	Klystron	WR2300 (FH/HH)
DTL	352.21	2900	5	Klystron	WR2300 (FH/HH)

Spec	Value	Units
Beam Voltage	115	kv
Beam current	50	A
Frequency	352.2 ± 1	MHz
Peak Power	3	MW
Average Power	150	kW
Saturation Gain	42	dB
Efficiency	56	%
Duty	5	%

3MW
352MHz
Pulsed
Klystron
VKP-8352A
CPI

Long Pulse Issue

- Four VKP-8352A klystrons already purchased and delivered form CPI
- These Klystrons were initially designed and developed for 1.6ms RF pulse width, 30Hz Rep rate
- They are going to be utilized for ESS but that requires operation with 3.5ms and 14 Hz repetition rate



- Some concerns raised that due to larger RF pulse width there might be some **collector heat cycling fatigue** effect which could potentially reduce the klystron lifetime or lead to failure.
- After more in-depth simulations and analysis by CPI the result was promising, showing that **after a short conditioning**, klystrons can **work safely** with 4ms pulses

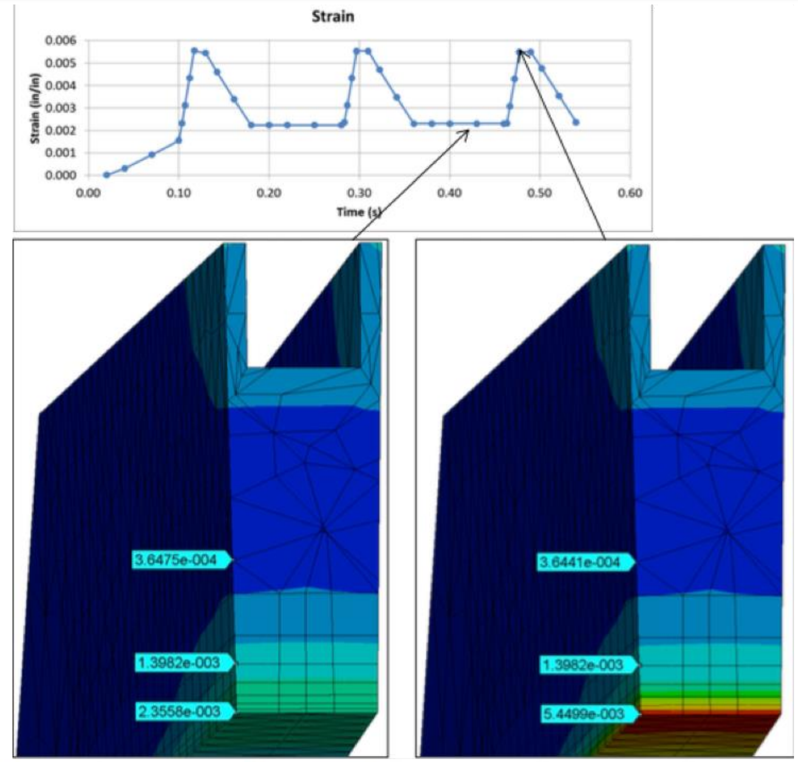
Long Pulse Issue: Simulations by CPI

The temperature cycling induce strain in the material. The variation of this strain (referred to as “strain range”) causes fatigue failure in materials.

The strain range is highest at the surface, 0.003 in/in, and drops to near zero at .040” depth from the surface. Past this depth the fatigue life is beyond material data, greater than 20,000 hours.

This is lifetime in hours of operation with HV only, with no RF.

Surface cracking will occur at depths less than 0.040”. This will be evidenced as “processing” during test with temporarily elevated gas levels.



Verification Plan:

In order to practically verify the analysis, additional testing will be carried out by CPI in Palo Alto, CA on the first VKP-8352A klystron. Subsequent testing of the remaining 3 klystrons will be performed at ESS-Bilbao with technical support from CPI.

Depth (in)	Strain (in/in)			Lifecycles	Lifetime (hrs)
	Hot	Cold	Range		
0	0.0055	0.0024	0.003111	2.00E+04	0.40
0.005	0.0048	0.0023	0.002524	3.00E+04	0.60
0.013	0.0039	0.0022	0.001647	7.00E+04	1.39
0.024	0.0029	0.0022	0.000712	3.00E+05	5.95
0.041	0.0019	0.0019	0.000005	~1E+09	~20,000
0.066	0.0014	0.0014	0.000001		
0.104	0.0011	0.0011	0.000001		
0.161	0.0006	0.0006	0.000005		

Courtesy of CPI

Modulators

ESS BILBAO MODULATOR SPECS (JEMA)

Parameter	Specification
Output Voltage	120 kV (pulsed)
Output current	60 A
Pulse Width	1.81 ms (adjustable)
Pulse Repetition Rate	2 - 50 Hz
Peak Power	7.2 MW
Average Power	648 kW
Duty Cycle (%)	9%
Input Voltage	30 kV (50Hz)
Efficiency	> 90%

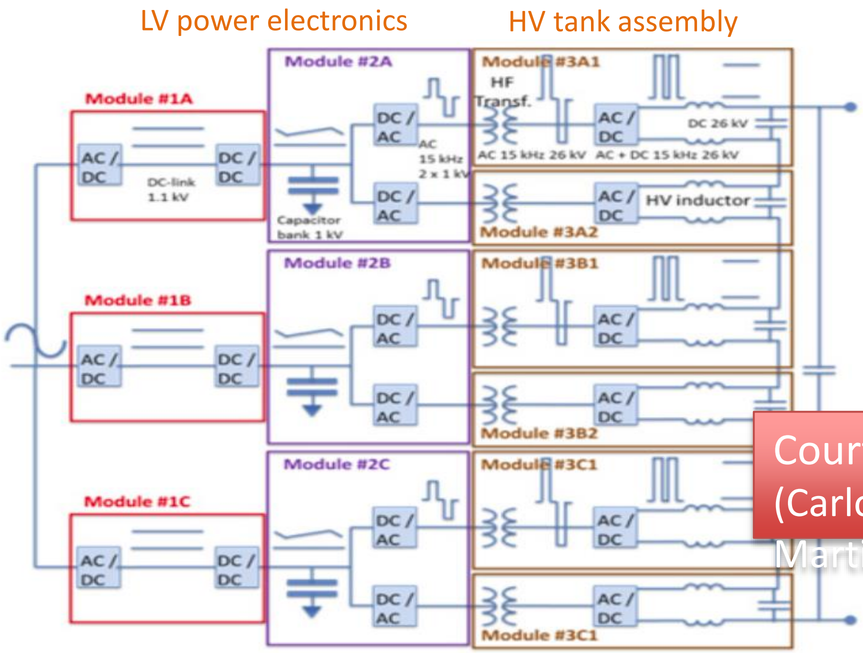
First test at SNS Q1,2015: Satisfactory
30-day test at full power: soon

3.5ms pulse but low average power test at ESS-Bilbao: Recently finished successfully

Main features:
- Topology: Mixed between Marx generator – Direct Modulator
- Outstanding rise/fall times and pulse flatness characteristics
- No oil: Dry Transformers (epoxy insulation)

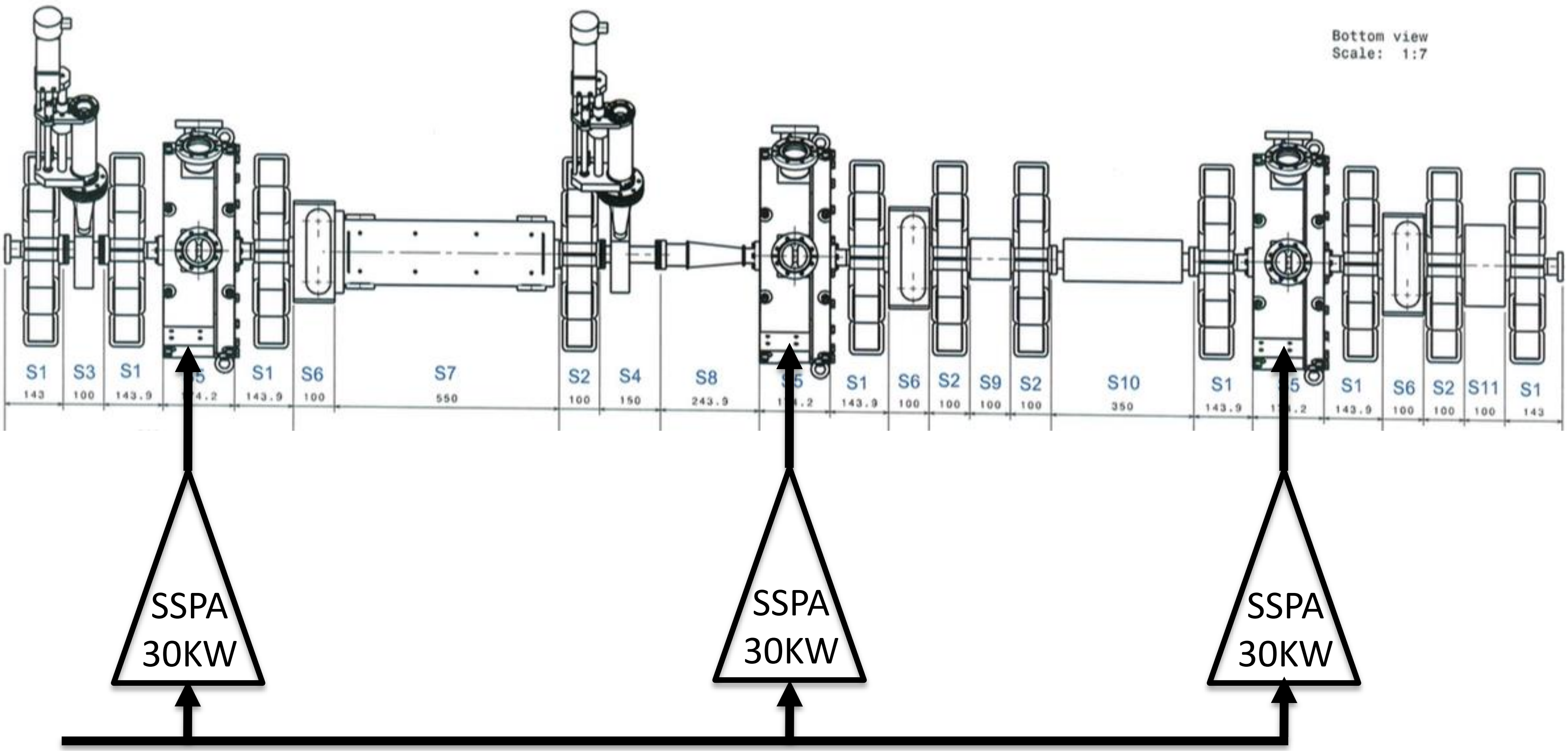
Modulators for ESS

- Three 660 KVA Modulators will feed the six klystrons
- They will be based on SML (Stacked Multi-Level) topology (ESS design)
- A 115kV/20A for 3.5ms/14Hz prototype is under test at Lund University
- Last week a 15-minute test with 115kV output done successfully
- It is being prepared to do the heat run test
- ESS-Bilbao will be in charge of tendering and procurement based on ESS design



Courtesy of ESS (Carlos A. Martins)

Medium Energy Beam transport (MEBT)



MEBT Buncher Cavities

- Power requirements:
  - $V_{cavity(effective)}$ = 140 kV
  - Cavity shunt Impedance = 1.3 MΩ

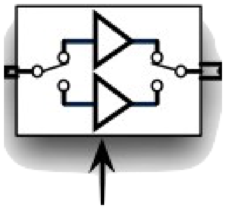
$$\Rightarrow P_{Cavity} = \frac{V^2_{cav(eff)}}{R_s} = \frac{140^2_{kv}}{1.3_{M\Omega}} = 15kW$$

  - Plus ~2kW for energy adjustment between RFQ and DTL if needed
  - Plus 25% overhead for LLRF regulation
  - Plus 1.5 dB transmission line losses

⇨ Required Power ≅ 30kW

30kW SSPAs for Buncher Cavities

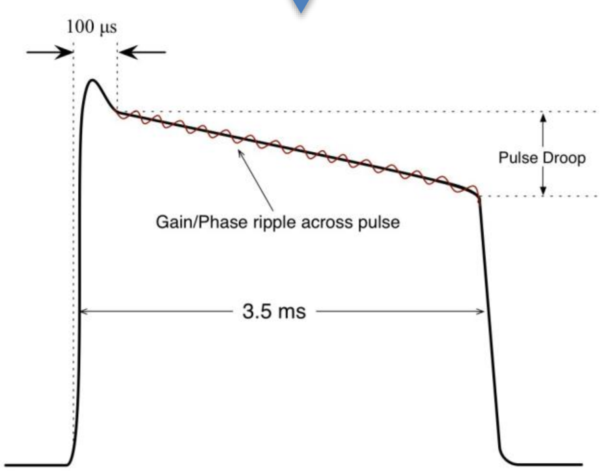
- Call for tender for three 30kW peak solid-state power amplifiers is going to be lunched shortly
- Reliability and availability for these amplifiers are the key points
- The amplifiers should be maintenance-free for at least 8000 hours continues operation (annual running period till the machine shot-down), to achieve that:
  - Any internal driver amplifier must be equipped with a redundant amplifier which can be switched automatically to be replaced in case of failure.



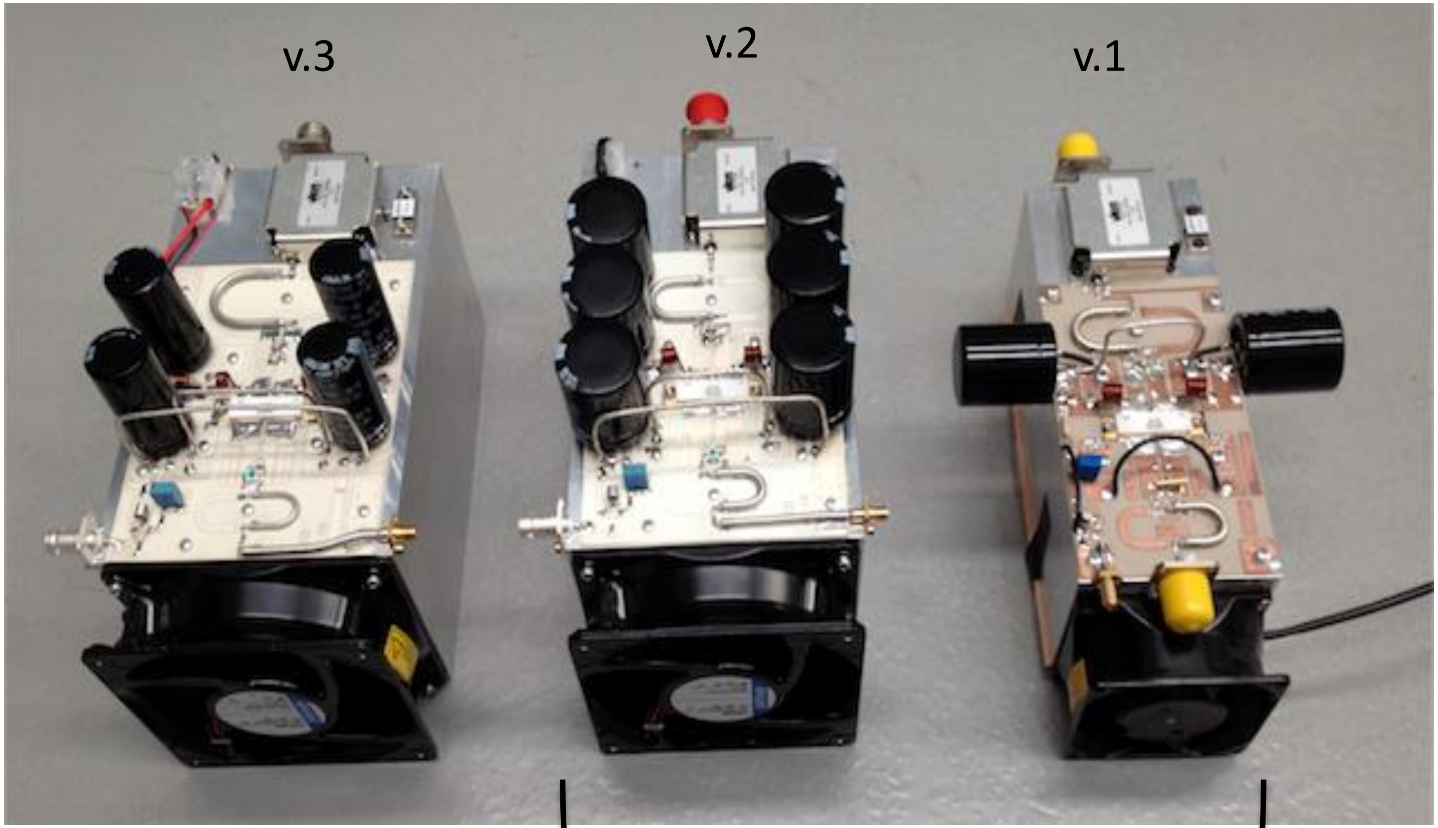
  - High power amplifier (HPA) modules should be hot-plug to be changed within a few minutes if one module in down
  - In case of failure in one HPA, SSPA will continue working but with reduced output power enough not to lose the beam in LINAC due to loss increment in other sections.
  - Power supplies or DC/DC converters must be modular and distributed

SSPA Technical Specifications

Frequency	**352.21 MHz ± 5MHz**
Nominal power	30 kW peak
Pulsed RF	3.5ms/14 Hz (5% Duty Cycle)
Gain Linearity	≤± 0.5dB in 10dB dynamic range
Phase Linearity	≤ 2˚ in 10 dB dynamic range
Gain ripple within pulse	≤ 0.25% rms
Phase ripple within pulse	≤ 0.25˚ rms
RF power droop	≤ 0.45 dB
Cooling	De-mineralized water



R&D Activities in Amplifiers at ESS-Bilbao

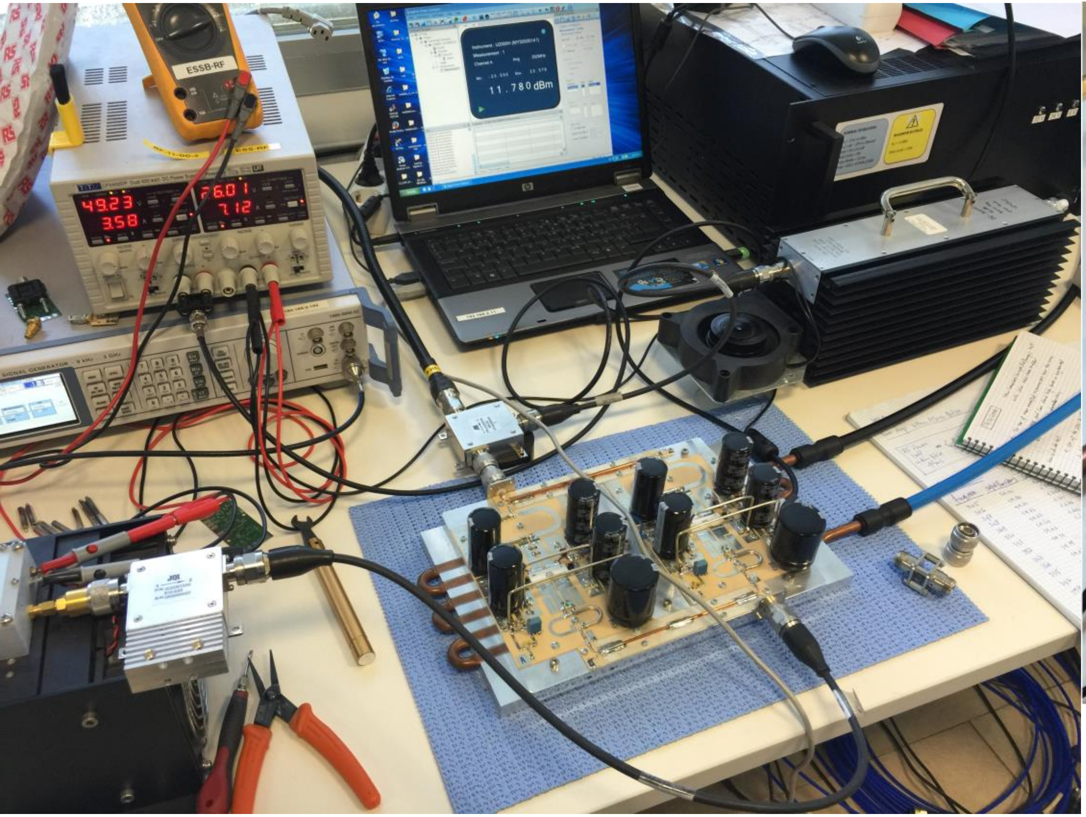


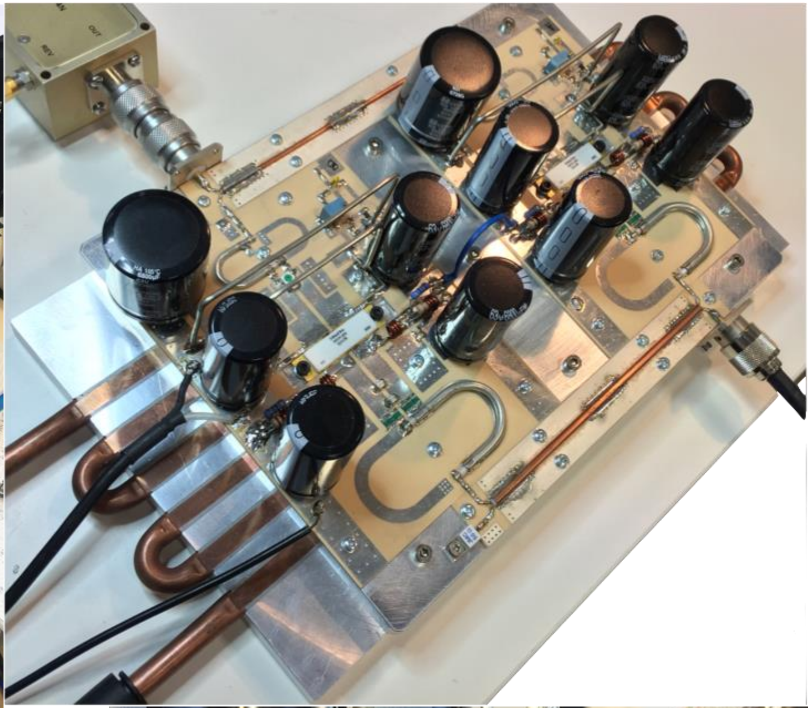
With 25Ω baluns

With 50Ω baluns

1kW Amplifiers

2kW Compact Balanced Amplifier

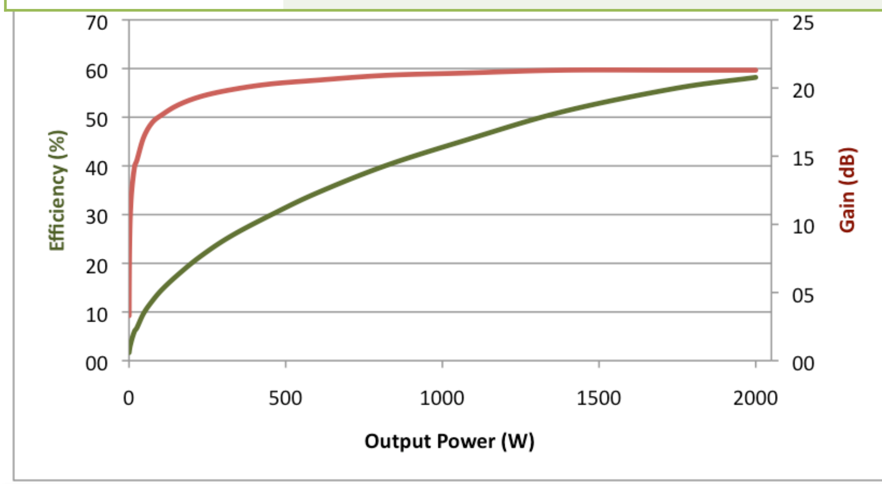


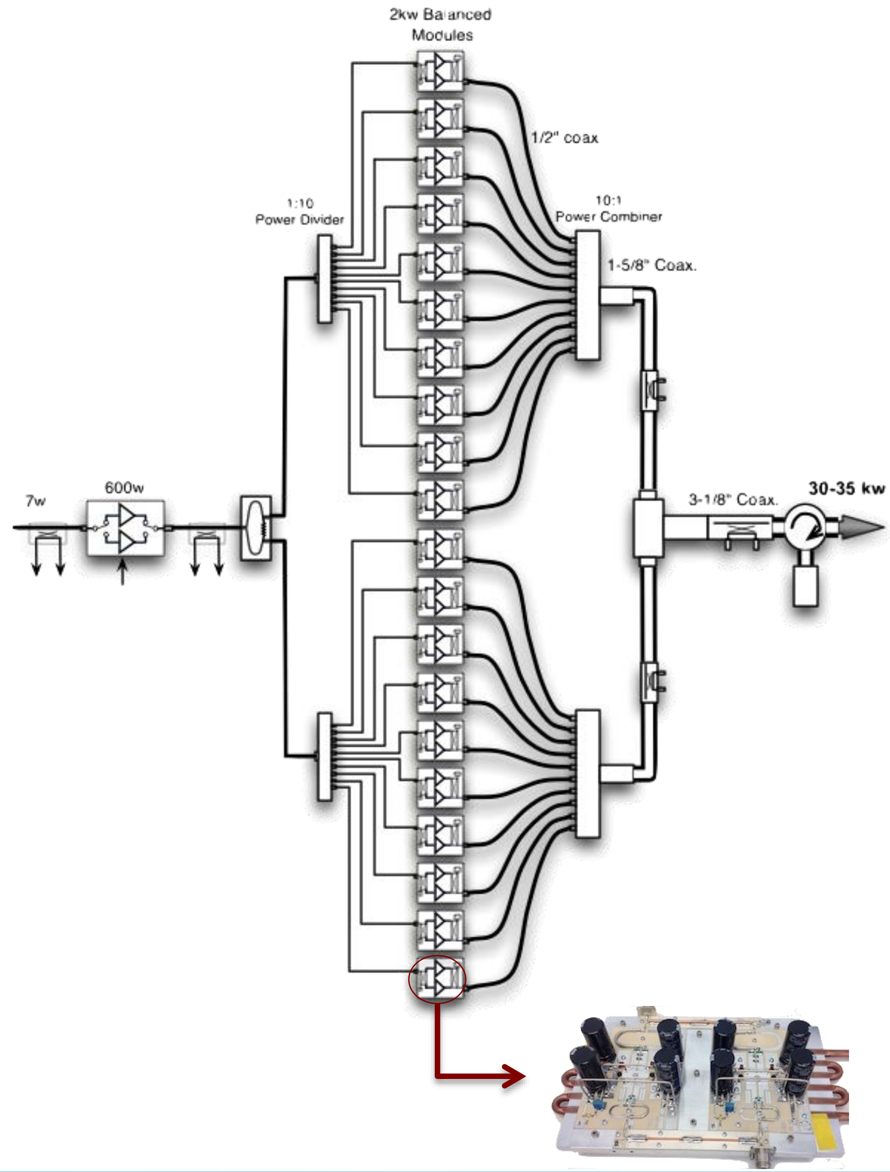


20x 2kW HPA Modules, each one equipped with Bias circuit, Gate voltage modulation, temperature compensation and current monitoring tools, will be combined to reach 30 to 35 kW Output.

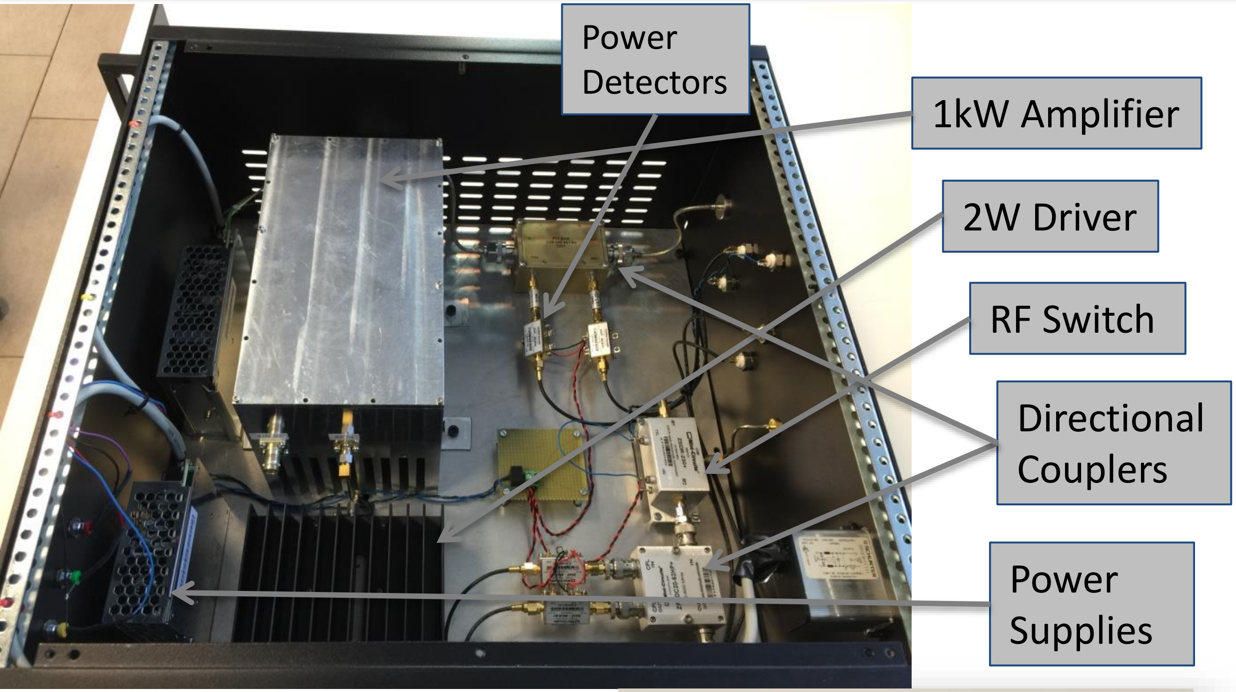
2kW Amplifier Test Results

Parameters	Test Results	Conditions
Frequency	352.2 MHz	
Output Power	2000 W	0.5dB Compression
Bandwidth (1dB)	40 MHz	± 0.25 dB
Efficiency	58%	Class AB continued bias
Gain	21.3 dB	@ full power
Input Return Loss	29.7 dB	@ 352.2MHz
Duty Cycle	5%	3.5ms/14Hz
RF Pulse Droop	2.7% (Voltage) 0.23 dB (Power)	1.5ms pulse
	5% (Voltage) 0.42 dB (Power)	3.5ms pulse



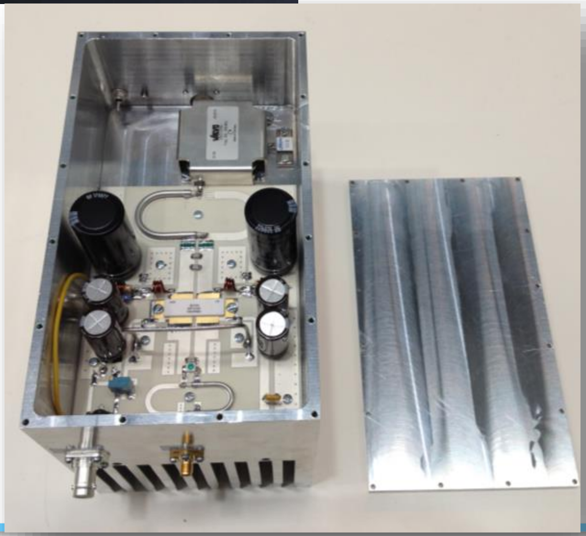


Klystron Driver



Parameter	Value
Class of Amplifiers	A + AB
Output Power (0.5 dB Compression)	270 W
Total Gain	50 dB
Band Width (1dB)	37 MHz
Overall Efficiency (Including fan, PS, etc.)	20%
Cooling	Air
Bias	Continues
RF switch Speed (Max)	4 µs

Six Klystron drivers' technical specifications are to be ready to call for tender in Q1 2017

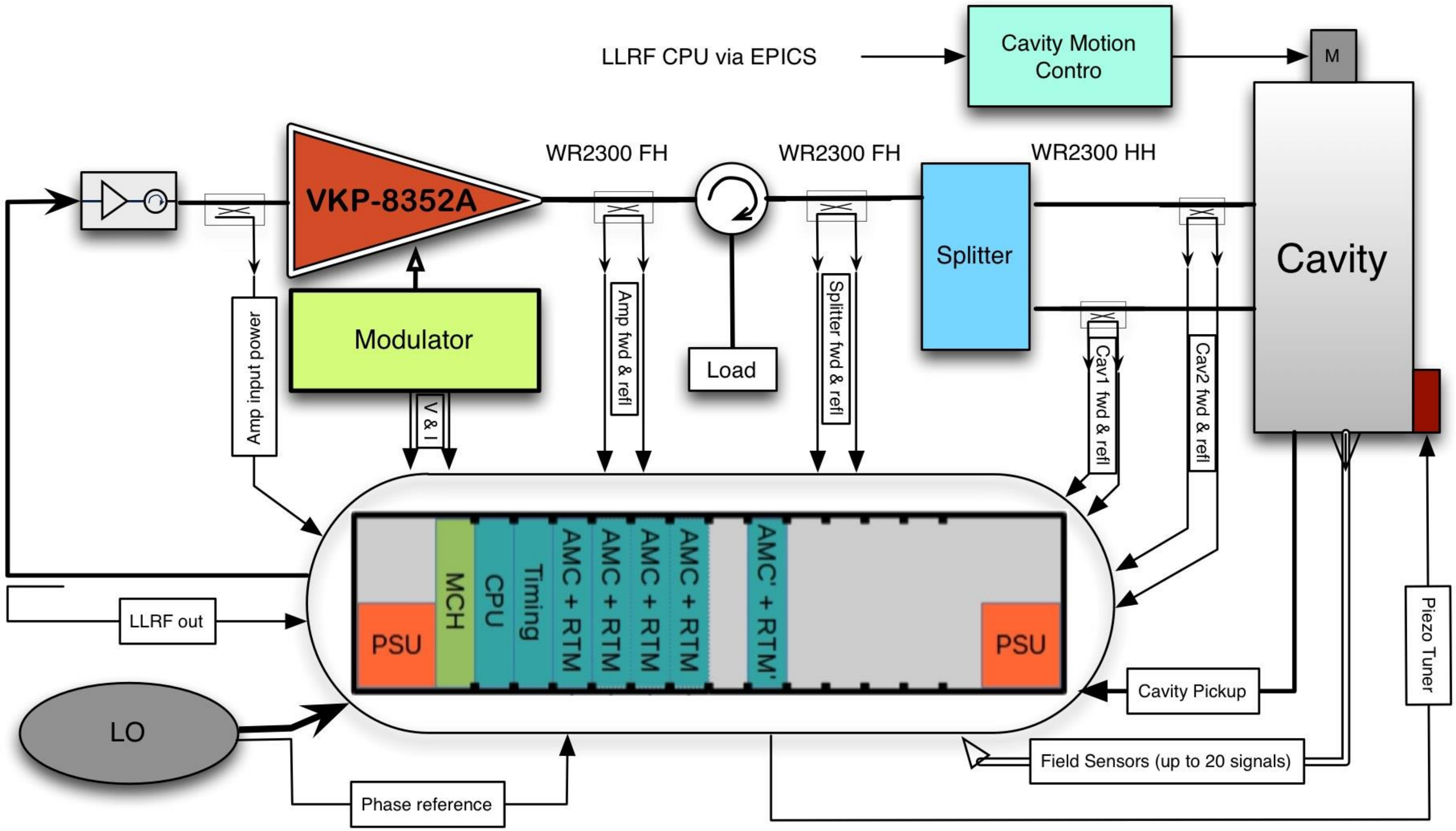


Low Level RF

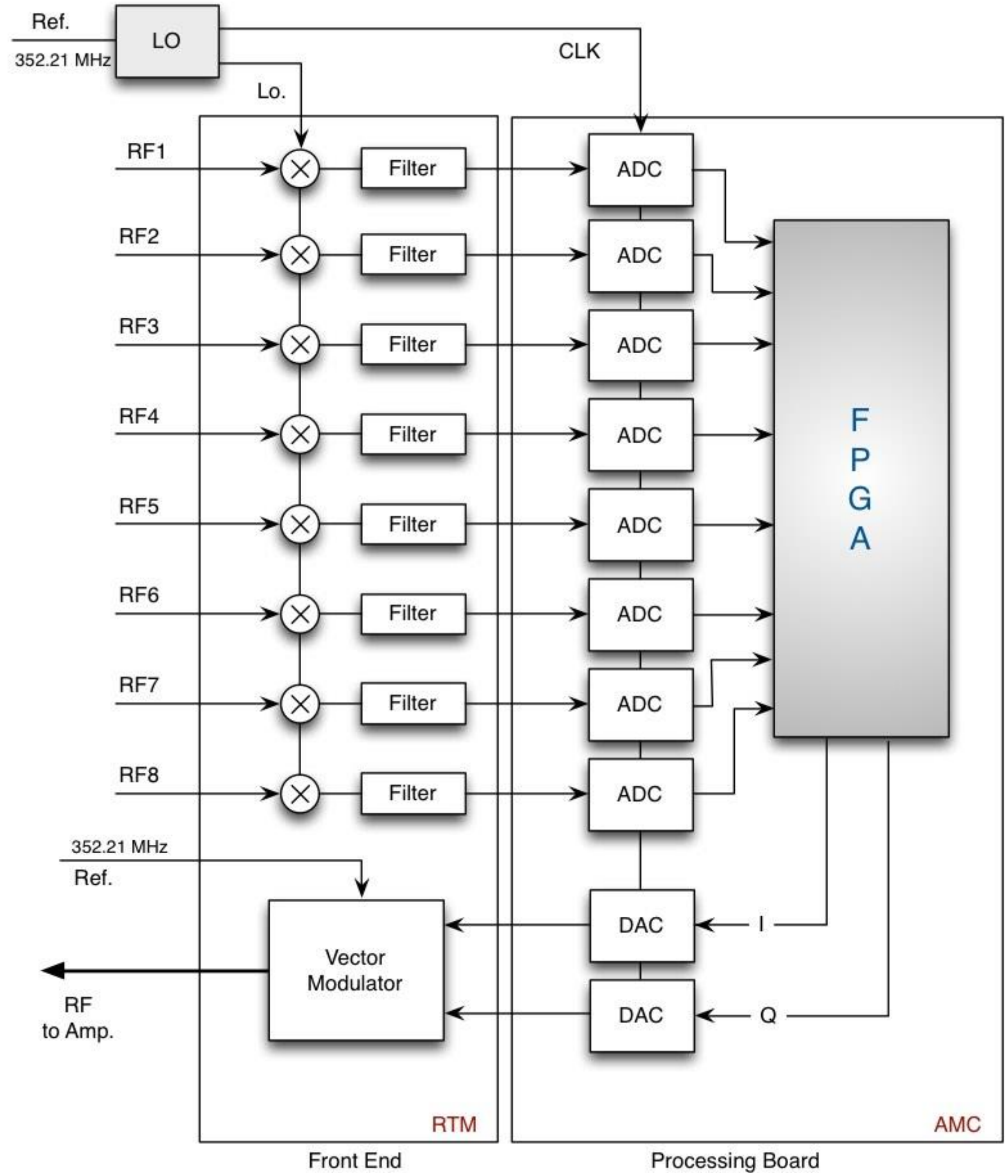
- Total 35 Digital LLRF units will be delivered to ESS as our in-kind contribution.
- They will be all based on µTCA4 standard
- These 35 DLLRFs will be similar but vary slightly depends on amplifier type and number of signals processed by the LLRF system.
- Number of signals to LLRF will be from 10 to 34 per cavity

	No. of Cavities	Power inside cavity	Phase accuracy (RMS)	Amplitude accuracy (RMS)	Temp.	Tuning system
RFQ	1	1600kW	0.2˚	0.2%	~300K	Water temp
MEBT	3	22kW	0.2˚	0.2%	~300K	Plunger
DTL	5	2200kW	0.2˚	0.2%	~300K	Plunger
Spoke	26	330kW	0.1˚	0.1%	~2K	Deformation + piezo

LLRF Signals



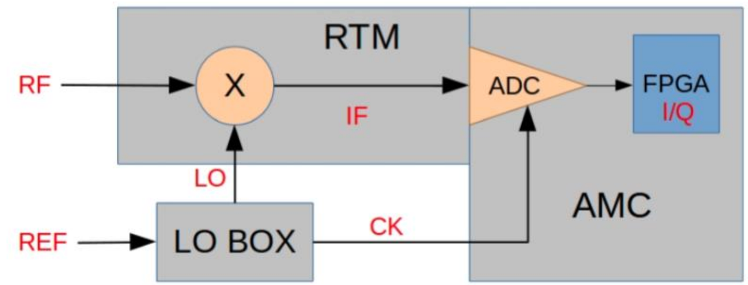
LLRF Block Diagram



Local Oscillator

CLK = LO/P		RF	352,210 MHz			CLK	
Name	**P**	**FLO**	**FIF**	**M**	**N**	**FS**	**Ref**
Generic		**FIF+Ref or N/(N-1)**	**1/(N-1)**	**M**	**N**	**FLO/P**	**352**
Alt 5	4	7/6	1/6	**4**	**7**	1/4	**FRF**
(MHz)		410,911666667	58,701666667			102,727916667	**352,210**
Alt 6	4	9/8	1/8	**4**	**9**	1/4	**FRF**
(MHz)		396,236250000	44,026250000			99,059062500	**352,210**
Alt 7	4	11/10	1/10	**4**	**11**	1/4	**FRF**
(MHz)		387,431000000	35,221000000			96,857750000	**352,210**
Alt 8	4	13/12	1/12	**4**	**13**	1/4	**FRF**
(MHz)		381,560833333	29,350833333			95,390208333	**352,210**
Alt 9	4	15/14	1/14	**4**	**15**	1/4	**FRF**
(MHz)		377,367857143	25,157857143			94,341964286	**352,210**

CLK=REF/M		RF	352,210 MHz			CLK	
Name	**N_DIV**	**FLO**	**FIF**	**M**	**N**	**FS**	**Ref**
Generic	**N_DIV**	**REF(N+1)/N**	**REF/N**	**M**	**N**	**REF/M**	**352**
Alt 1	7	8/7	1/7	**3**	**7**	1/3	**FRF**
(MHz)		402,525714286	50,315714286			117,403333333	**352,210**
Alt 2	8	9/8	1/8	**3**	**8**	1/3	**FRF**
(MHz)		396,236250000	44,026250000			117,403333333	**352,210**
Alt 3	10	11/10	1/10	**3**	**10**	1/3	**FRF**
(MHz)		387,431000000	35,221000000			117,403333333	**352,210**
Alt 4	9	10/9	1/9	**4**	**9**	1/4	**FRF**
(MHz)		391,344444444	39,134444444			88,052500000	**352,210**
Alt 5	11	12/11	1/11	**4**	**11**	1/4	**FRF**
(MHz)		384,229090909	32,019090909			88,052500000	**352,210**



	Freq. range	**#outs**	**Jitter**
LO	377 – 411 MHz	4	200 fs
CLK	88 – 125 MHz	4	200 fs

- RTM will be developed by SLAC
- IF to IQ by non-IQ sampling

1. $f_{CK} = \frac{1}{M} f_{REF}$

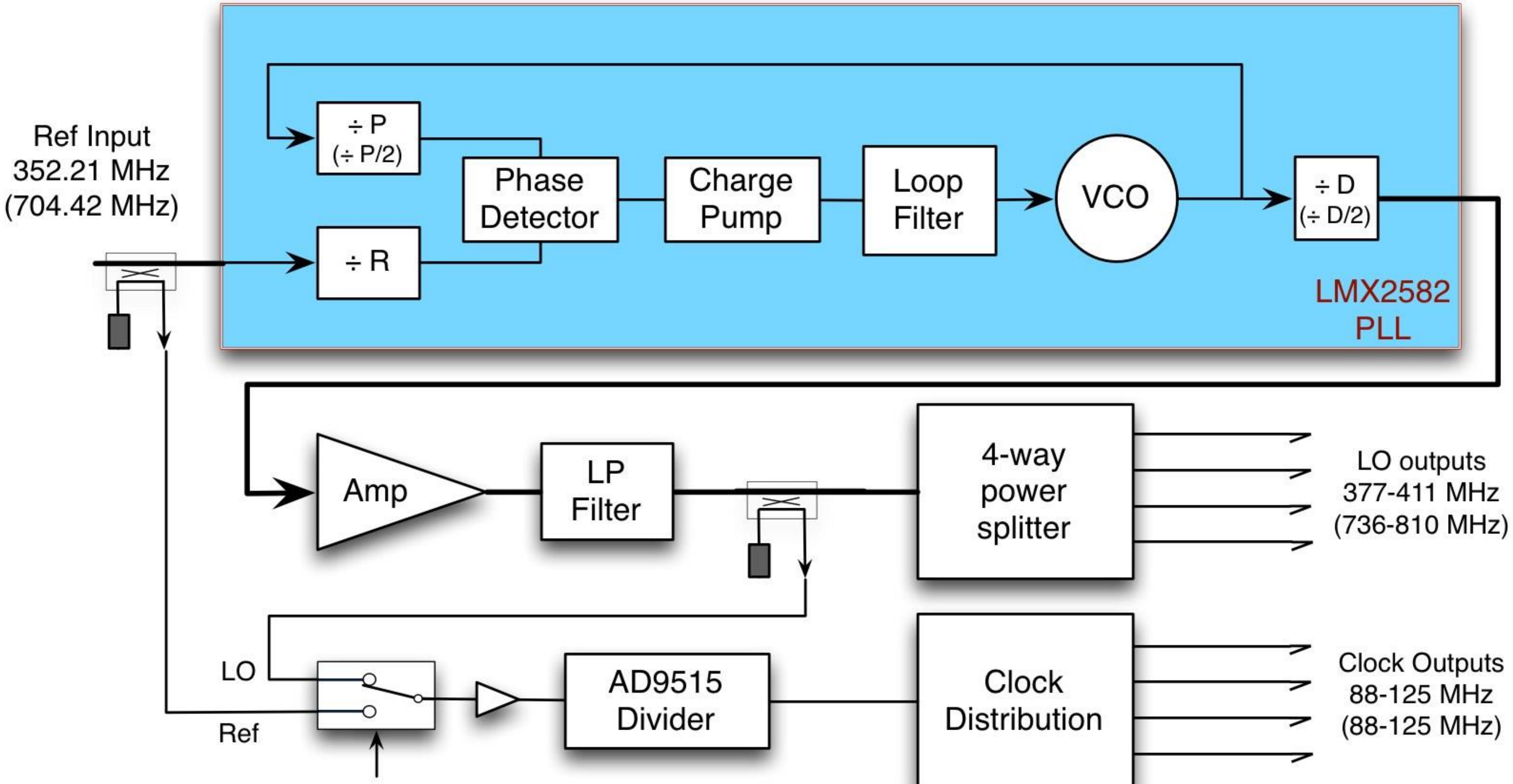
   $\Rightarrow f_{LO} = \frac{N+1}{N} f_{REF}$

2. $f_{CK} = \frac{1}{M} f_{LO}$

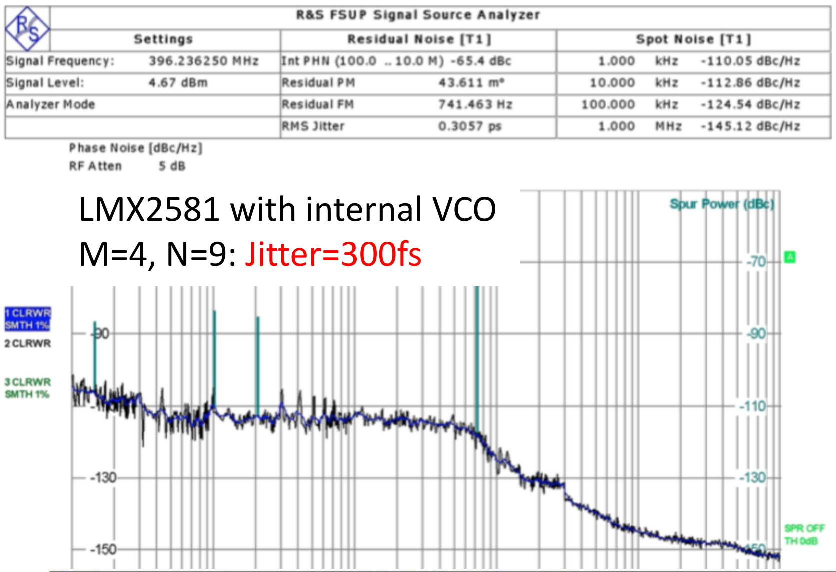
   $\Rightarrow f_{LO} = \frac{N}{N-1} f_{REF}$

Local Oscillator

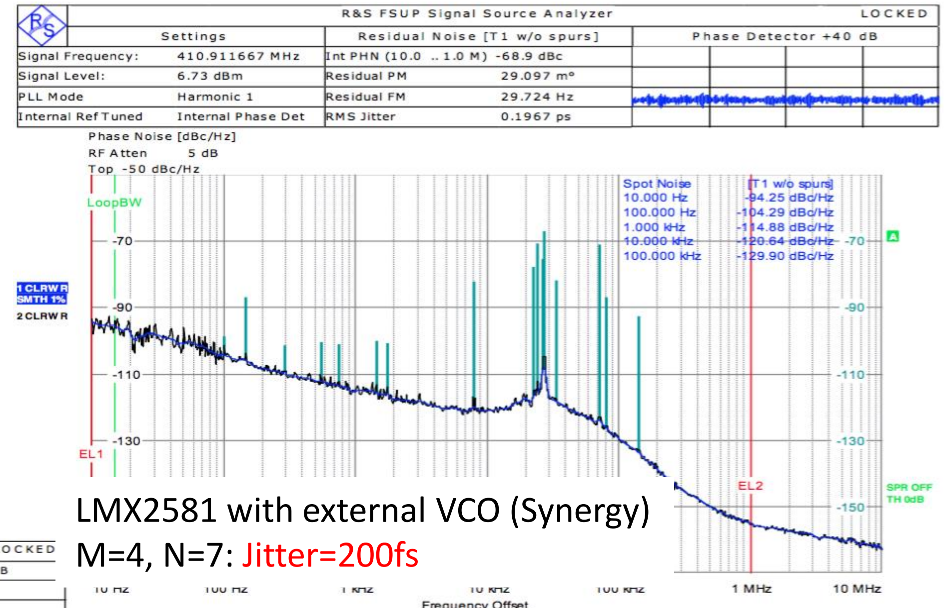
Local oscillator tests and validation in collaboration with Santander university



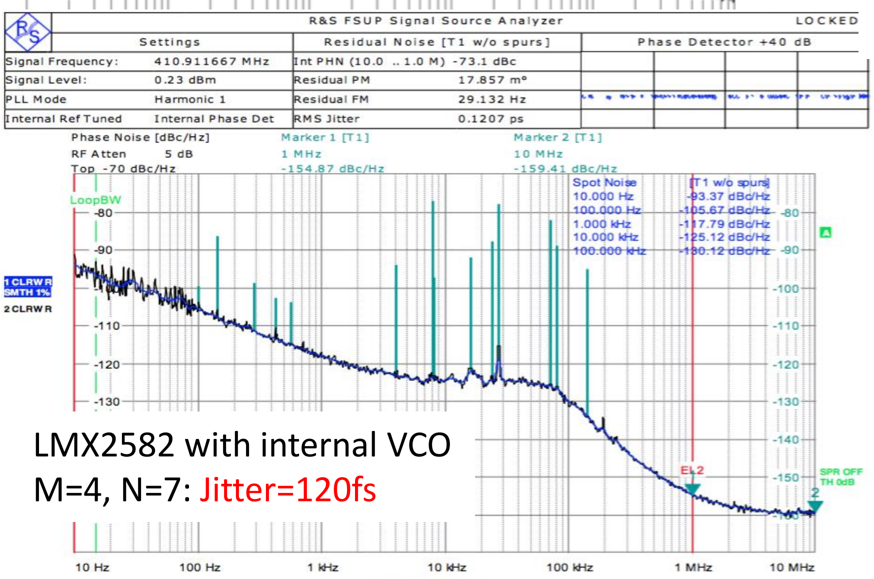
Local Oscillator



LMX2581 with internal VCO
M=4, N=9: Jitter=300fs



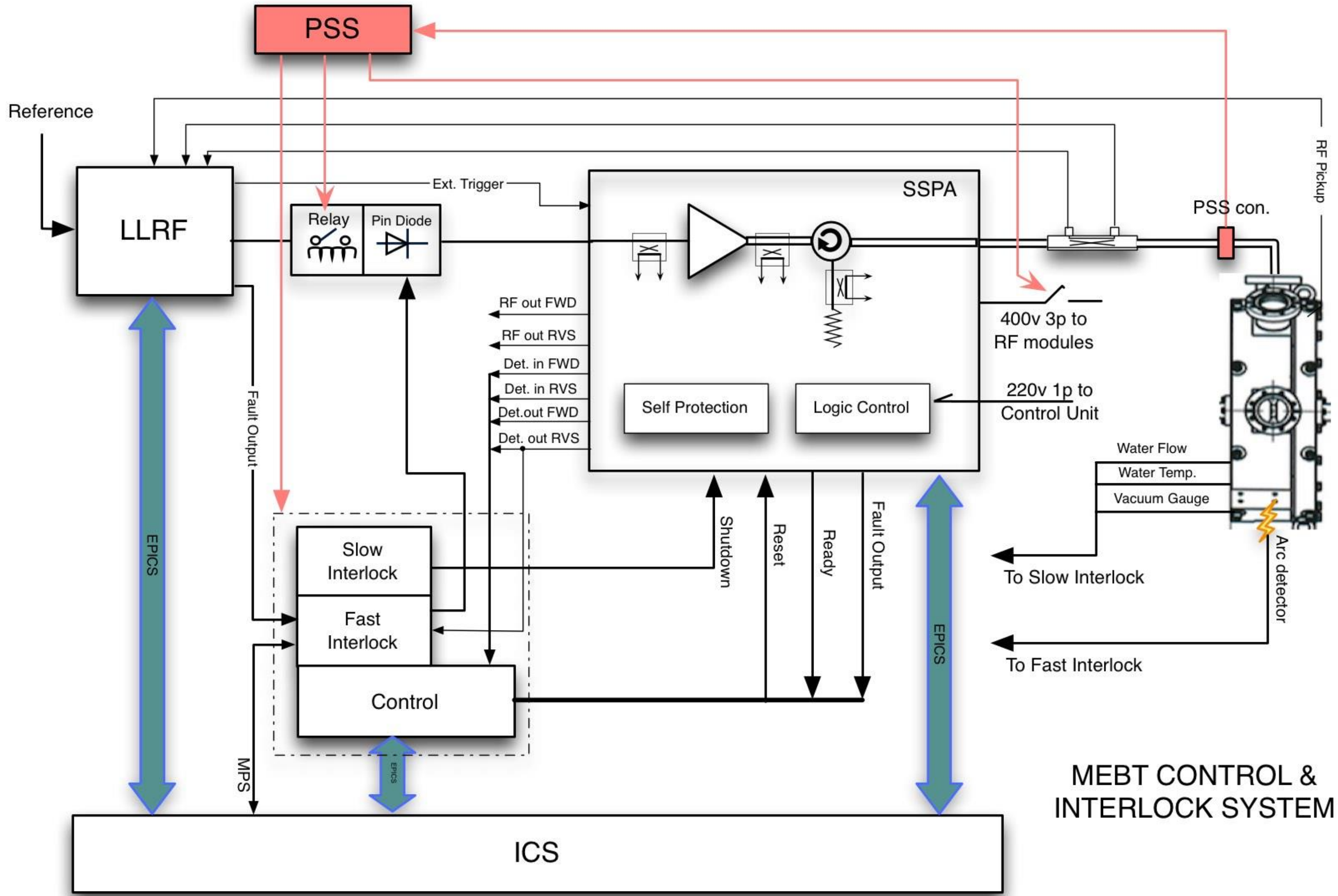
LMX2581 with external VCO (Synergy)
M=4, N=7: Jitter=200fs



LMX2582 with internal VCO
M=4, N=7: Jitter=120fs

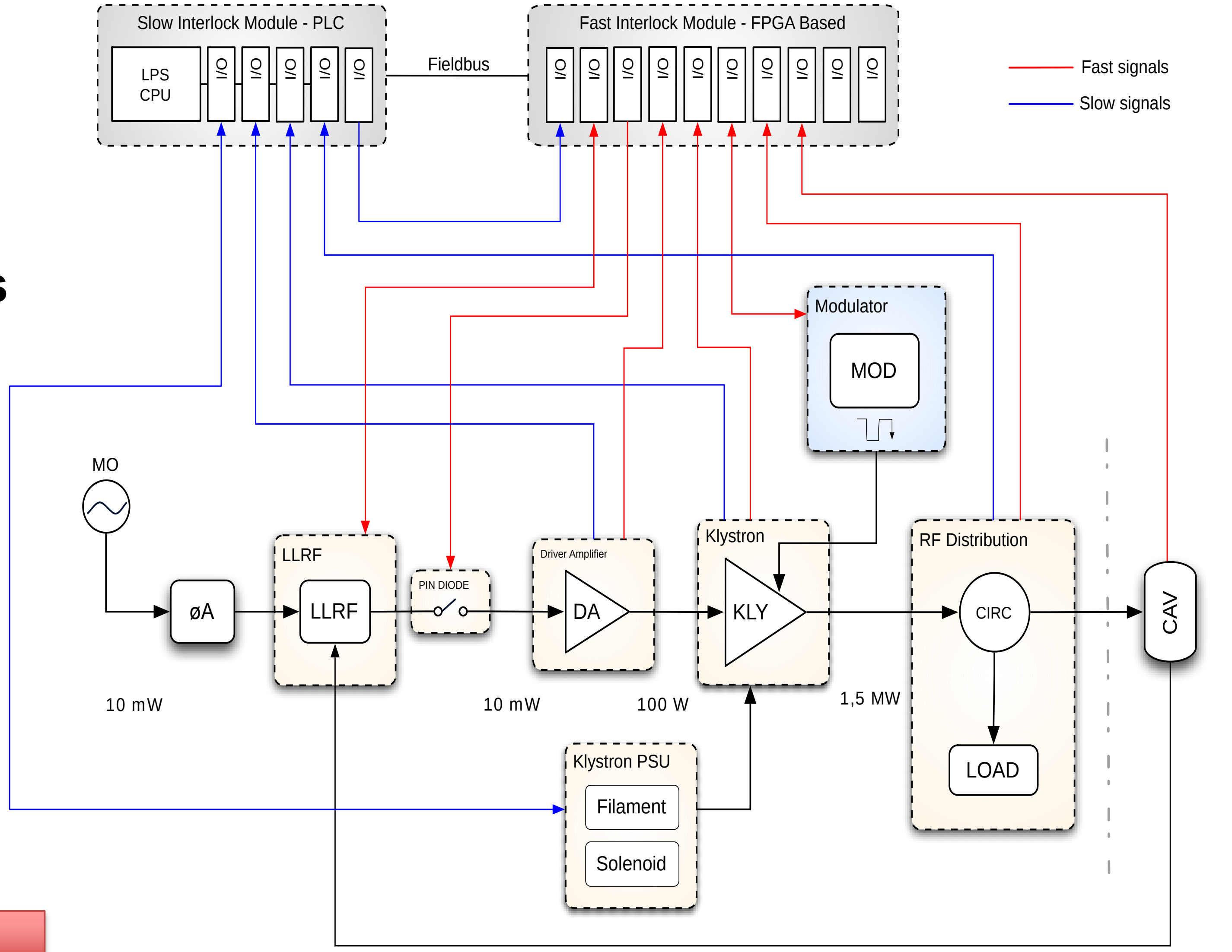
LMX2582

MEBT RF Interlock Diagram



RFQ and DTL RF interlocks

- **FIM**: < **10μs**
- **SIM**: < **50ms**



Courtesy of ESS

RF Interlocks Hardware

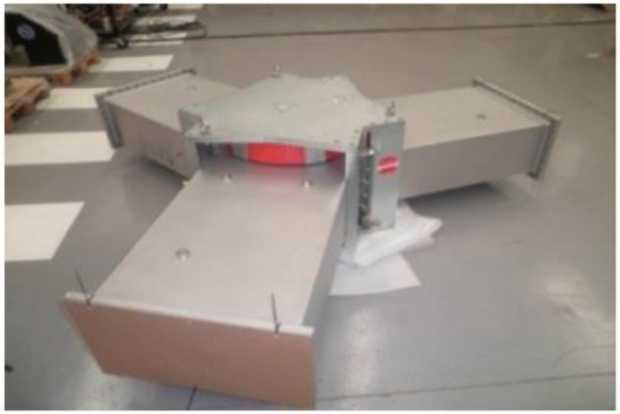
	ESS-BILBAO	ESS ERIC	
	RF Transmitter System	PROTOTYPE	SOLUTION
Slow Interlock	**PLC** (Schneider Electric)	**PLC** (Siemens) ▪ S7-1500 ▪ S7-300/400	**PLC** (Siemens) ▪ S7-1500
Fast interlock	Dedicated **PCB**s (in-house developed)	▪ **VME** (IOxOS) ▪ **cRIO**-9066	**µTCA** (IOxOS)
Control Layer (Machine State)	**cRIO**-9024 (NI) LabVIEW 2014	**PLC** (Siemens)	**PLC** (Siemens)

RF Distribution System

- Transmission lines: EIA 1-5/8” for Buncher cavities and WR2300 waveguides Full Height (FH) and Half Height (HH) for RFQ and DTL

- Circulators and Loads from AFT and Ferrite are under test and validation

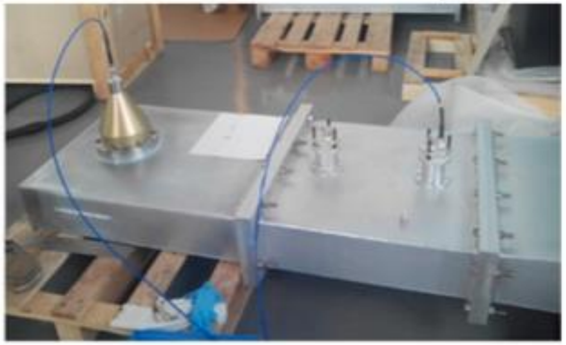
AFT: Water temp. control



Ferrite: Pfwd and Prev control

Transmission line components

- In-house Designs:
  - Straight sections
  - Dual directional couplers
  - FH to HH tapers
  - Power splitters: Magic T and 3dB hybrid coupler
  - WR2300 to Coax transition
  - Flexible waveguides




Thank you