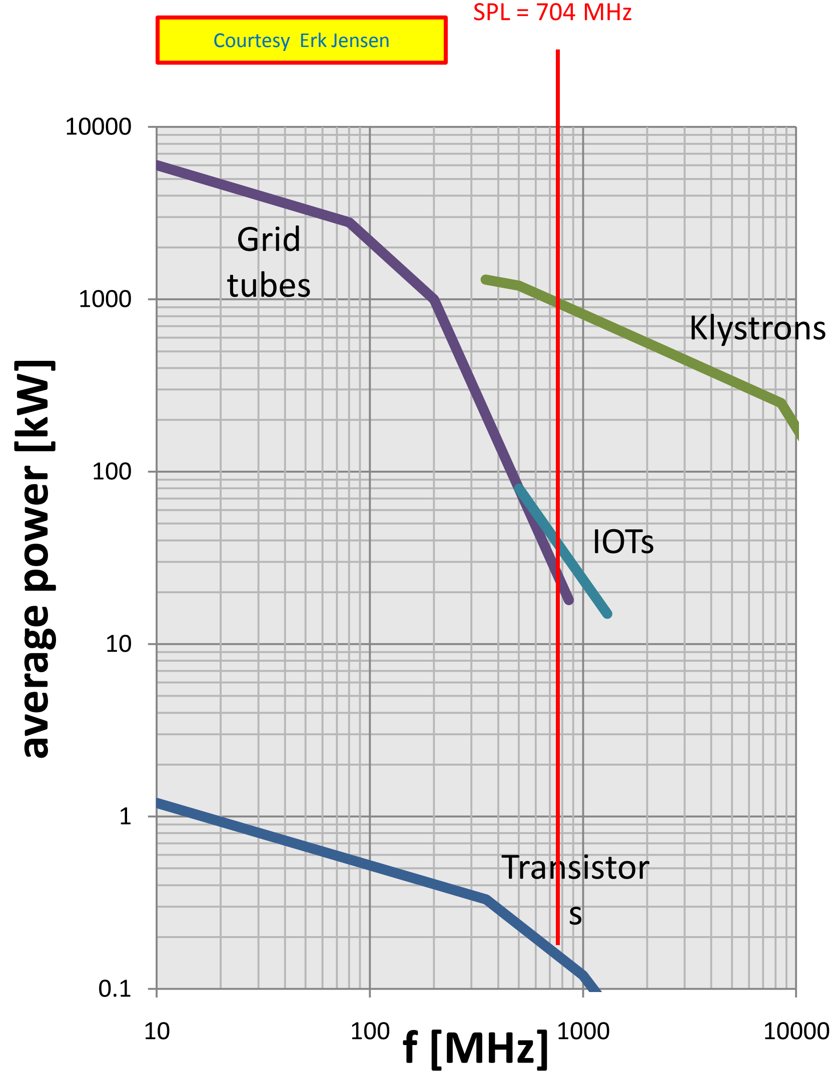
Summary

Working Group 1

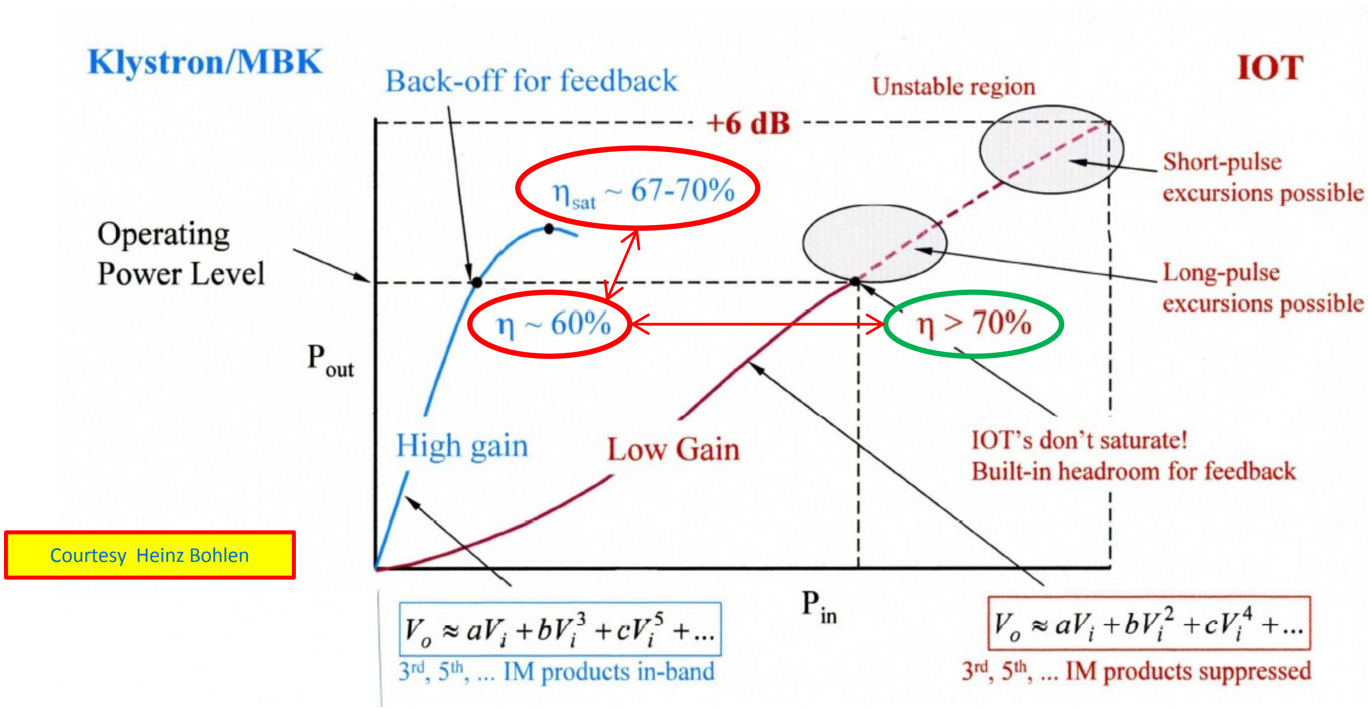
E. Ciapala

E. Montesinos

- Klystrons:
  - One klystron per two cavities
  - One klystron per cavity
- IOTs:
  - One IOT per cavity
  - Multiple IOTs combined per cavity
- Solid State Amplifiers (SSA)
- Magnetron



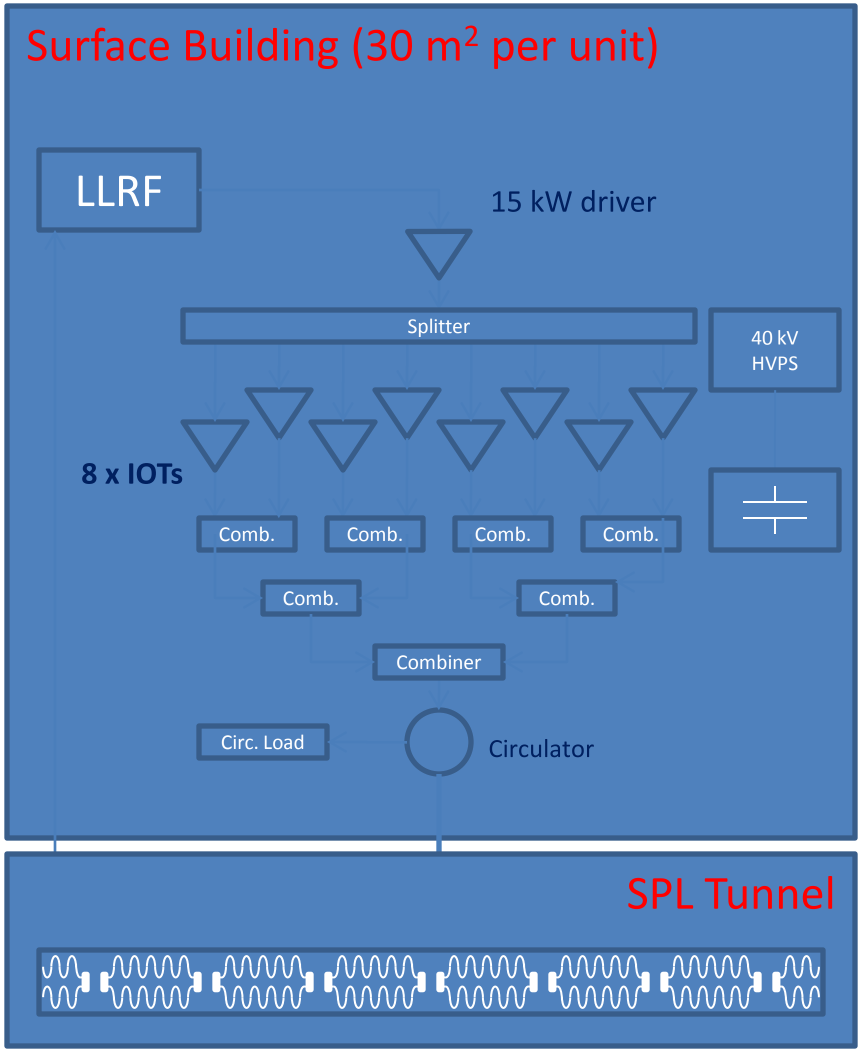
Alternative : IOTs



- ↗ **IOTs do NOT saturate** -> margin for LLRF already included !
- ↗ **No pulsed modulator needed** -> pulses via RF drive
- ↗ pulse excursions possible
- ↗ **Better efficiency** than klystron at operating point

- ↘ Less gain
- ↘ Lower peak power

8 x single beam IOTs



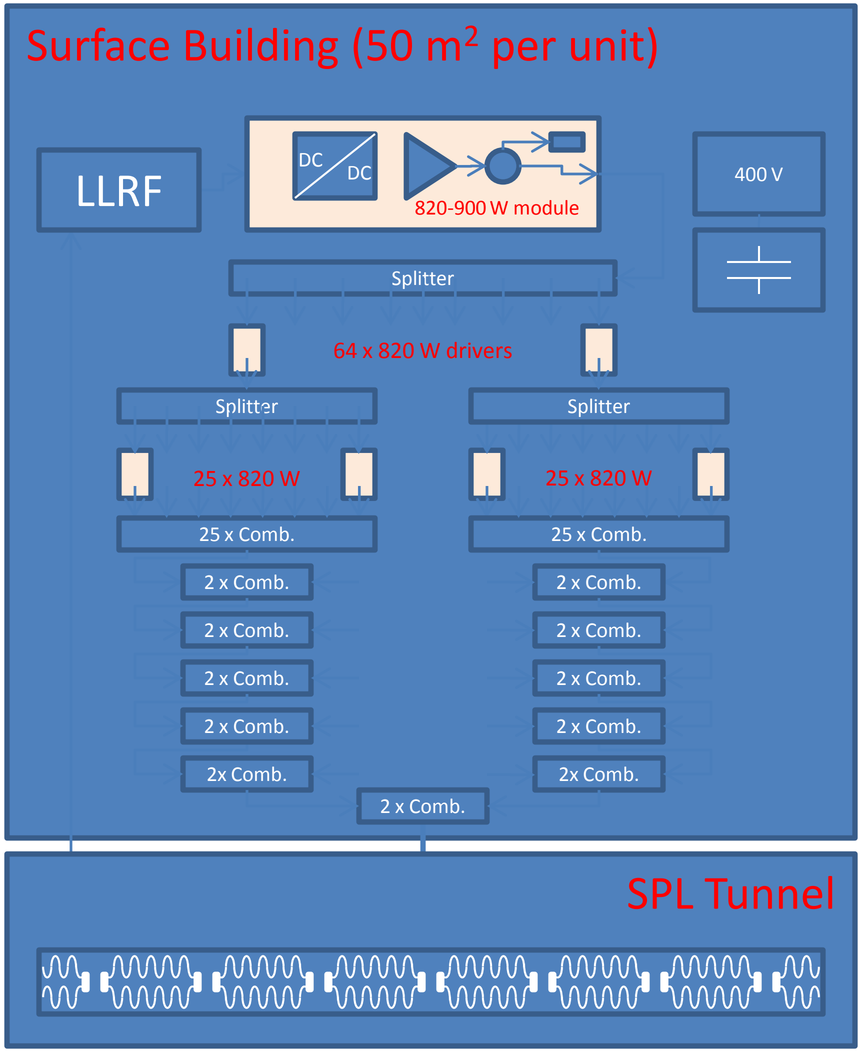
- ↗ Quasi 'off the shelf' IOT products
- ↗ Typical DC voltage range 40 kV
- ↗ Pulses via RF drive
- ↗ Easiest for control, individual LLRF per cavity

- ↘ **8 x 184 + 4 x 62 = 1720 IOTs**
- ↘ Production capability of such an item would be of ~ 150 per year per supplier
- ↘ It would then required ~ **12 years production**, even with three suppliers -> 4 years full production !

Total power from IOT, $\eta_{RF\ dist.}$ = 91 %		**160 kW**
Combiners	+8.7 dB	155 kW
Circulator	- 0.1 dB	1'125 kW
Power to Cavity Input		**1'100 kW**

Total power from IOT, $\eta_{RF\ dist.}$ = 93 %		**160 kW**
Combiners	+5.8 dB	160 kW
Circulator	-0.1 dB	615 kW
Power to Cavity Input		**600 kW**

Solid State Amplifier (SSA)



- Mandatory principle for reliability, module with:
  - Individual circulator
  - Individual DC/DC converter
  - Long life DC capacitors
- Foreseen reliable power unit = 1 kW
  - (perhaps 2 kW within coming years ?)
- 1665 x 184 + 833 x 62 = 358’006 single modules

- ↗ Lifetime > 20 years with less than 1% faulty module per year:
  - ↗↘ turnover of ~ 3’500 modules per year
- ↗ No HV needed (↘ but high current !)
- ↗ Gain = 20 dB
- ↗ Single low level per cavity

↘ Total surface needed: ~ 11’000 m²

Total power from SSA (x 1600), $\eta_{RF\ dist.}$ = 85 %		**820 W**
Combiners	+31.3 dB	815 W
Power to Cavity Input		**1’100 kW**

Total power from SSA (x 800), $\eta_{RF\ dist.}$ = 87 %		**900 W**
Combiners	+28.4 dB	870 W
Power to Cavity Input		**600 kW**

Based on very tentative data

HP-SPL 40 mA : 0.78 ms / 50 Hz (cav #246 : 1.1 MW max)	½ 3.4 MW Klystron	1.6 MW klystron	1.125 MW MB-IOT	2 x 600 kW MB IOTs	8 x 160 kW IOT	1665 x 820 W SSA
Total	546	499	459	550	803	1084
Risk to fail	Medium	Low	High	High	Low	Low

LLRF and Layout
Wolfgang Hofle
Outline

Motivation for LLRF simulation

RF layout

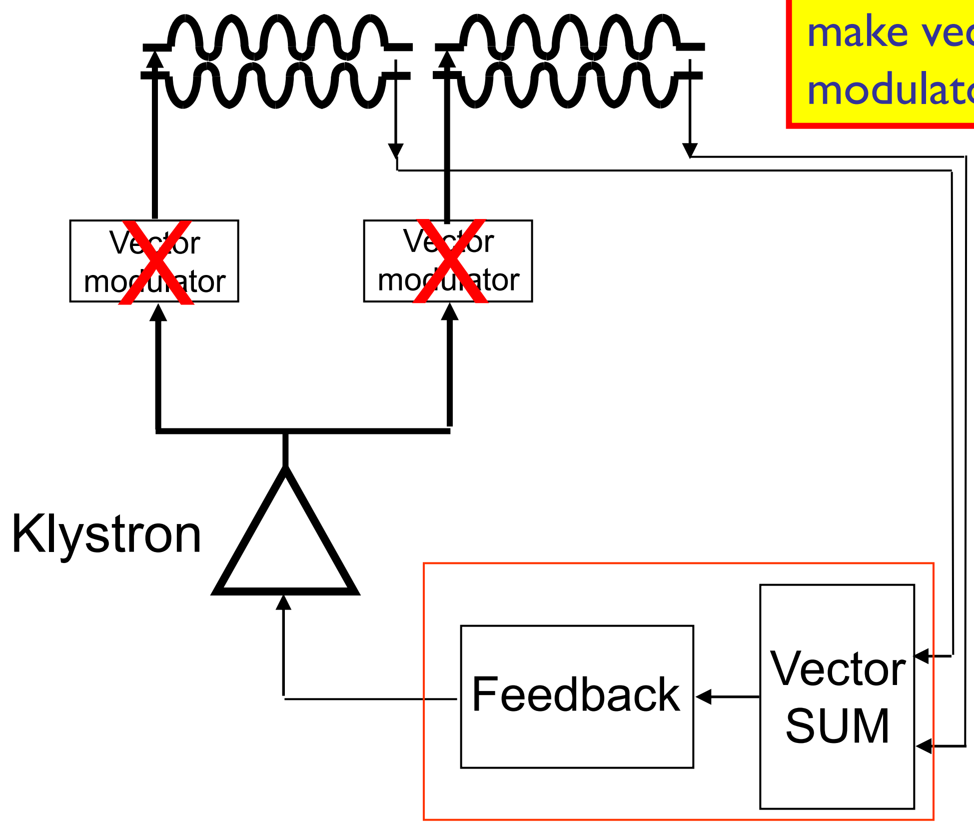
Update on the simulations (→ M. Hernandez Flano)

Recent results from tests with piezo compensation at CEA Saclay test stand

Proposal for full LLRF hardware for tests at CEA Saclay

Conclusions

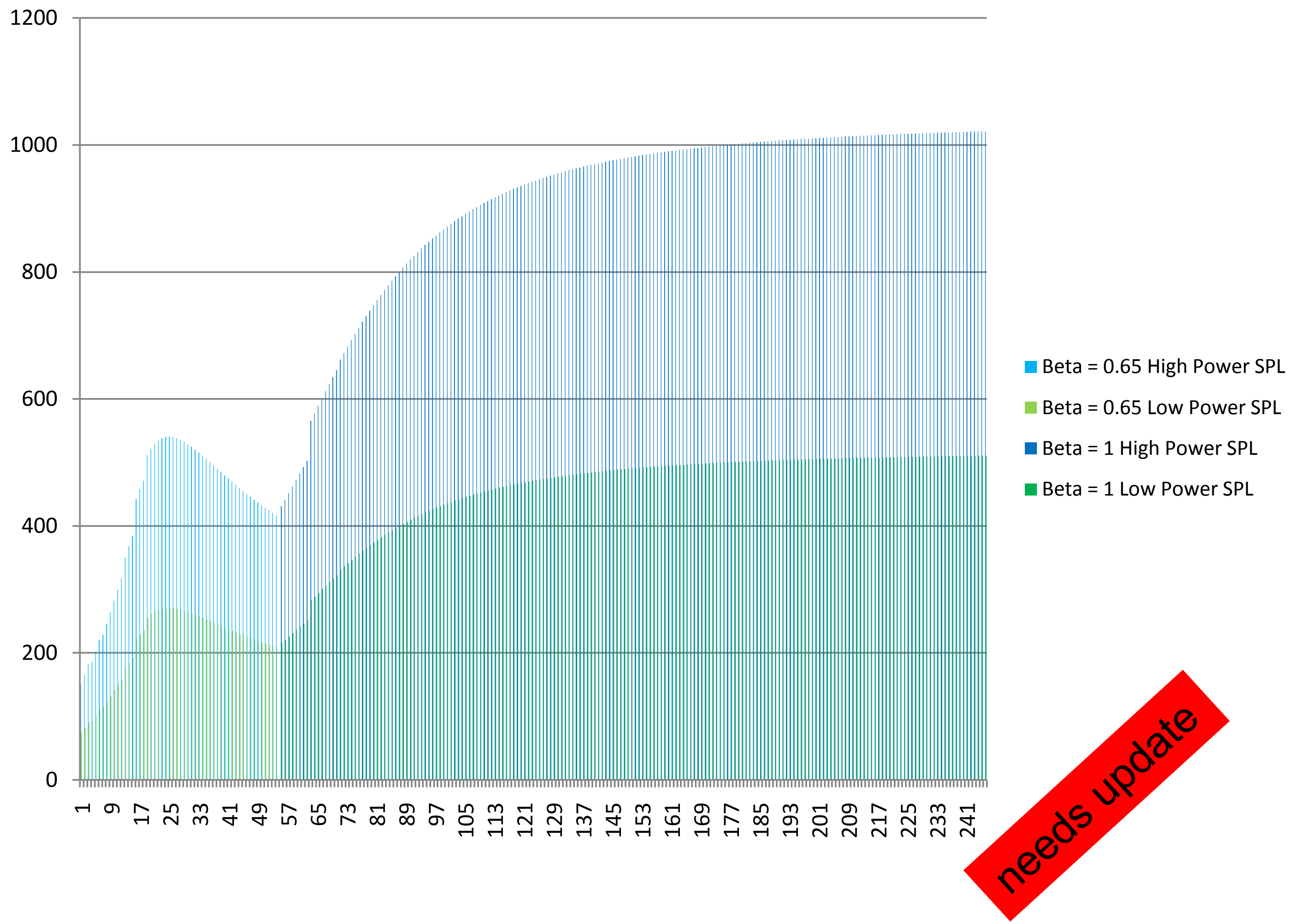
Layout with 2 cavities per klystron



piezo tuner crucial to make vector modulator obsolete

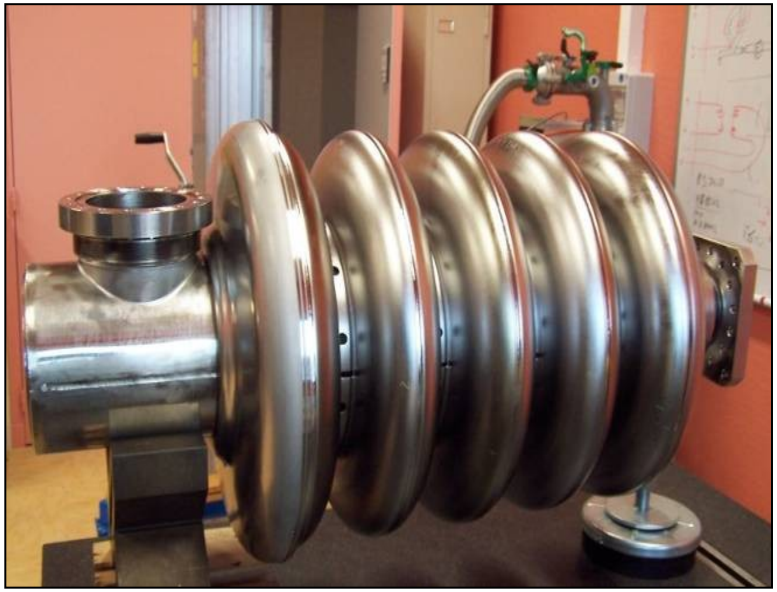
Simulation program developed for LLRF simulations, user interface for 1, 2 and 4 cavities per klystron, for an update see presentation by M. Hernandez Flano

Optimization along Linac (Q_{ext}), filling time to minimize (peak & installed) power ?

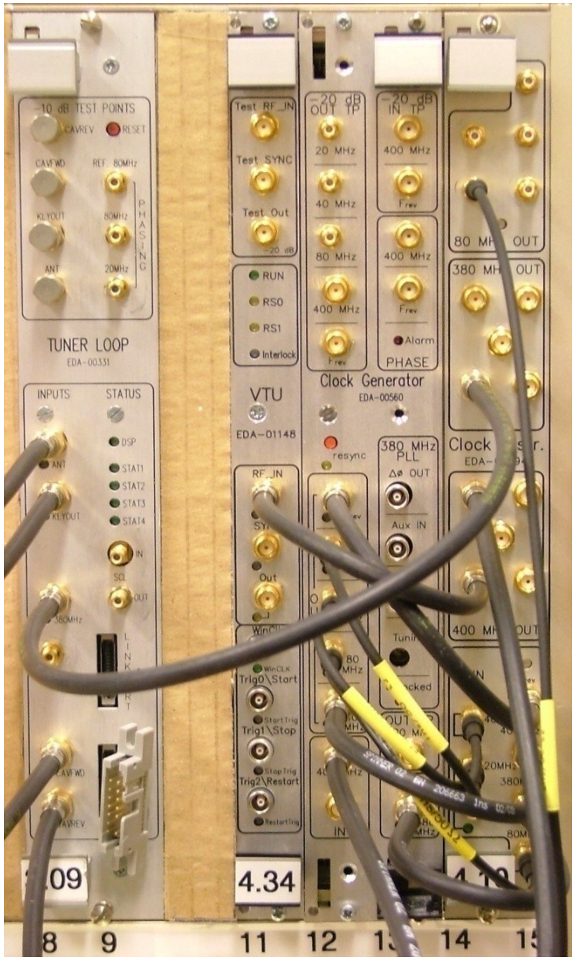


CEA cavity tested and characterized incl. piezo tuner

Frequency [MHz]	704.4
Epk/Eacc	3.36
Bpk/Eacc [mT/(MV/m)]	5.59
r/Q [Ω]	173
G [Ω]	161
Q_0 @ 2K Rs=8 nΩ	2 10^{10}
Optimal β	0.52
Geometrical β	0.47
Total length [mm]	832
Cavity stiffness [kN/mm]	2.25
Tuning sensitivity Δf/Δl [kHz/mm]	295
K_L @ k_{ext} = 30 kN/mm [Hz/(MV/m)²]	-3.9
Δf @ 12 MV/m, k_{ext} = 30kN/mm [Hz]	-560
K_L with fixed ends	-2.7
K_L with free ends	-20.3



Measurement set-up for cavity tuner characterization in pulsed mode



modified LHC hardware:
four channels analog down conversion to IF

$f_{RF} = 704.4$ MHz

$f_{LO} = (39/40)\ f_{RF} = 686.79$ MHz

$f_{IF} = f_{RF} - f_{LO} = 17.61$ MHz

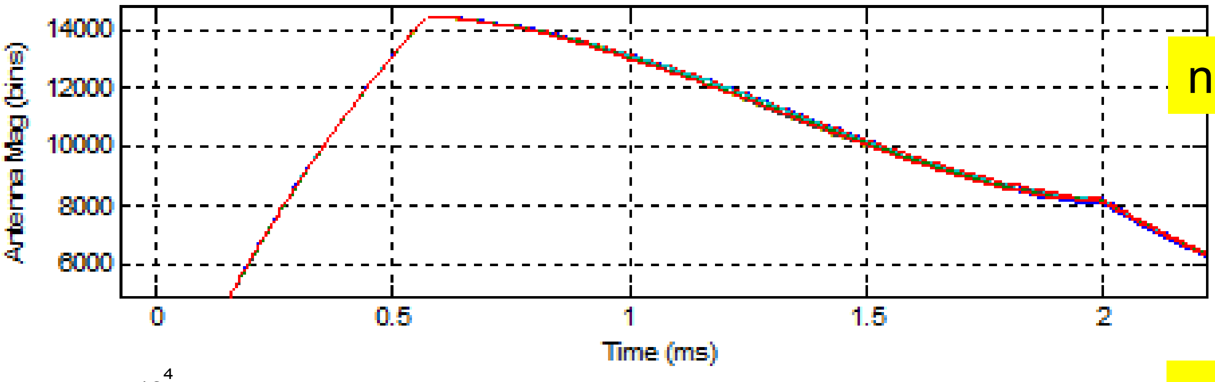
digital IQ demodulation with
sampling at $4xf_{IF} = 70.44$ MHz

rate of (I,Q) samples: 17.61 MS/s

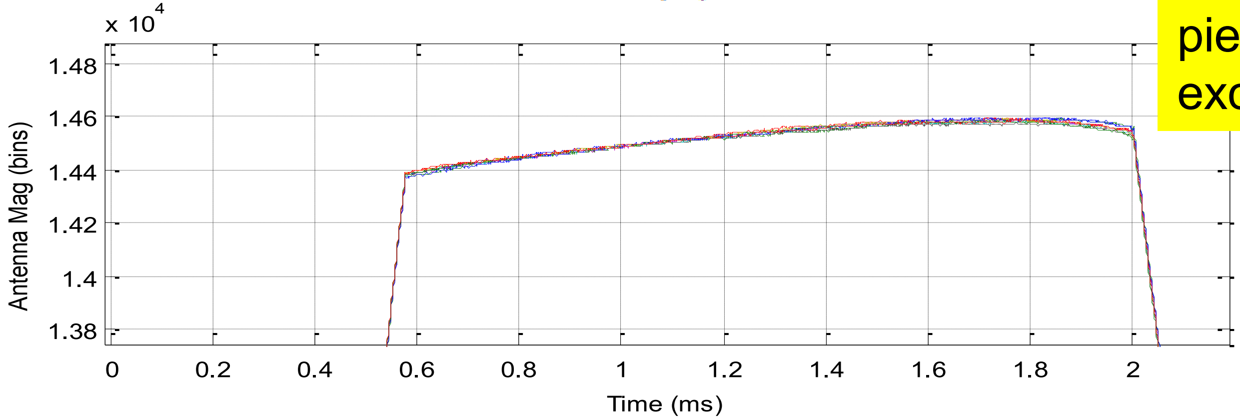
actual bandwidth lower and
depending on desired precision

Next steps → evolution to full LLRF system
with RF feedback

Field flatness with and without piezo compensation (open loop → no RF feedback) acquired with CERN system installed at CEA Saclay



no piezo

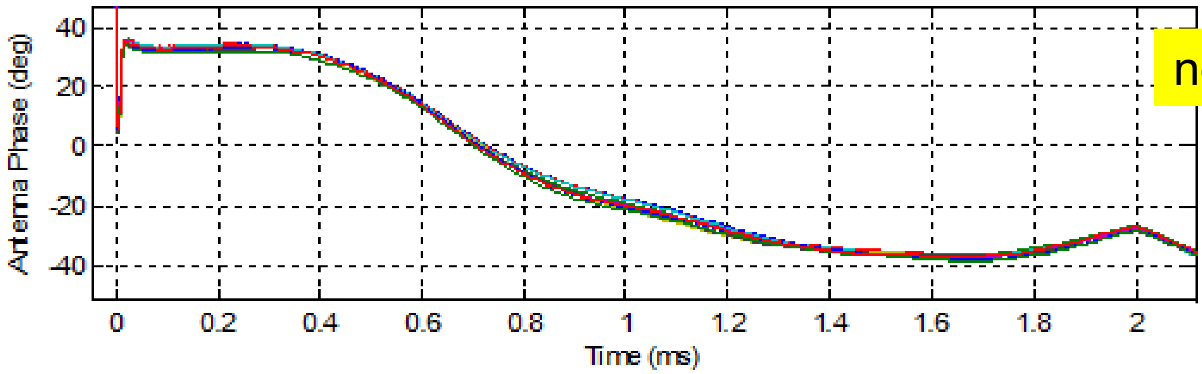


piezo excited

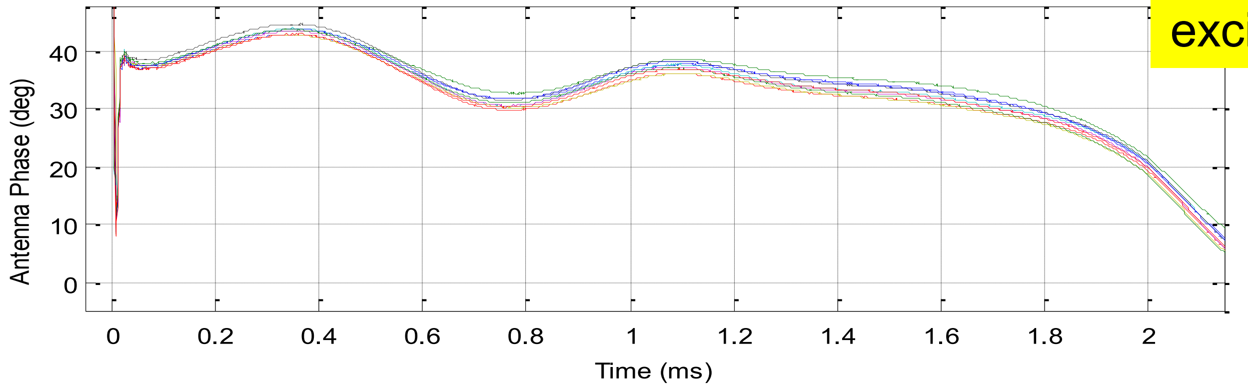
+/- 0.7 % field flatness In amplitude achieved by using piezos !

use of piezo minimizes additional RF power needed to further improve the field flatness to the design target of +/- 0.5 %

Field flatness for phase, with and without piezo compensation (open loop → no RF feedback)



no piezo



piezo excited

+/- 8 degrees flatness In phase, achieved by only using piezo ! Needs RF feedback to achieve design goal of +/- 0.5 degrees

Conclusions

new parameters need to be taken into account (shorter pulses of low/high current SPL)

move towards considering the whole accelerator with the different beam β's

parameter variations will have a large impact on required power overhead and performance

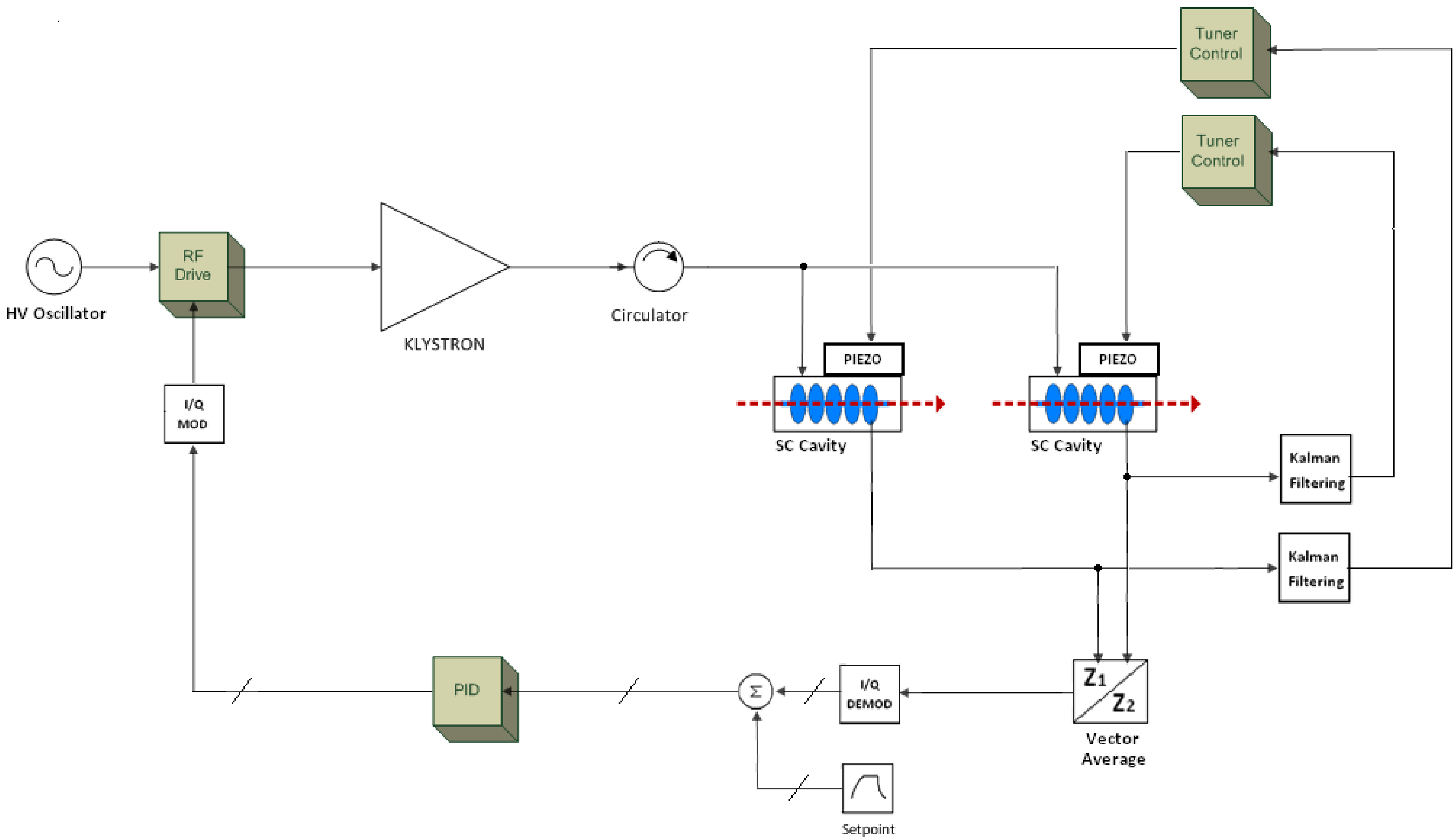
test stands indispensible for the development of the LLRF systems, plans exist to build a test stand at CERN for 704 MHz, currently collaboration with CEA Saclay

results with piezo tuner demonstrate its capabilities to keep cavity on tune during the beam passage, essential to minimize the power requirements

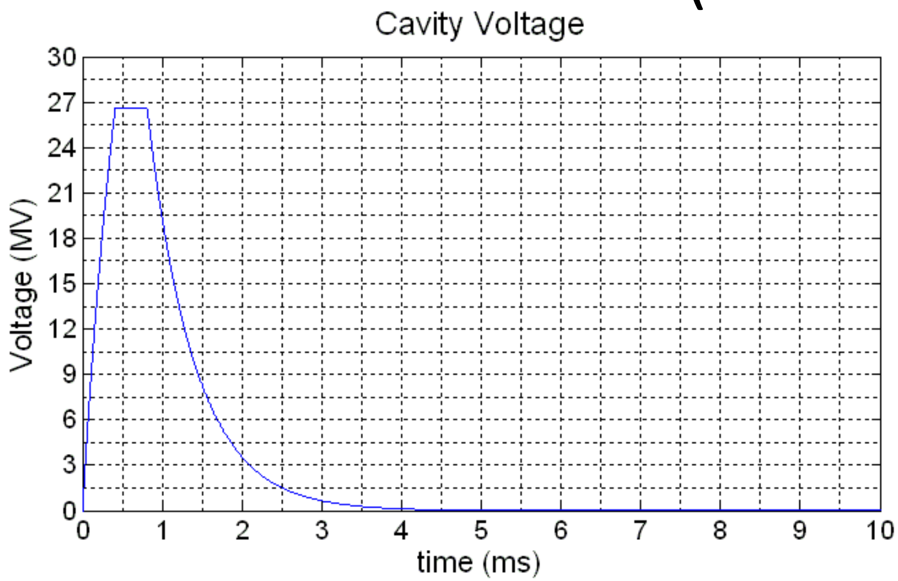
having a test stand at CERN would be very important to build up momentum at CERN in the area of LLRF developments

LLRF Simulations - Mathias Hernandez Flano

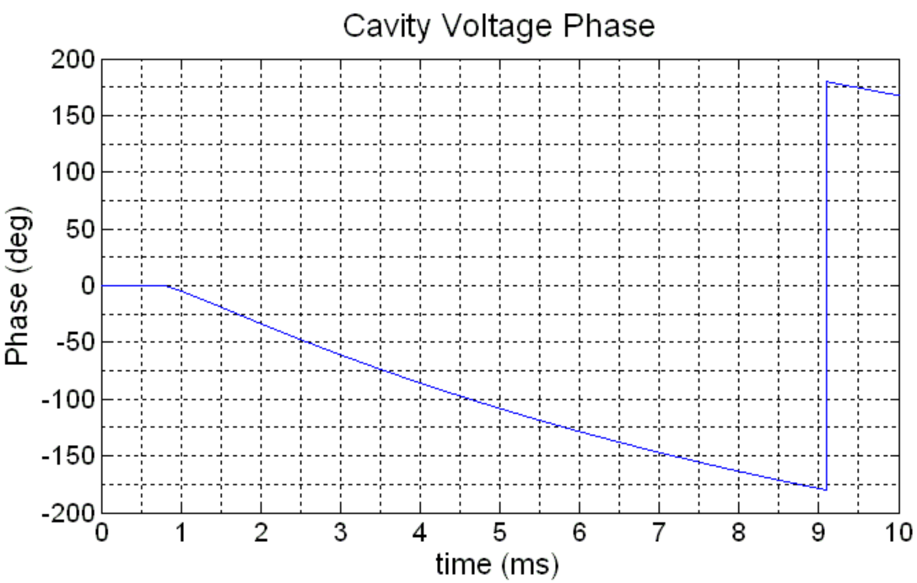
High Level Diagram for Dual Cavity + Control System



Vcav Magnitude and Phase for Dual Cavity Case (K=-1 and -0.5)

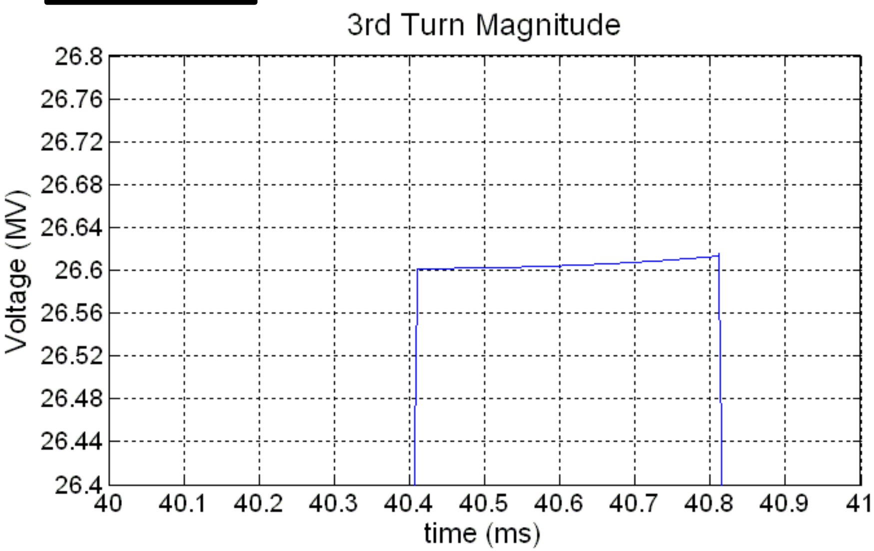


Voltage magnitude and phase of vector average

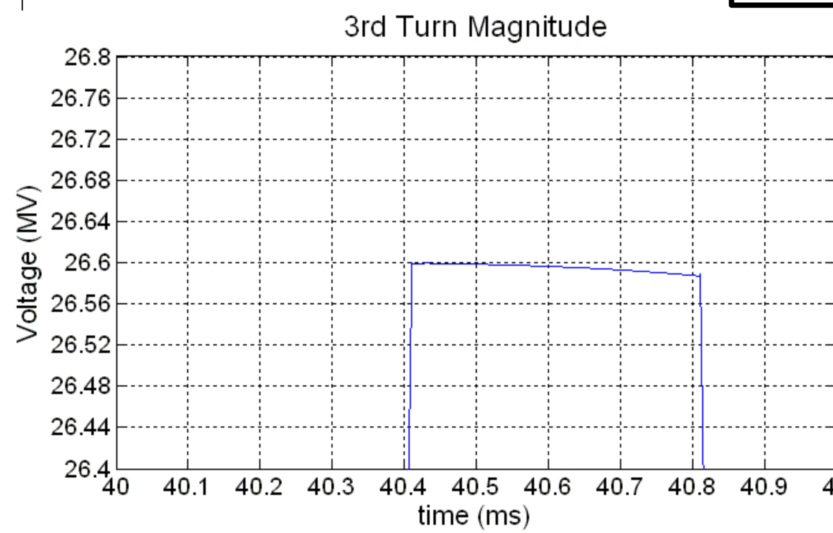


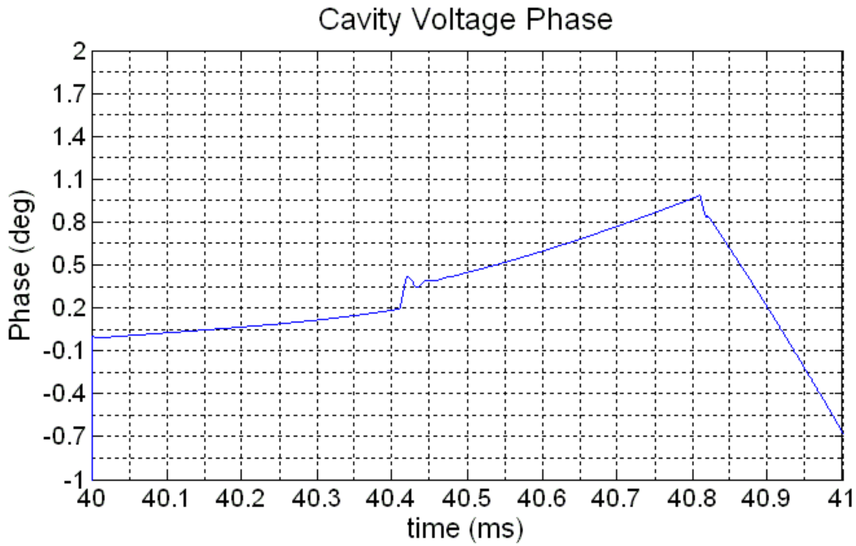
Vcav Magnitude and Phase for Dual Cavity Case (Without Piezo Feed-Forward)

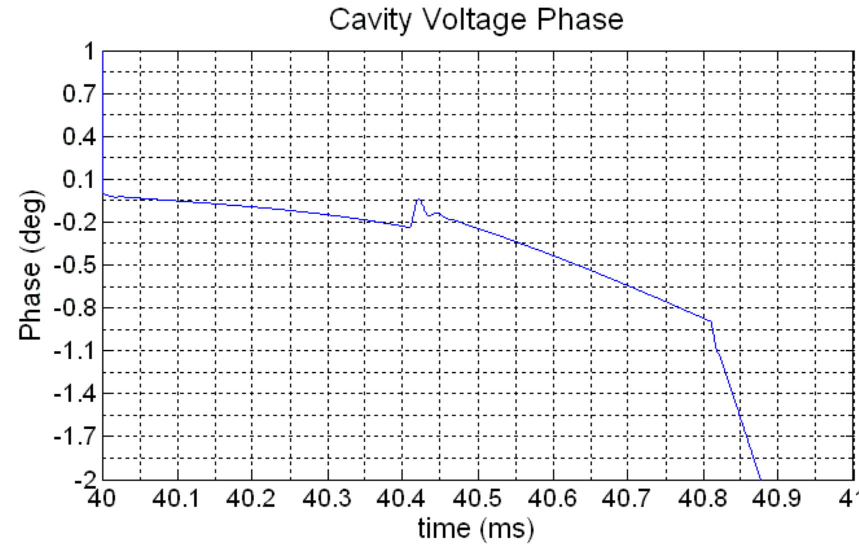
K=-0.5 $Hz/\left(\frac{MV}{m}\right)^2$



K=-1 $Hz/\left(\frac{MV}{m}\right)^2$

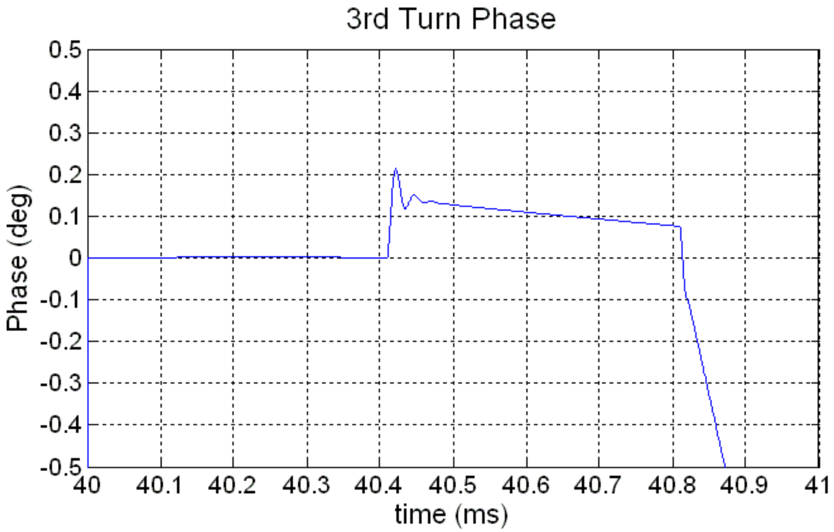




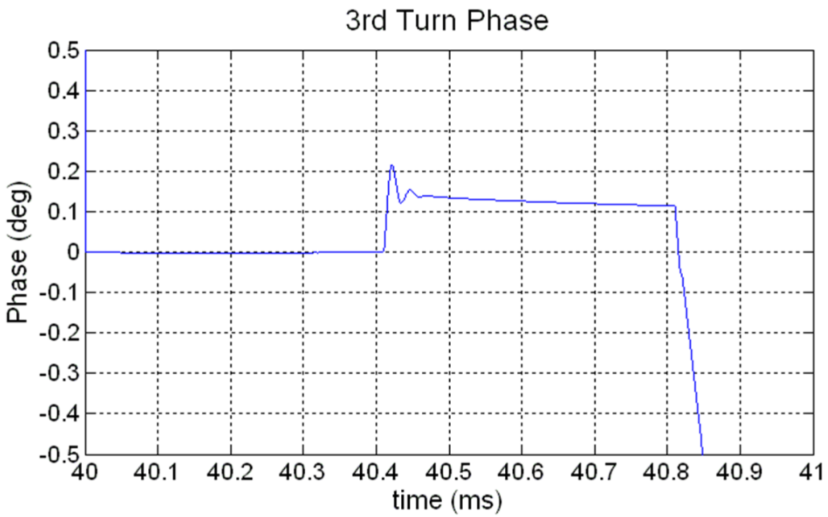


Vcav Magnitude and Phase for Dual Cavity Case (With Piezo Feed-Forward)

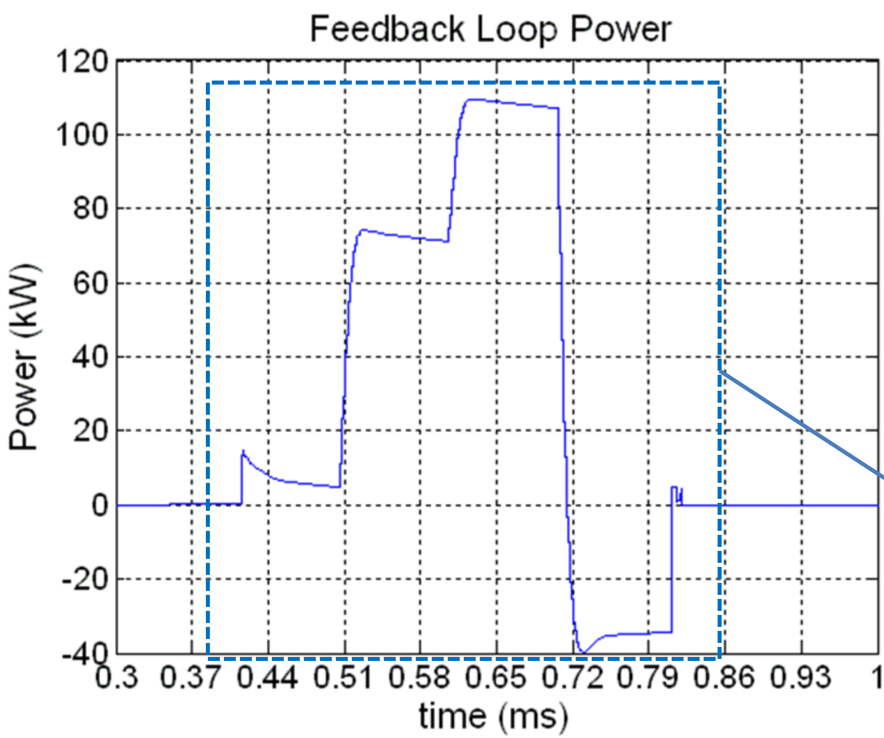
Cavity 1 (K=-1 $Hz/\left(\frac{MV}{m}\right)^2$)



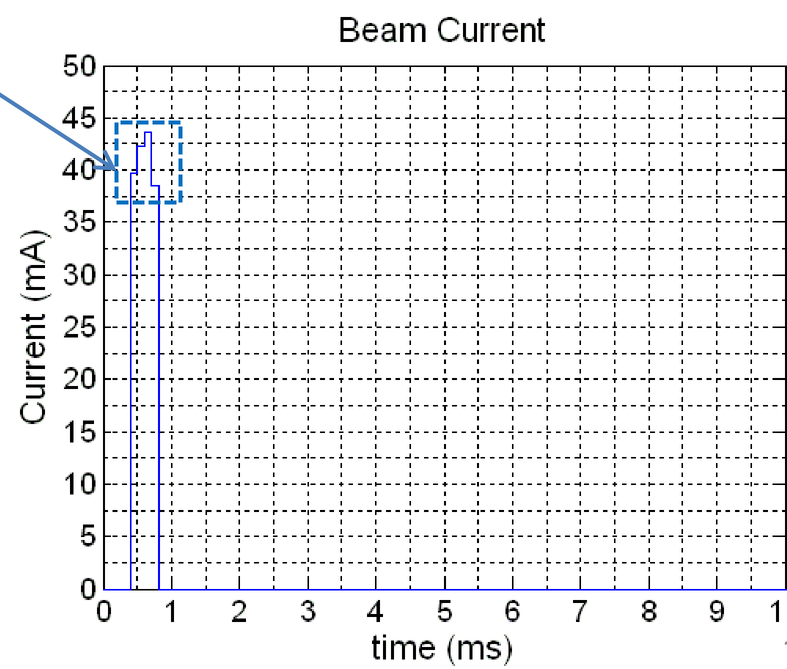
Cavity 2 (K=-0.5 $Hz/\left(\frac{MV}{m}\right)^2$)



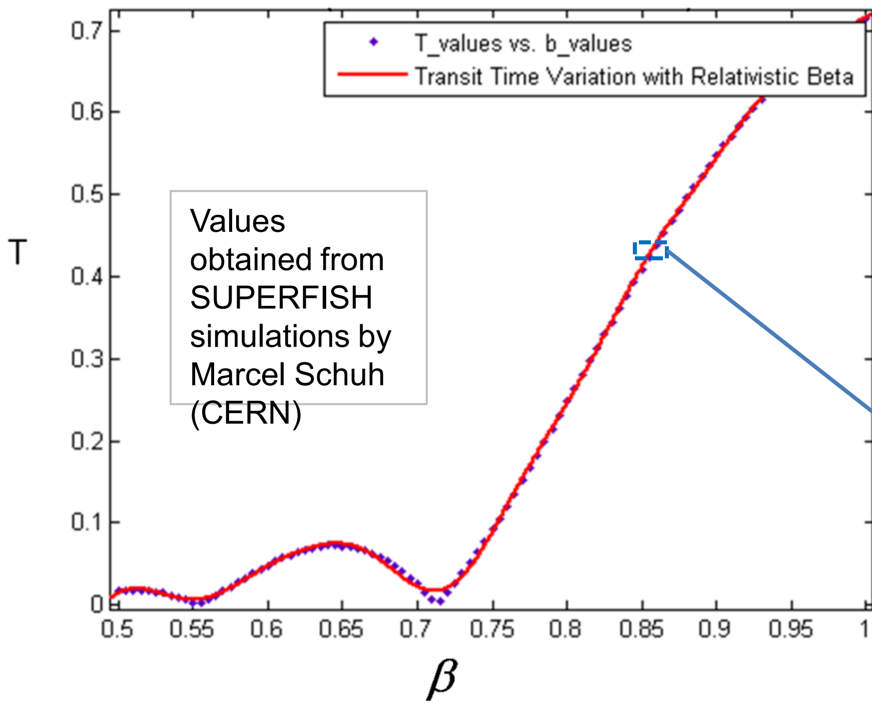
Effects of Source Beam Current Variation

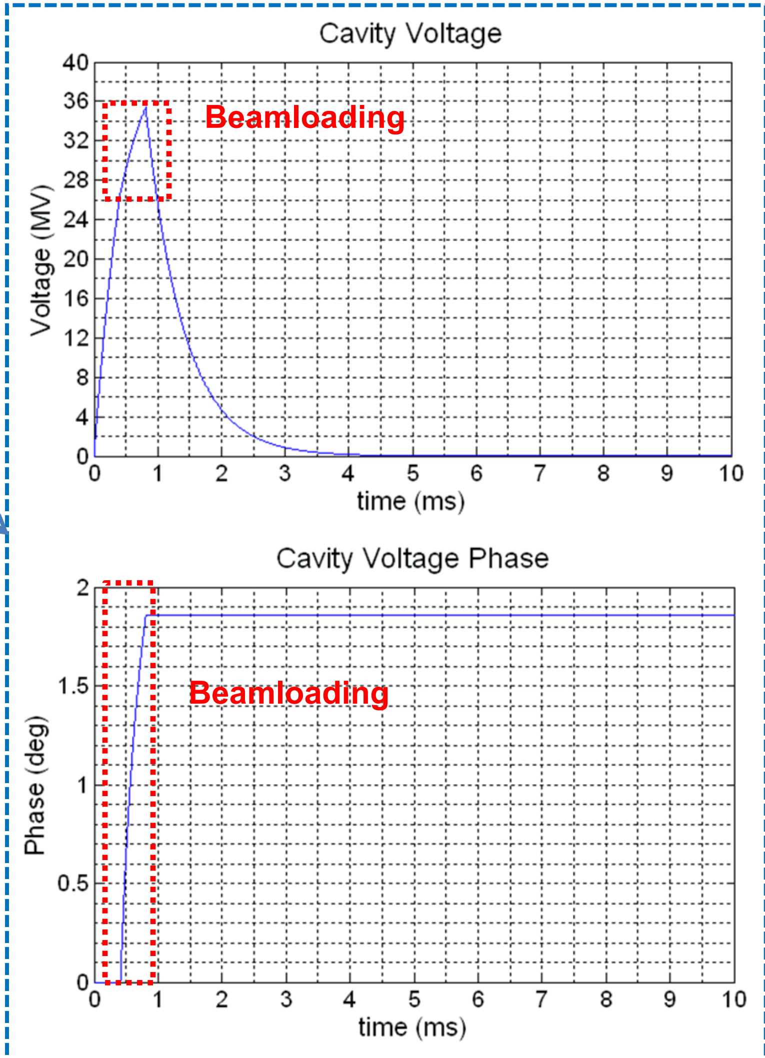


5% variation in Ib for 40mA case requires approximately 60kW of additional power.



Transit Time Factor Variation with Relativistic Beta (SPL β=1 cavities, open loop simulation)





- Weaker beam loading will result in a higher flattop equilibrium and less phase detuning of the cavity for the same generator power.

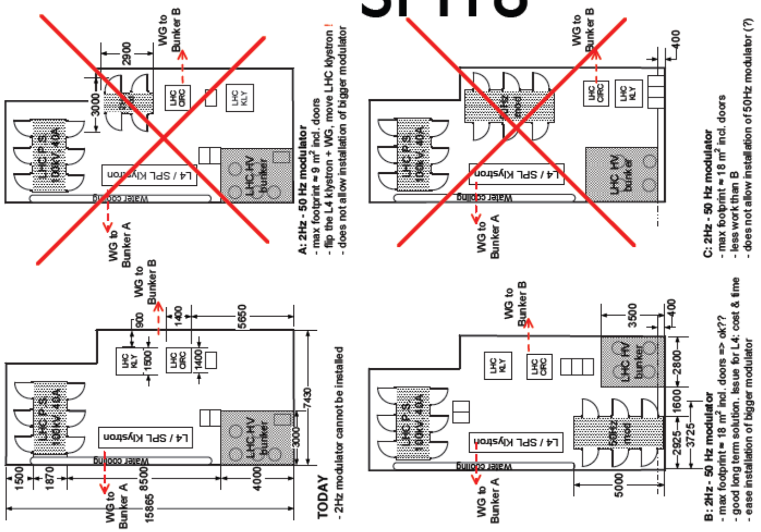
- Beta value taken from beam energy at beginning of SPL β=1 section.

Critical components

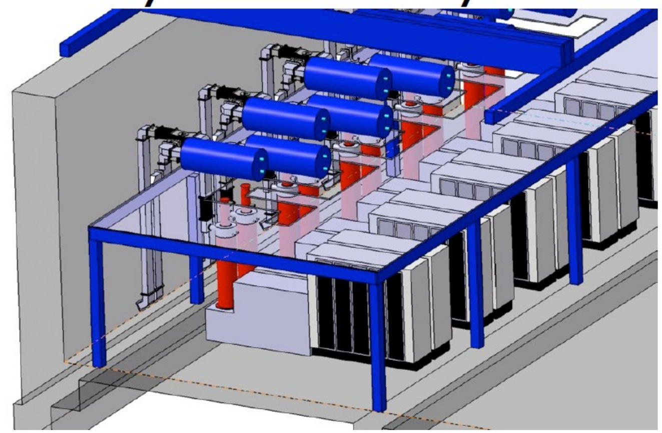
- Technology:
  - High voltage
  - Long pulses
  - High average power
  - High repetition rate
- Footprint:
  - 18 sqm in SM18
  - 1.4 m between cavity to cavity at ESS
- Time
  - Less than 24 month until installation in the SM18 test stand
  - Production capacity => multiple vendors.
  - Orders for the ESS modulators needs to be placed in 2014
- Cost
- Legal issues => do it right from the beginning.

Space Constraints !

SM18



Klystron Gallery ESS



RF power system space as much, if not more, a constraint than cavity length !

Klystron Modulators for for SM18 and ESS

ESS Modulator

Power to beam:

- Pulse repetition rate: 20 Hz
- Pulse length: 2 ms
- Peak Power: 0.9 MW

• Klystron:

- Pulse length: 2.5 ms
- Peak power: 1.5 MW

• Modulator

- Pulse length: 2.8 ms
- Peak power: 2.2 MW
- Average power: 123 kW

ESS proposed scheme

	50 Hz	20 Hz
tau_l (40 mA)	2.70E-04	2.70E-04
$P_{nominal}$	1.06E+06	1.06E+06
P_{gen}	1.10E+06	1.10E+06
HV pulse length	1.12E-03	2.80E-03
RF pulse length	8.20E-04	2.50E-03
$P_{av, modulator}$	123,200	123,200

flat top at nominal cavity field

	50 Hz	20 Hz
1 cav >V_0	0.46	2.14
1 cav >0.95*V_0	0.48	2.16
1 cav >0.90*V_0	0.51	2.19
2 cav	0.18	1.86
2 cav >0.95*V_0	0.24	1.92
2 cav >0.90*V_0	0.29	1.97
4 cav	-1.34	0.34
4 cav >0.95*V_0	-0.64	1.04
4 cav >0.90*V_0	-0.34	1.34

SPL requested scheme

	50 Hz	20 Hz
tau_l (40 mA)	2.70E-04	2.70E-04
$P_{nominal}$	1.06E+06	1.06E+06
P_{gen}	1.10E+06	1.10E+06
HV pulse length	1.80E-03	4.50E-03
RF pulse length	1.50E-03	4.20E-03
$P_{av, modulator}$	198,000	198,000

flat top at nominal cavity field

	50 Hz	20 Hz
1 cav >V_0	1.14	3.84
1 cav >0.95*V_0	1.16	3.86
1 cav >0.90*V_0	1.19	3.89
2 cav	0.86	3.56
2 cav >0.95*V_0	0.92	3.62
2 cav >0.90*V_0	0.97	3.67
4 cav	-0.66	2.04
4 cav >0.95*V_0	0.04	2.74
4 cav >0.90*V_0	0.34	3.04

SM 18 Modulator

- Repetition rate: 20 Hz and 50 Hz
- Pulse length: 4.5 ms and 1.8 ms
- Average power: 200 kW

Competitive dialog

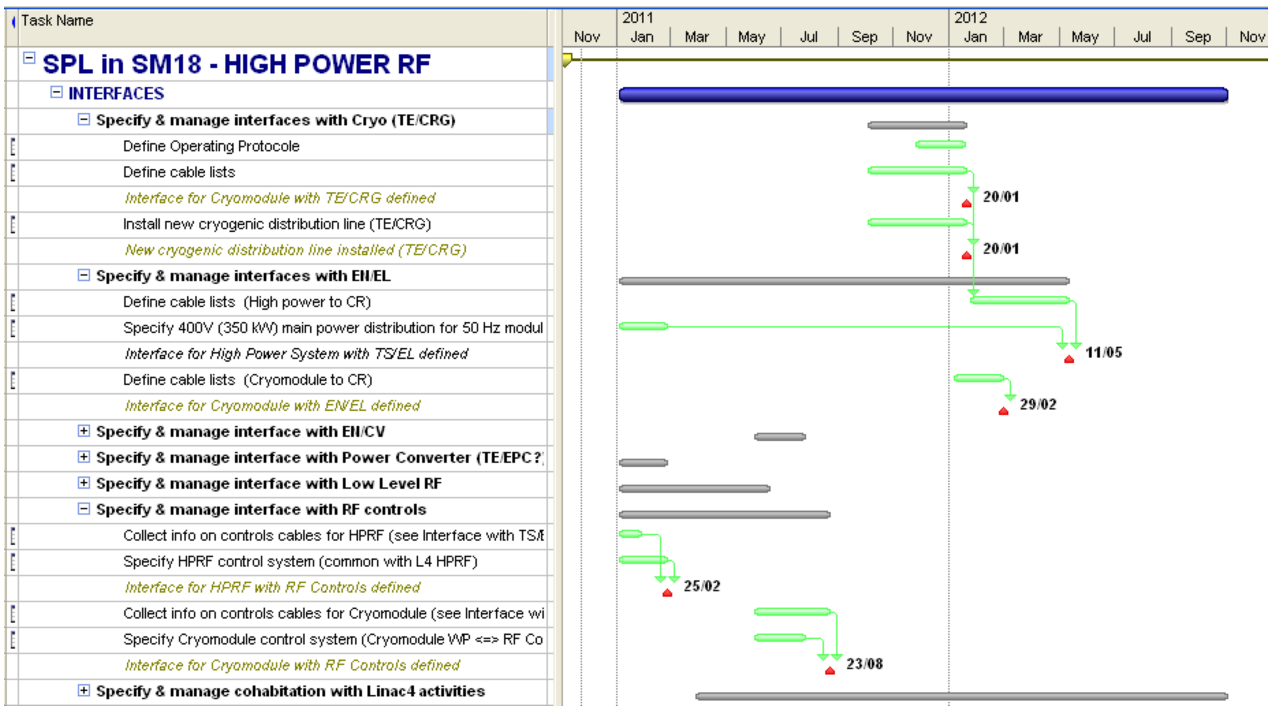
- Invite companies to tender
  - Selection criteria for companies (experience, turnover, facilities, etc...)
  - 1to 3 systems
  - Functional specification as a preliminary
    - Average power: 123 kW minimum, 180 kW maximum
    - Repetition rate: 20 Hz with 50 Hz as an option
  - Awarding criteria
    - Cost
    - Maintainability
    - Delivery times
- Select 3 companies to continue discussions with.
- After discussions, the finial specification will be written.

- Tender for 1-3 systems – 2 Suppliers ?
- 50 Hz as option for SPL
- Specs in preparation – Aim to order in 2011, for delivery October 2012

- Scope of the Work Package / Prerequisites
- Description of the work
  - Interfaces with other activities (cryogenics, electricity, water distribution,..)
  - Modulator
  - Klystron
  - RF power distribution system
  - Interlocks & controls
  - Auxiliaries
  - Installation
- Budget

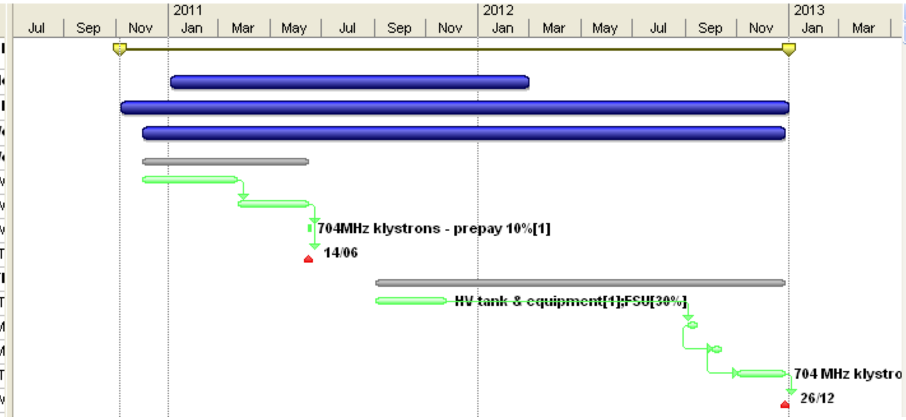
SM18 Equipment

- A Linac4 test place is now being prepared in SM18 => compatible with SPL requirements
- New helium (2K) distribution line will (might) be installed end 2011
- Need 400 V distribution line for the 50Hz modulator
- Must take into account the L4 planning in SM18 (in bunker A)



Klystrons

	Task Name	Duration
1	SPL in SM18 - HIGH POWER RF	28,1 mons
2	INTERFACES	15,15 mons
32	50 Hz MODULATOR	28,1 mons
42	704 MHz KLYSTRON	27,05 mons
43	Specify and order 704 MHz Klystron	7,05 mons
44	Define specs and send offer for tender	4 mons
45	FC & Sign contract	3 mons
46	Pay 10% of contract	1 day
47	*704 MHz klystrons ordered*	0 days
48	Test & validate 704 MHz klystrons	17,25 mons
49	Built HV tank	3 mons
50	Perform validation tests at factory	2 wks
51	Equip and install klystron on SM18 test stand	2 wks
52	Perform validation tests	2 mons
53	*704 MHz klystron tested and validated*	0 days



Option1:

1 MW 704 MHz tube based on CPI specs

- Specs ready (except HV interface to modulator)
- The tube exists. No development costs
- Specs do NOT include LLRF requirements

Option2:

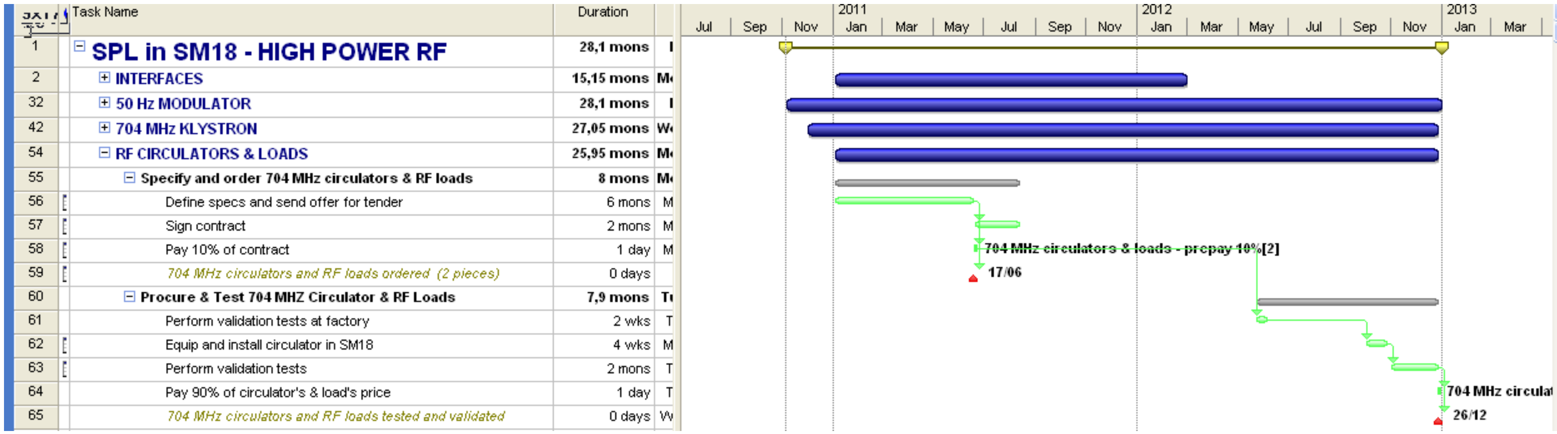
3 MW 704 MHz tube including LLRF specifications

- Allows for full SPL (ESS?) RF power system distribution validation (incl. LLRF)
- More expensive! (≈ + *1.5 MCHF)*
- *Bigger modulator !? Feasible?*

Option3:

1.5 MW 704 MHz tube – compat ible ESS – common order (off the shelf ??ESS

RF Power Distribution



Circulators and RF loads specs 80% ready

Cption1: 1 circulator and 2 RF loads

- Cheapest solution
- Impact on Qext& phase and power quality (crosstalk,…) will be studied (N. Schwerg)

Option 2: 2 circulators and 3 RF loads

- Allows for full SPL (ESS?) RF power system distribution validation
- More expensive (+ 1 circulator + 1 magic T + 2 RF loads + WG +..)

Overall Plan for SPL work

ID	Task Name	Duration	Start
1	SPL in SM18 - HIGH POWER RF	28,1 mons	Fri 05/11/10
2	INTERFACES	23,95 mons	Mon 03/01/11
44	50 Hz MODULATOR	28,1 mons	Fri 05/11/10
54	704 MHz KLYSTRON	27,05 mons	Wed 01/12/10
66	RF CIRCULATORS & LOADS	25,95 mons	Mon 03/01/11
78	INTERLOCKS & CONTROLS	22,7 mons	Fri 05/11/10
89	AUXILIARIES	23 mons	Mon 03/01/11
146	HIGH POWER SYSTEM INSTALATION	23,95 mons	Mon 03/01/11
147	Prepare HV Zone in SM18 for L4 & SPL	3,05 mons	Mon 03/01/11
148	Built new LHC HV Bunker & dismantle old bunker	2 mons	Mon 03/01/11
149	Prepare Zone for 2 Hz & 50 Hz modulator	1 mon	Mon 28/02/11
150	Install 400 V distribution for L4 (63 A)	2 mons	Tue 01/02/11
151	Install 400 V distribution for SPL (350 kW, 700 A?)	2 mons	Tue 01/02/11
152	*HV Zone in SM18 for L4 & SPL Ready*	0 days	Mon 28/03/11
153	Install Waveguide Systems	5,5 mons	Fri 01/06/12
154	All Waveguide ready for installation	1 day	Fri 01/06/12
155	Prepare Offer for tender - job description	3 mons	Fri 01/06/12
156	Waveguide installation	2 mons	Fri 07/09/12
157	*Waveguides Systems Installed*	0 days	Thu 01/11/12
158	Install 50 Hz Modulator	4 mons	Fri 13/07/12
161	Install and Align Klystron, Circulators and RF loads	1 mon	Fri 05/10/12

Key dates & constraints to be ready for cryomodule tests in January 2013:

- Linac4 PIMS CW RF tests must be finished by end 2010 at the latest
- Installation of L4 test place in SM18: January –March 2011
- L4 tests: April 2011 –November 2012
- installation: September -October 2012
- 704 MHz equipment tests: November –December 2012L4 tests in SM18

2 months overlap !!!Linac 4

WG1 Conclusions

RF Power

- 600 kW MB-IOT is a very interesting option to study:
- Solid State options to be pursued. (easy configurability for different powers)
- Studies on waveguide tuners not presented but under way

LLRF

- Two cavity model now being used, extend results to low beta section
- Saclay Piezo tuner gives good results, essential to minimize power and enable dual cavity operation
- Source intensity stability is important, feedback will incur power loss
- Tests on CEA cavity with all feedbacks is essential to validate the modelling
- Optimization of Q ext along the linac ? (cavity batches ?)

SM18, Modulators, Klystron

- Ordering of SM18 modulator on track for October 2012
- Space constraints for modulators are a concern !
- Common klystron order to arrange 1.5 MW ?
- SM18 test place planning is tight, but feasible

Spare Slides

RF System Summary - points from 5th Meeting

- Power splitting: from one klystron to 2 cavities, (use fixed 3-stub tuners instead of vector modulators),
- IOTs or solid state (<350 kW) for low beta section (one per cavity)
- Planning and preparation of RF test place in progress (consolidation with other projects at CERN is done, assembly procedure for cavities to be clarified,
- Preparation of low-power tests in vertical cryostats started, diagnostics being prepared (T-mapping, second sound, etc),
- JEMA is working on a ESS/SPL type 60 Hz modulator prototype, to be tested in 2011 at SNS,
- CERN will do design effort on Modulators up to 2014/15,
- Scandinova has done a pre-study with ESS specs, ESS is preparing tendering for test stand modulators
- LLRF code with GUI for drive of 1 versus 2 (or more) cavities with one klystron and without vector modulators, models for cavities (w. Lorentz force detuning) taking beam current & Qex variations, test data from 704 MHz cavity tests at Saclay incorporated,
- LLRF 2-cavity model w/o vector modulator seems feasible with feed-forward and piezo tuning, results now to be checked by beam dynamics,