sLHC

SLHCpp
Work Package 7
"Critical Components for Injectors"

Status
February 2011

reported by
Wolfgang Hofle

Participation

CEA Saclay, CERN, DESY, INFN Milano, STFC

Acknowledgement: S. Simrock, DESY

SLHC-pp Project WP 7 final status

Work package 7 (WP7, work package leader R. Scrivens)

subject
"Critical Components for Injectors" for a super conducting H- LINAC (such as SPL):

7.1 *H- source for SPL*
coordination R. Scrivens, participation: CERN, DESY, STFC

7.2 *Field stabilisation in pulsed superconducting low-β (v/c) accelerating structures*
coordination W. Hofle, participation: CEA Saclay, CERN, INFN Milano;

builds on hardware, cavities and test stands developed with support
from FP6-CARE/HIPPI program

SLHC-pp Project WP 7 final status

7.1 Objectives: H- source for SPL
demonstrate that the requirements for an SPL like machine can be achieved:
stable operation of Plasma source, 50 Hz pulsed, at high reliability;

☐ thermal simulations or 50 Hz operation, design guidelines for high reliability
☐ design of high duty factor plasma generator
☐ development of a test place (RF generation, gas injection, pumping …)
☐ demonstration of plasma operation

7.2 Objectives: Field stabilisation in pulsed superconducting cavities

builds on hardware, cavities and test stands developed with support
from FP6-CARE/HIPPI program, including 704 MHz test place at CEA Saclay

☐ characterization of cavities/tuners from FP6 program (CEA & INFN design)
☐ chose RF layout for SPL, component specification, feasibility by simulations
☐ build prototype lowlevel RF (LLRF) hardware, use with actual cavities
☐ demonstrate field stabilisation (on actual cavity in the CEA test stand)

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sLHC pp 7.1 status report

A Plasma Generator for the HP-SPL

J. Lettry, S. Bertolo, A. Castel, E. Chaudet, J.-F. Ecarnot, G. Favre, F. Fayet, J.-M. Geisser, M. Haase, A. Habert, J. Hansen, S. Joffe, M. Kronberger, D. Lombard, A. Marmillon, J. Marques Balula, S. Mathot, O. Midttun, P. Moyret, D. Nisbet, M. O'Neil, M. Paoluzzi, L. Prever-Loiri, J. Sanchez Arias, C. Schmitzer, R. Scrivens, D. Steyaert, H. Vestergard and M. Wilhelmsson

H- sources

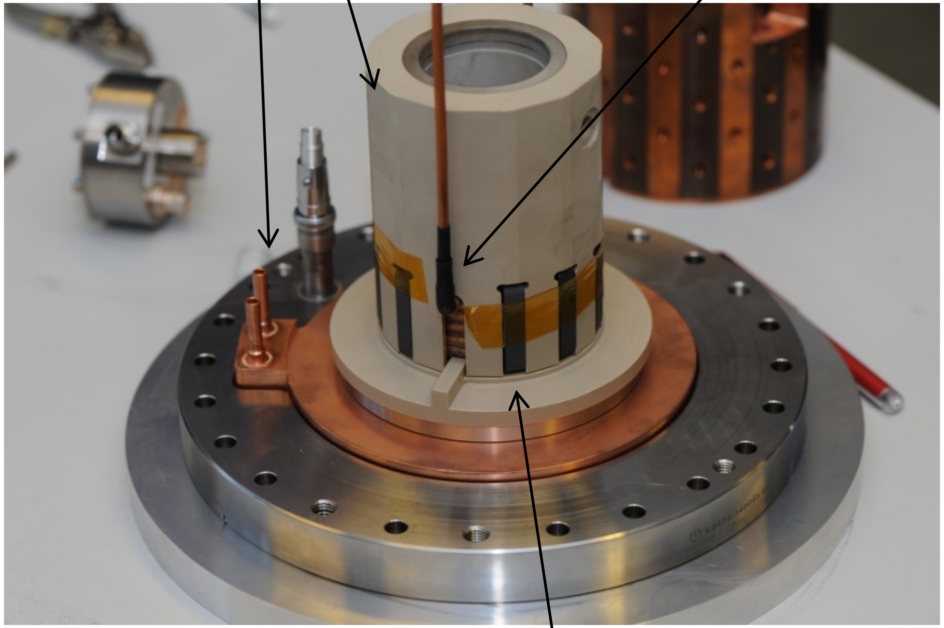
Volume	Power RF – Arc$^{(+)}$	H^- pulse
vs.	P ν HT	I τ ε
Cs-surface	kW Hz kV	mA ms πµm
DESY	30 3 35	40 0.15 0.25
*Linac4**	*100 2 45*	*80 0.4 0.25*
SPL*	***100 50 45***	***80 1.2 0.25***
SNS	80 60 65	65 0.5 0.25
ISIS	4^+ 50 35	70 0.25 0.5

SLHCpp-7.1 Schedule and deliverables

1 April 2008 : Project Start

- ✓ 31 March 2009: Report - Finite element thermal study of the Linac 4 design source at the final duty factor – Completed
- ✓ 31 May 2009: Report - List of required improvements for the design of the high duty factor plasma generator to function at a high duty factor – Completed
- ✓ 30 September 2009: Report - Design of a high duty factor plasma generator – Completed, published at ICIS-09
- ✓ 30 September 2010: Demonstrator - Construction of the plasma generator and sub-systems (e.g. 2MHz RF generator, hydrogen gas injection and pumping) – Completed, published at NIBS-10
- ➢ **31 March 2011**: Report - Plasma generation and study of the thermal and vacuum conditions

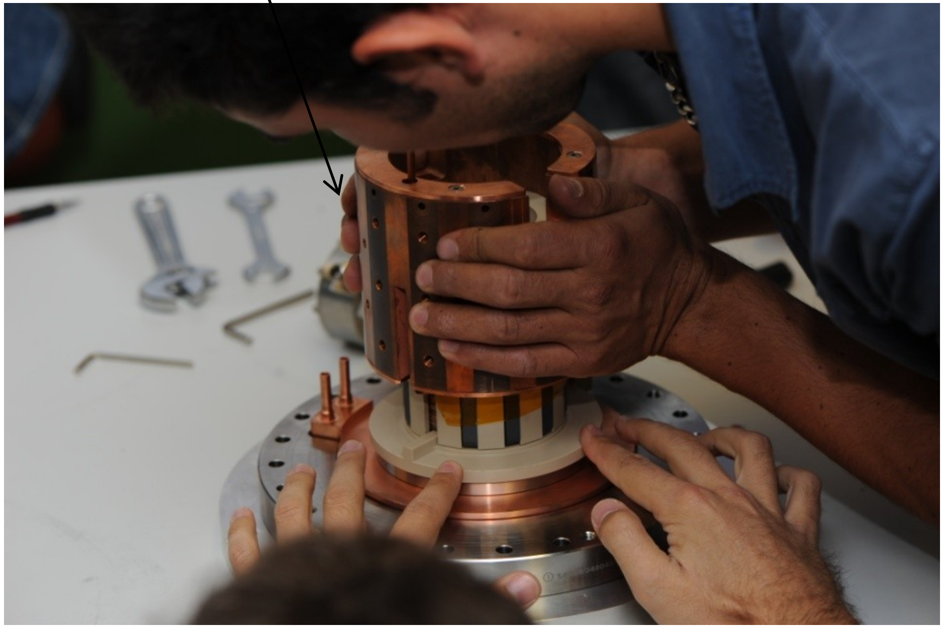
Plasma generator assembly



Cooling circuits

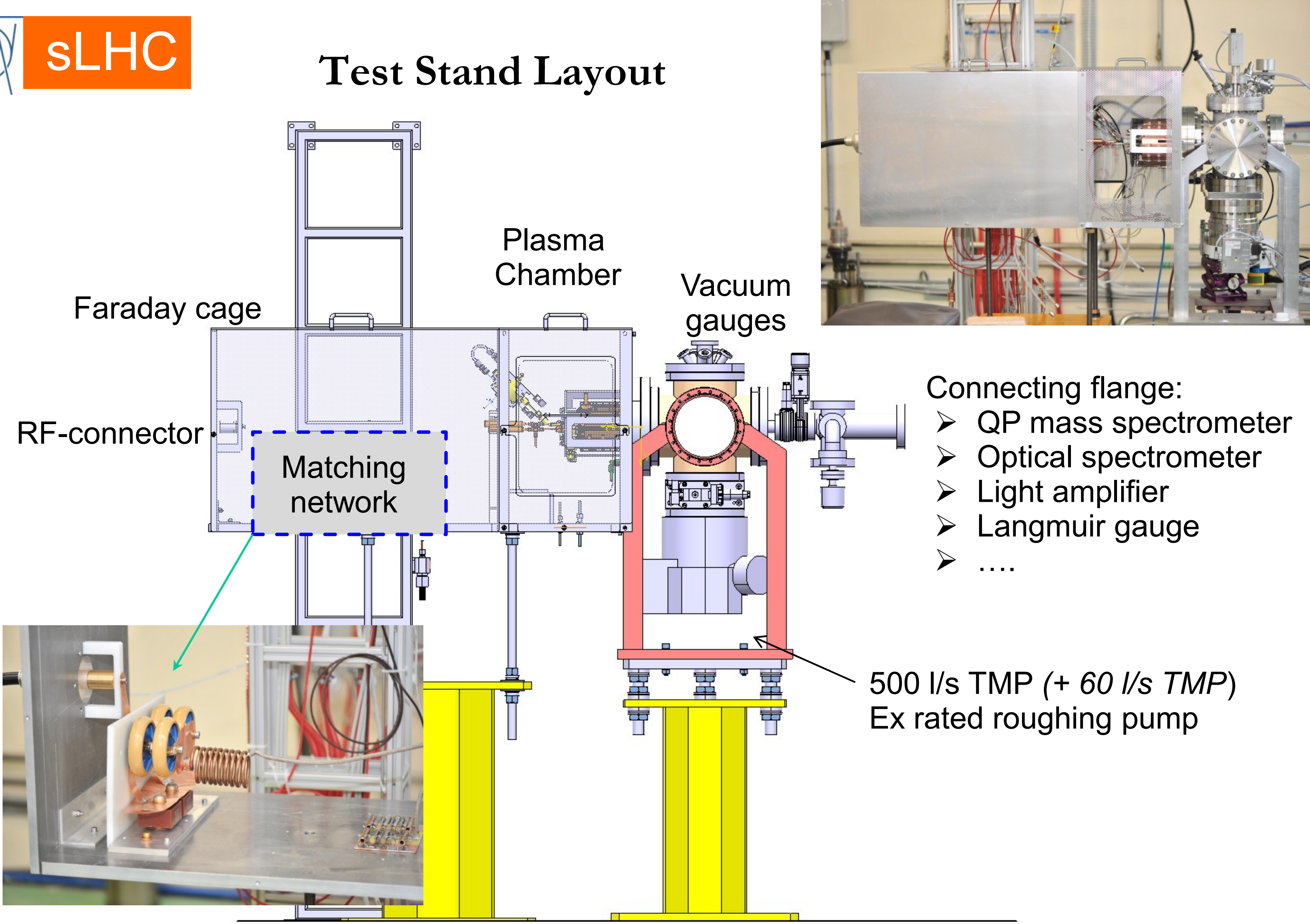
Antenna

ferrites



Cu-shield of Magnet cusp

Test Stand Layout



Faraday cage

Plasma Chamber

Vacuum gauges

RF-connector

Matching network

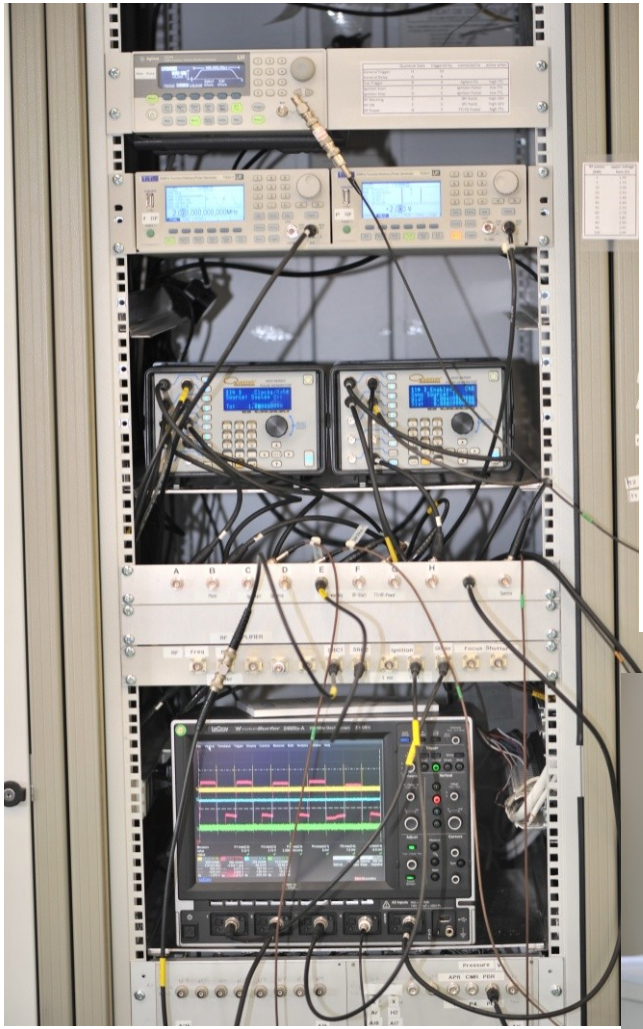
Connecting flange:

- QP mass spectrometer
- Optical spectrometer
- Light amplifier
- Langmuir gauge
- ….

500 l/s TMP (+ *60 l/s TMP*)
Ex rated roughing pump

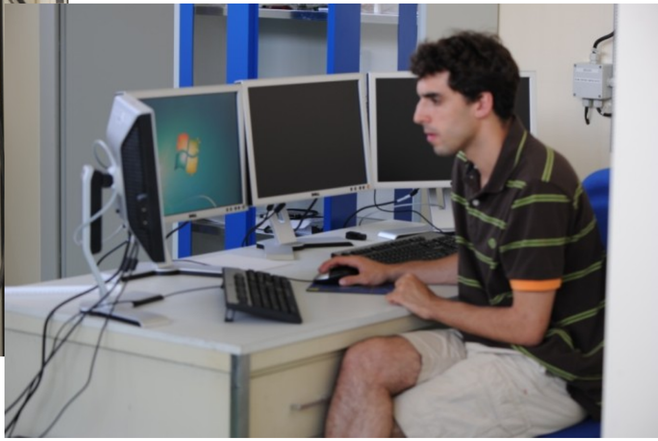
RF-Generator & control racks

1.9-2.1 MHz, 100 kW peak power
Up to 1.2 ms pulses at 50 Hz
Poster by M. Paoluzzi



Arbitrary Function Generators Agilent & TTi
- *Piezo valve control*
- *RF-frequency,*
- *RF-power*

Pulse Generators Quantum 8Ch
- *Power supplies and gas*
- *Measurement synchronization*



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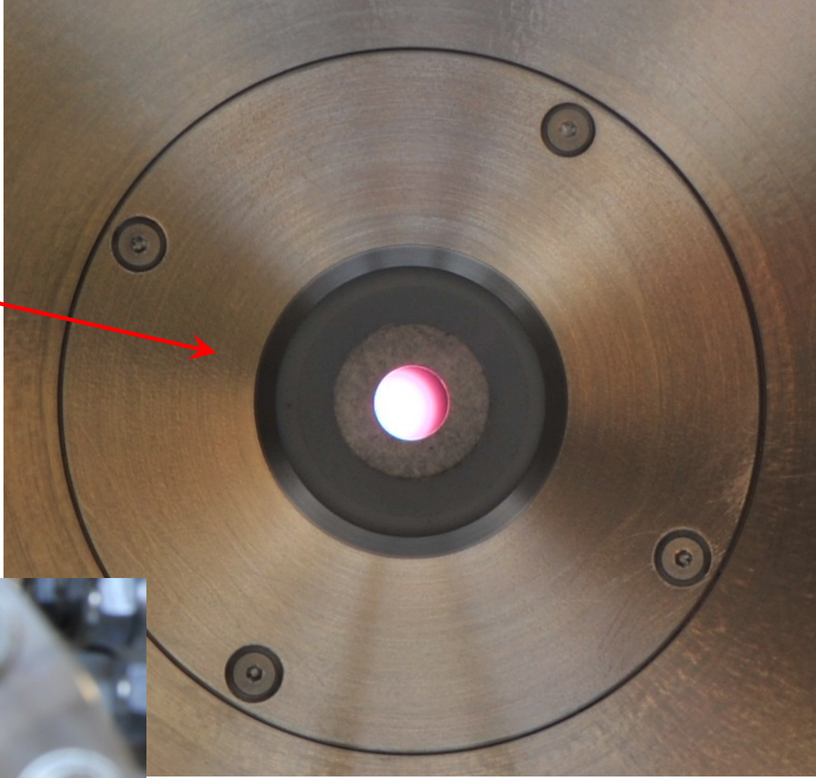
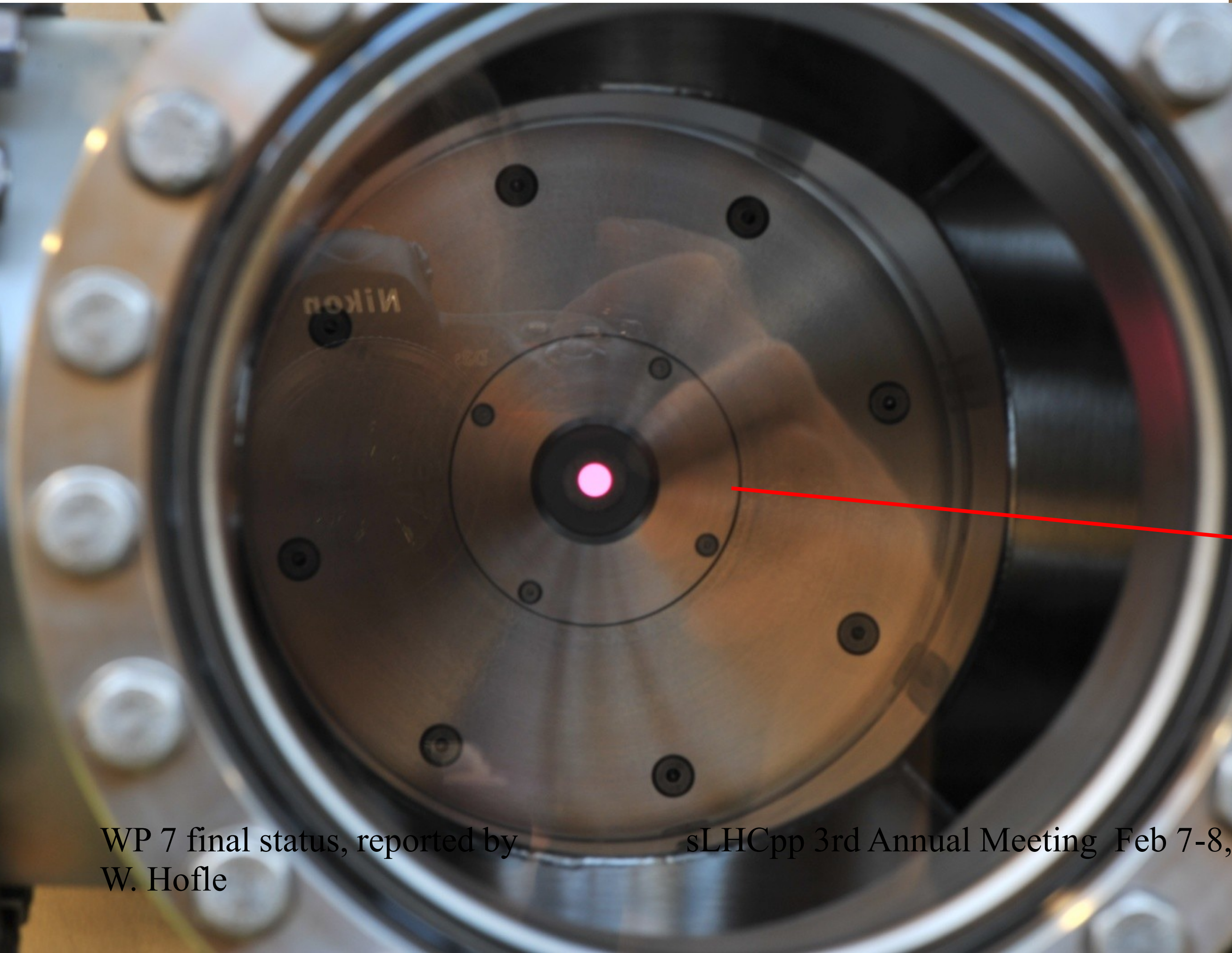
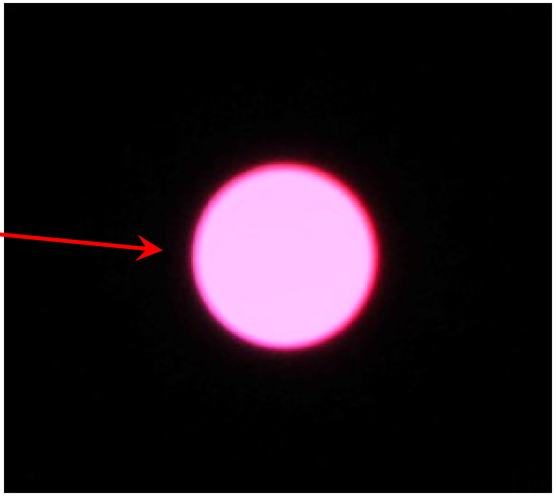
1st November 2010

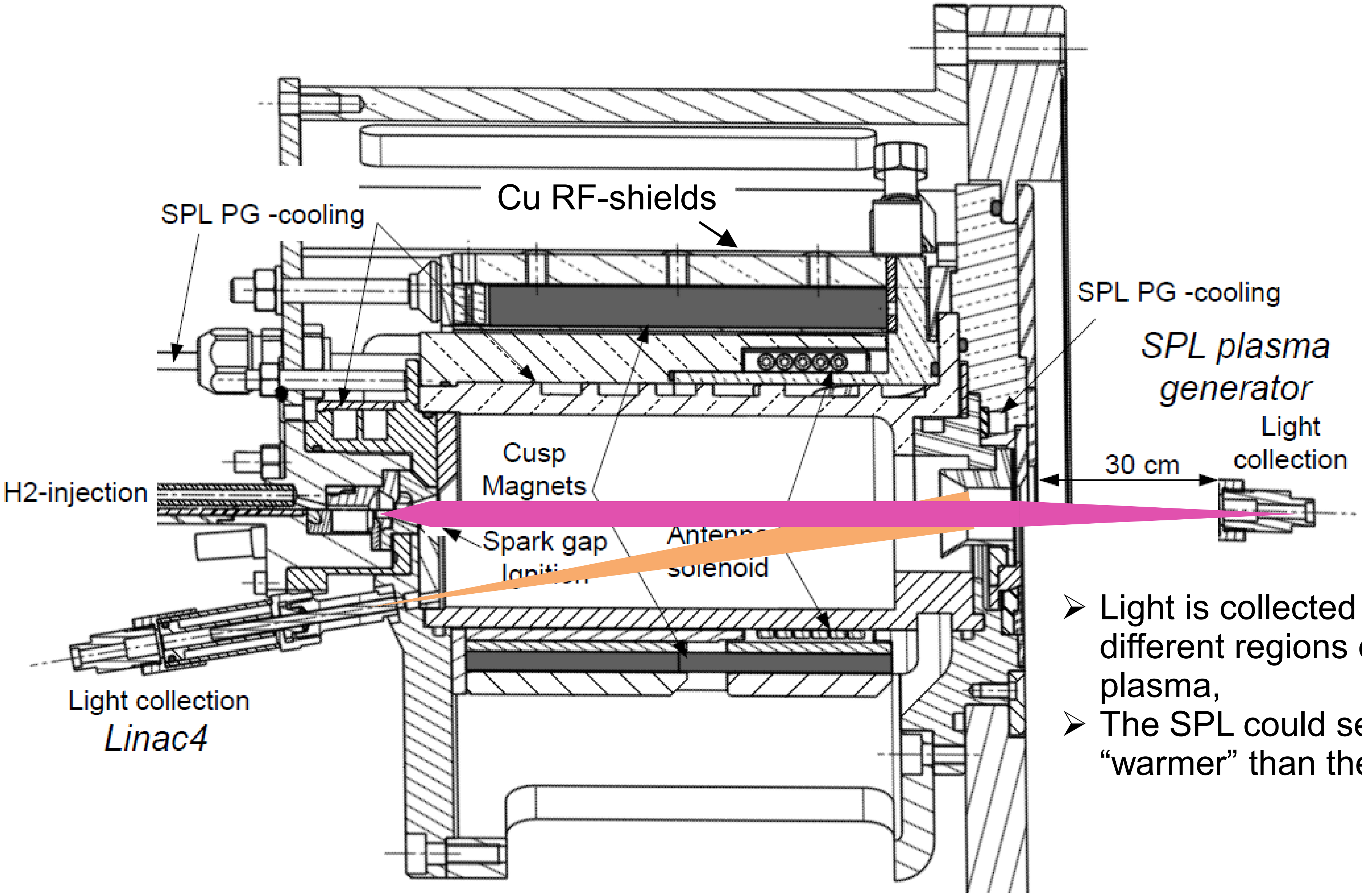
sLHC Plasma Generator's 1st Spark gap Ignition & 1st RF-H-plasma





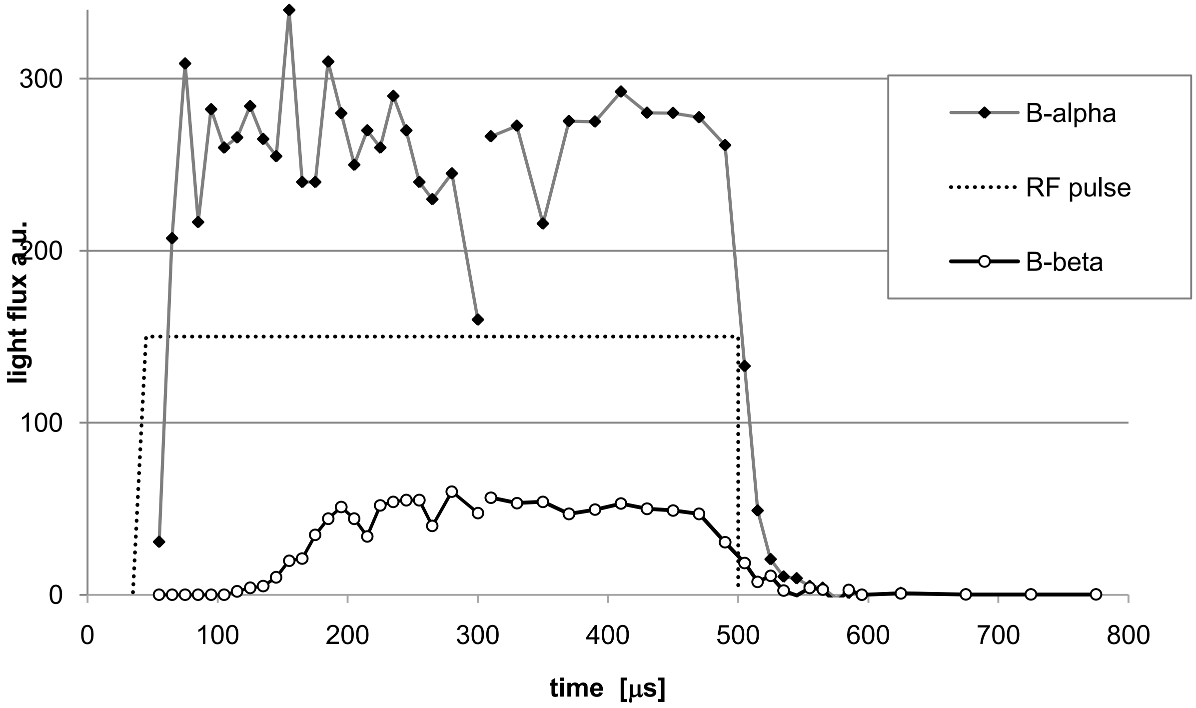


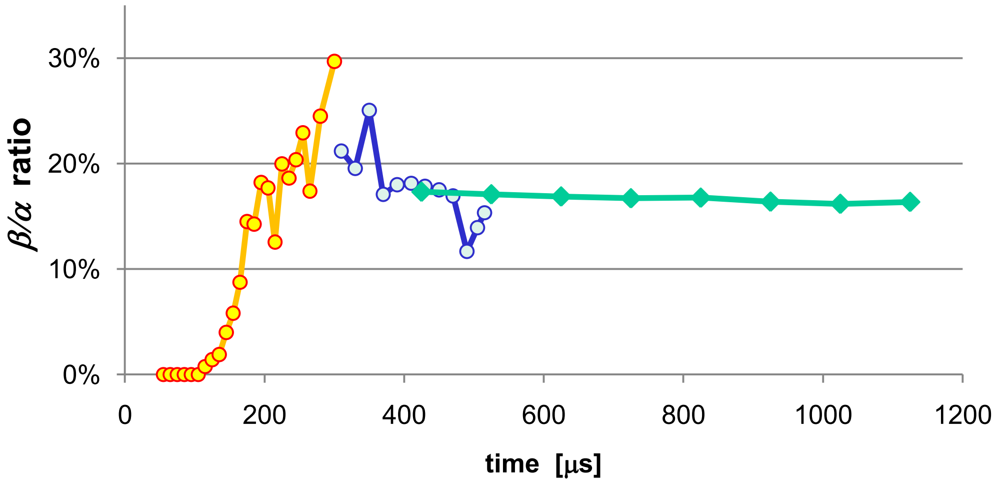
SPL plasma generator vs. Linac4 ion source



- ➢ Light is collected on different regions of the plasma,
- ➢ The SPL could seem “warmer” than the L4

Balmer Hα, Hβ line measurements SPL plasma generator test stand





For the sLHC plasma Fast optical emission Spectroscopy is the best characterization method to compare plasmas

Conclusion and outlook (1)

Plasma chamber prototype available on schedule

Improved Cu shielding of the permanent magnets demonstrated

Test stand and plasma chamber commissioning completed at low repetition rate (up to RF frequency shift)

Gas injection and ignition operated at 50 Hz few 1e-3 mbars → *non linear reaction of the pumping system* → *triple pumping speed*

Operation stable at 50 kW, peak 90 kW (with sparks), Plasma pulse of 1.2 ms at 25 kW RF power.

Ag-coated and water cooled matching network mandatory → *in production*

Conclusion and outlook (2)

Equivalent circuits RF & coupling measured: Linac4 (70%), SPL PG (40%), Contribution of the plasma to the impedance measured. *M. Paoluzzi*

Spectrometry of *a,b* Balmer lines successful

Ok for plasma status, *a*/*b* ratio of : 6-14 % (L4, 20-80 kW) and 16-18 % (SPL, 25 kW) measured. Different lines of sight includes extraction and “hot” plasma regions

Measurement of *a* Balmer line with light amplifier successful, optimization of sensor needed for the *b* line → *photomultipliers*

Sparking; Identified solenoid antenna sparking through Kapton foil, sparking issue requires further attention. → *new antenna in octupole cusp*

SLHCpp-7.2 Schedule and deliverables

1 April 2008 : Project Start

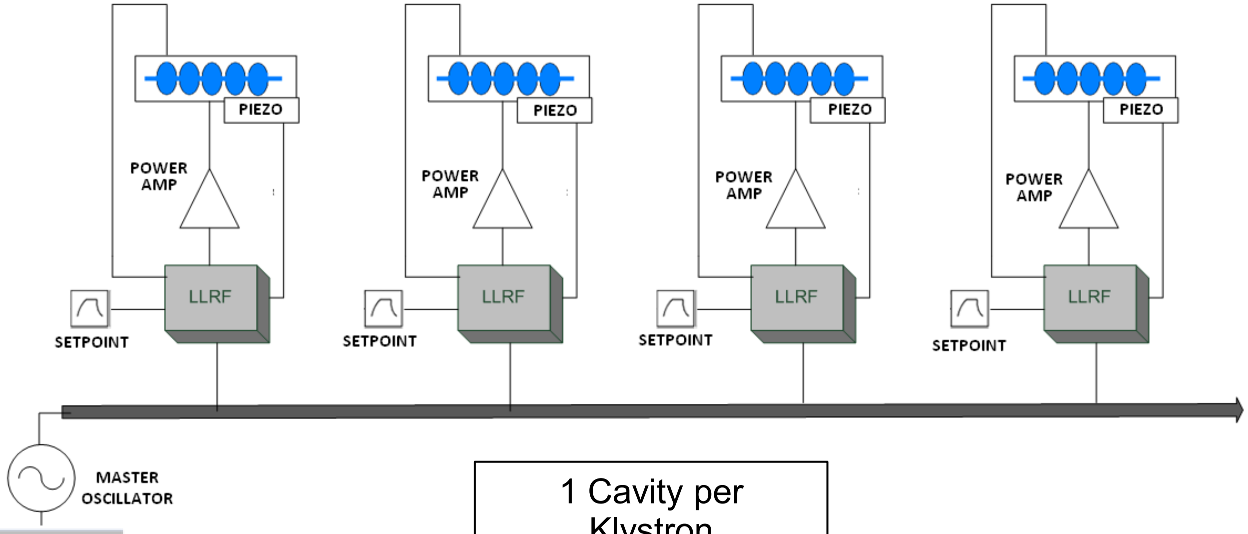
- ✓ Reports – Characterization of cavity and tuner – under approval

  part A, INFN cavity, March 2009, part B CEA cavity November 2010 completed
- ➢ RF layout and simulations: evolution well documented in the framework of the SPL collaboration meetings; **Report to be submitted by 31 March 2011**
- ➢ Prototype electronics developed, used for demonstration of field flatness as measurement system, reported at LLRF workshop in Tsukuba (October 2009)
- ➢ First results on field flatness achieved were published at LINAC10 conference (October 2010); Final report summarizing demonstration of field flatness using practical results from all cold tests and simulations: **planned for 31 March 2011**

CERN expressed interest to further develop the LLRF system and use it at the test stand at CEA Saclay with CEA Saclay cavity as preparation of a similar test stand at CERN (SM18); this would maintain momentum until SM18 test stand at CERN becomes available

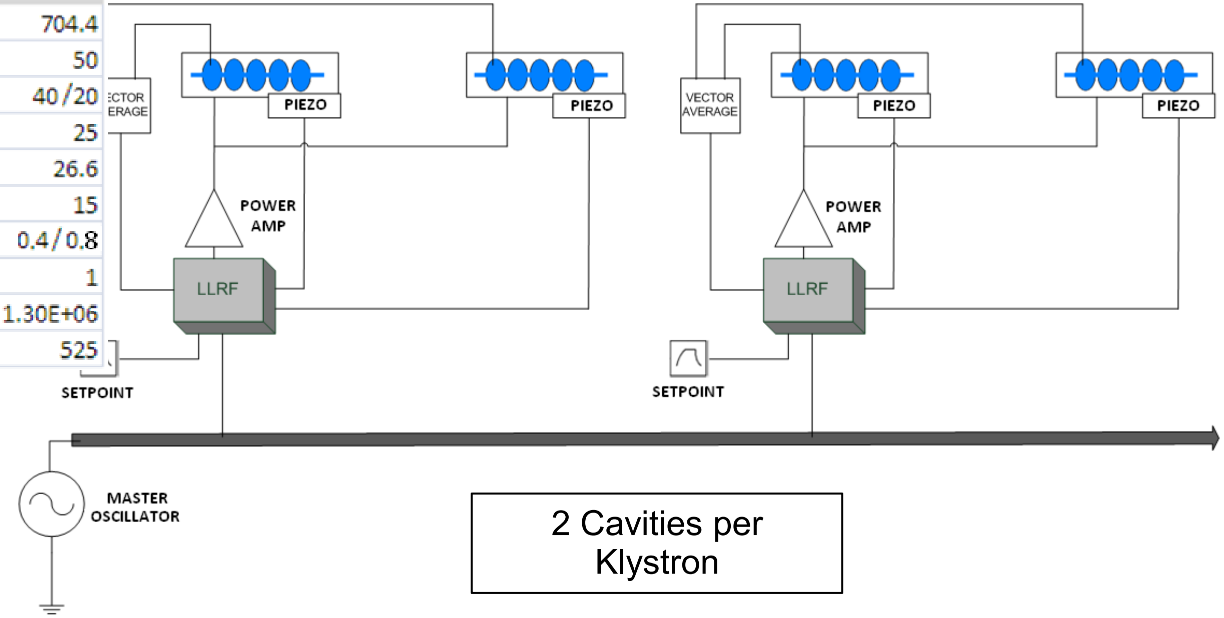
Simulations: SPL High Current Operation

Investigated in simulations possible operation using one, two or four cavities fed by a single power amplifier



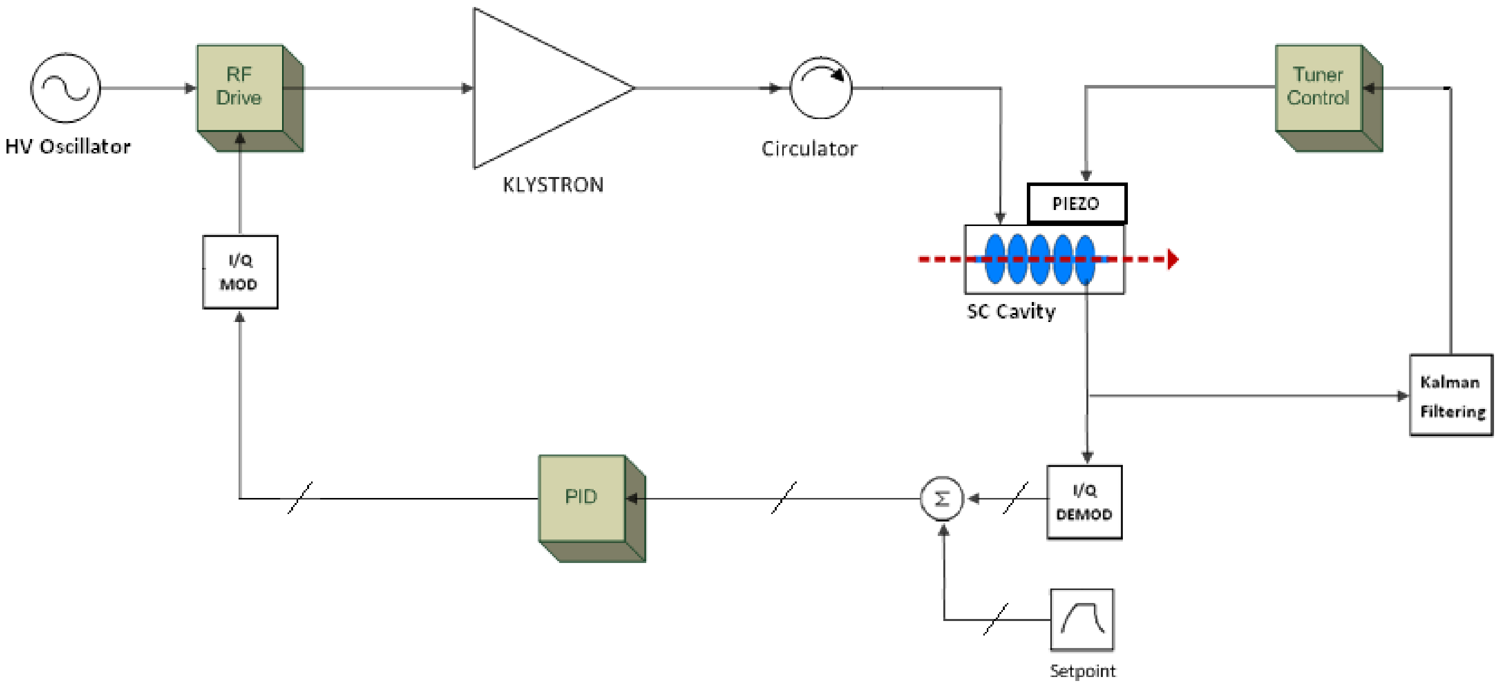
1 Cavity per Klystron

GENERAL PARAMETERS FOR HIGH POWER SPL		
PARAMETER	UNIT	VALUE
Resonant Frequency	MHz	704.4
Repetition Rate	Hz	50
Average Pulse Current	mA	40/20
Accelerating Field	MV/m	25
Accelerating Voltage	MV	26.6
Beam Synchronous Angle	Degrees (LINAC)	15
Length of Beampulse	ms	0.4/0.8
Power Delivered to Beam per Cavity	MW	1
Cavity/Generator Coupling Loaded Quality Factor		1.30E+06
Geometry Factor (R/Q)	Ohm (LINAC)	525



2 Cavities per Klystron

High-Level Diagram of Single Cavity Control



$$f_{\mathrm{RF}} = 704.4 \text{ MHz}$$

$$I_{\mathrm{b,DC}} = 40 \text{ mA}$$

$$\phi_{\mathrm{s}} = 15^{\circ} \text{ (LINAC)}$$

$$P_{\mathrm{b}} = V_{\mathrm{acc}} \times I_{\mathrm{b,DC}} \times \cos(\phi_{\mathrm{s}}) = 1.0285 \text{ MW}$$

$$Q_{\mathrm{L}} = 1.3113 \times 10^{6}$$

$$\frac{R}{Q} = 525\ \Omega \text{ (LINAC)}$$

$$\tau_{\mathrm{beampulse}} = 0.4 \text{ ms}$$

$$\text{rep period} = 20 \text{ ms}$$

$$R_{\mathrm{L}} = 680 \text{ M}\Omega$$

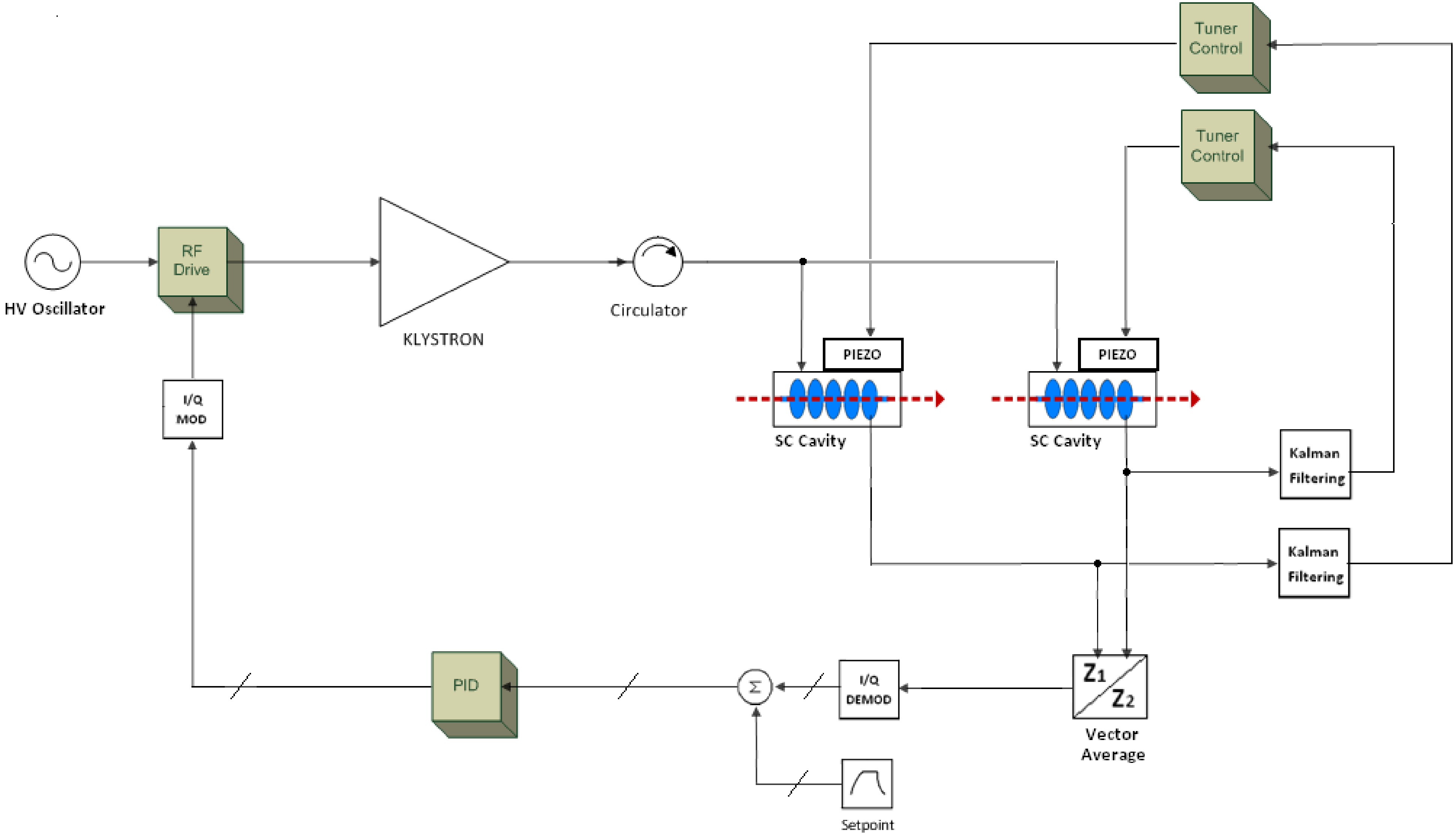
$$I_g = \frac{V_{acc}}{R_L} + I_{b,DC}\cos(\phi_s) = 77.3 \text{ mA}$$

$$\tau_{fill} = \frac{2Q_L}{\omega_{RF}} = 0.5926 \text{ ms}$$

$$\alpha = \frac{I_g}{I_{b,DC}\cos(\phi_s)} = 2$$

$$t_{inj} = \tau_{fill}\ln(\alpha) = 0.4108 \text{ ms}$$

High Level Diagram for Dual Cavity + Control System

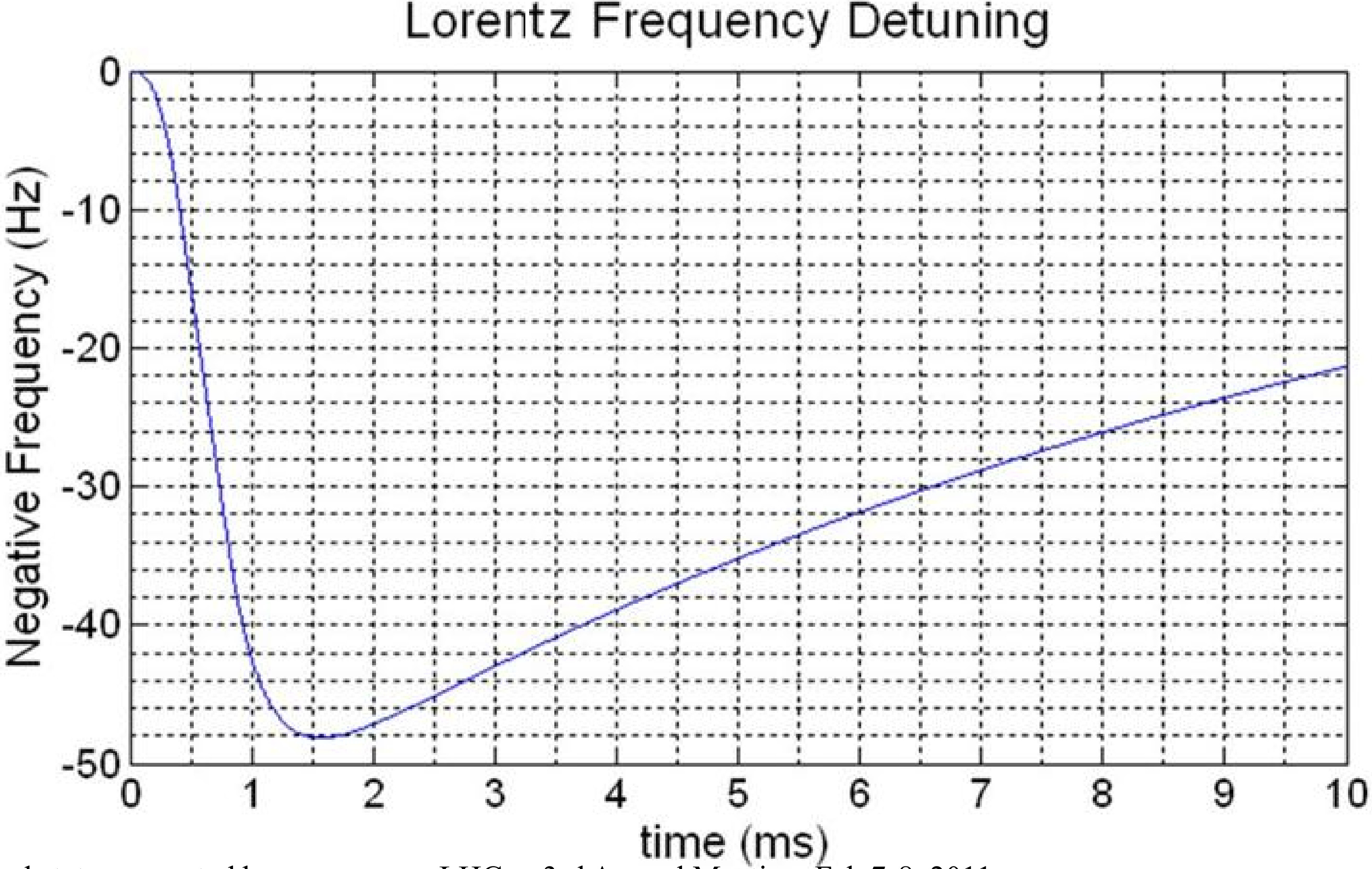


Lorentz Force detuning

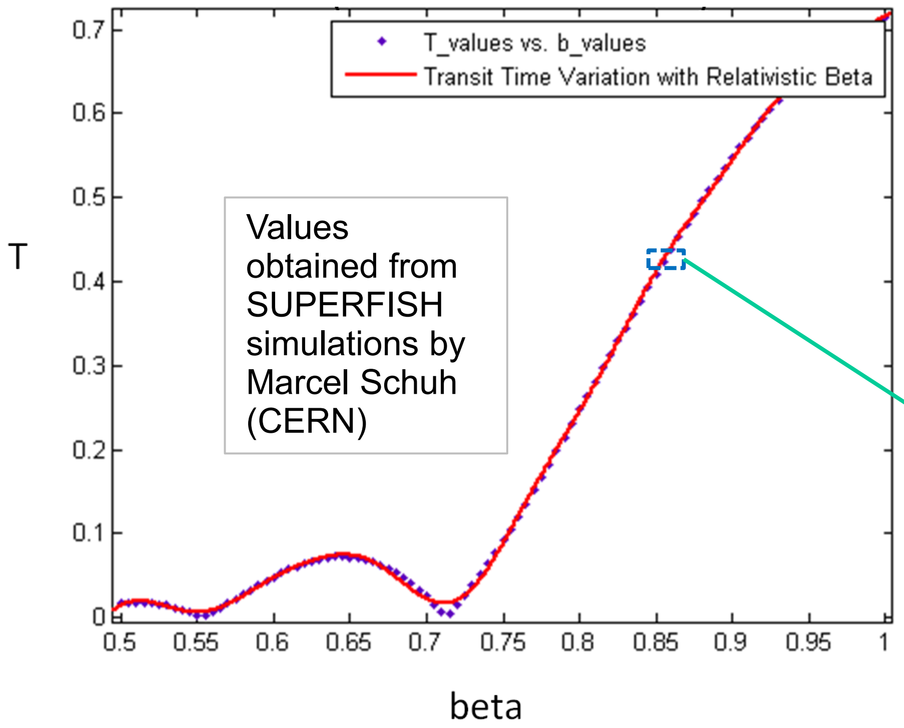
$$\frac{d\Delta\omega(t)}{dt} = \frac{-1}{\tau}\left(\Delta\omega(t) - \Delta\omega_T - 2\pi K E_{acc}^2\right)$$

K = -1 Hz/(MV/m)^2
τ = 1 ms

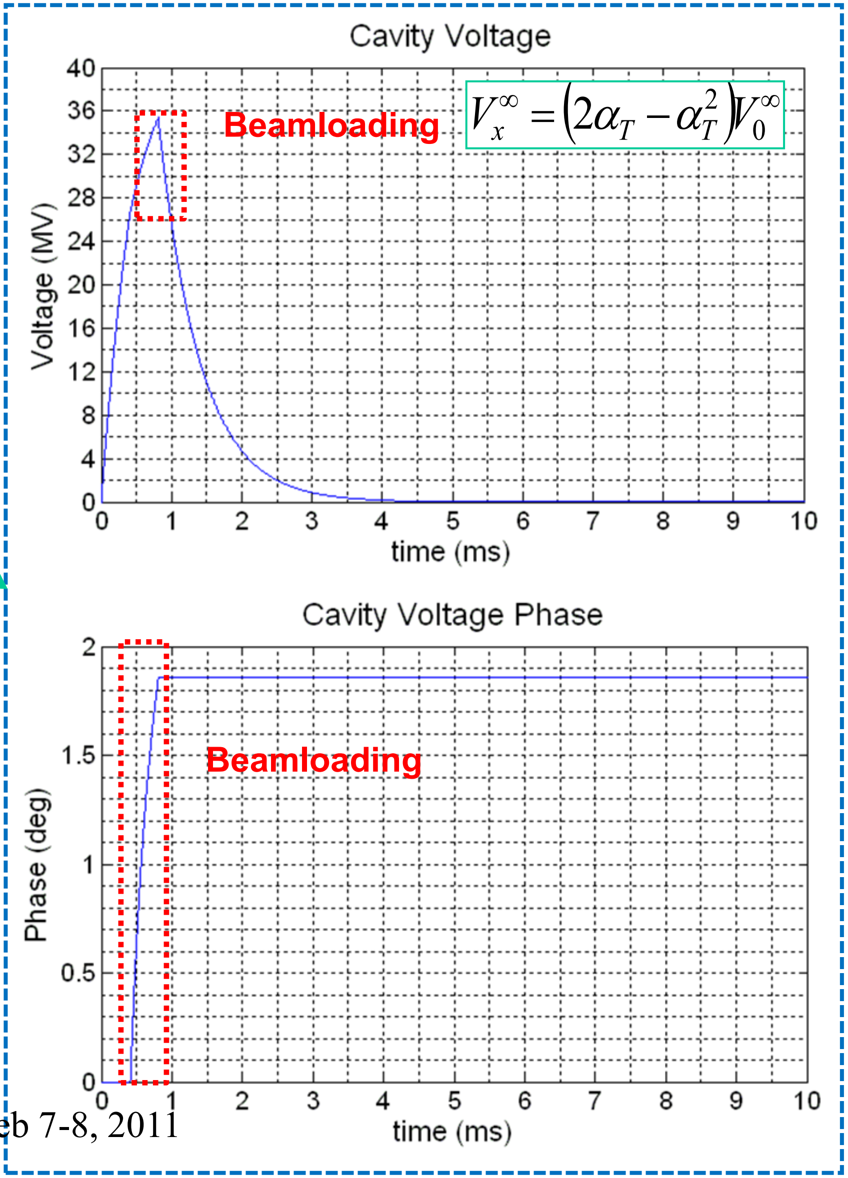
case of 0.4 ms beam pulse



Putting it together:
Transit Time Factor Variation with Relativistic Beta
(example: SPL β=1 cavities, single cavity/klystron open loop simulation)



Values obtained from SUPERFISH simulations by Marcel Schuh (CERN)

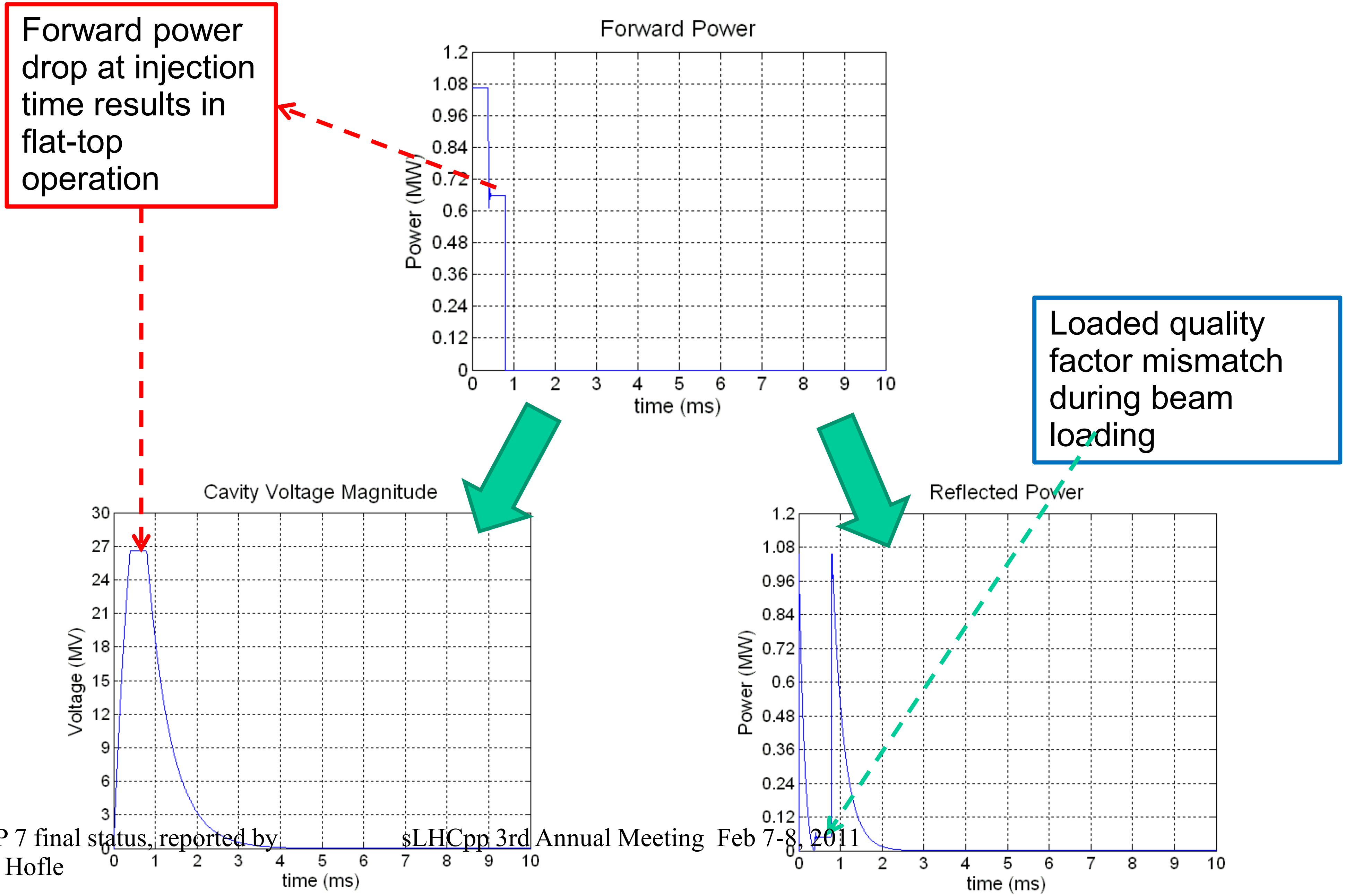


$$V_x^\infty = \left(2\alpha_T - \alpha_T^2\right) V_0^\infty$$

weaker beam loading results in a higher flattop equilibrium and less phase detuning of the cavity

β-value taken from beam energy at beginning of SPL (farthest from β=1)

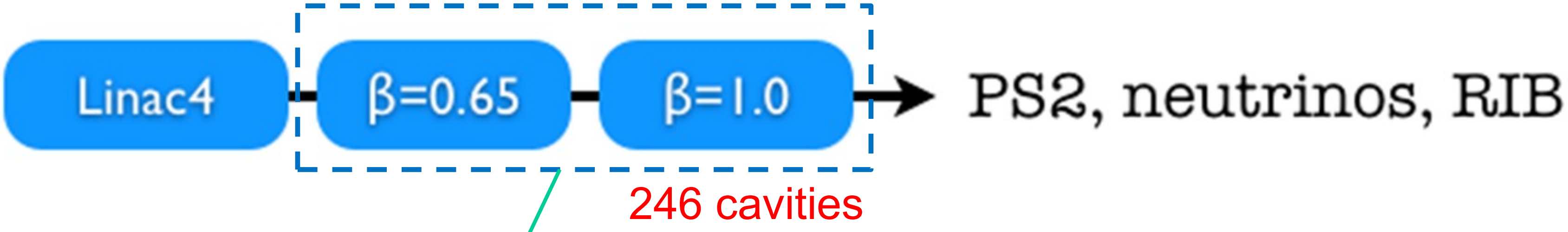
power reduction for β<1



Forward power drop at injection time results in flat-top operation

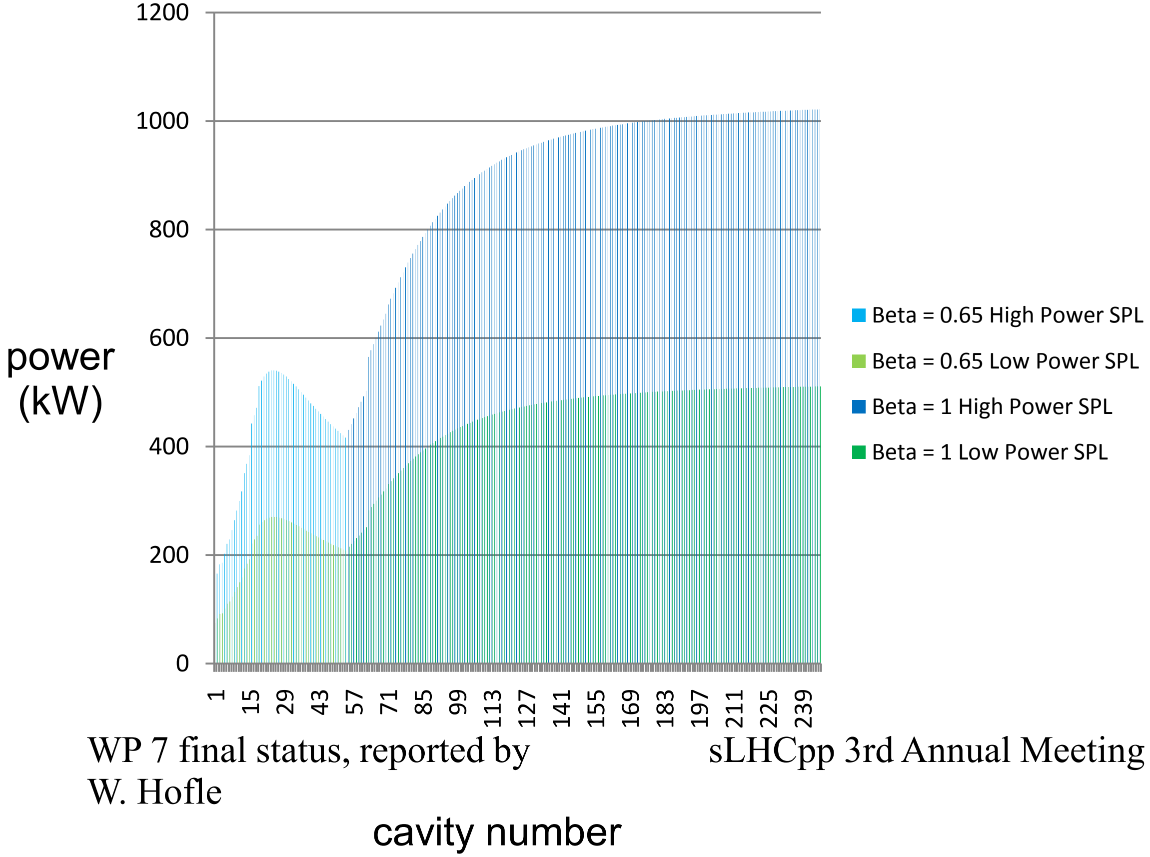
Loaded quality factor mismatch during beam loading

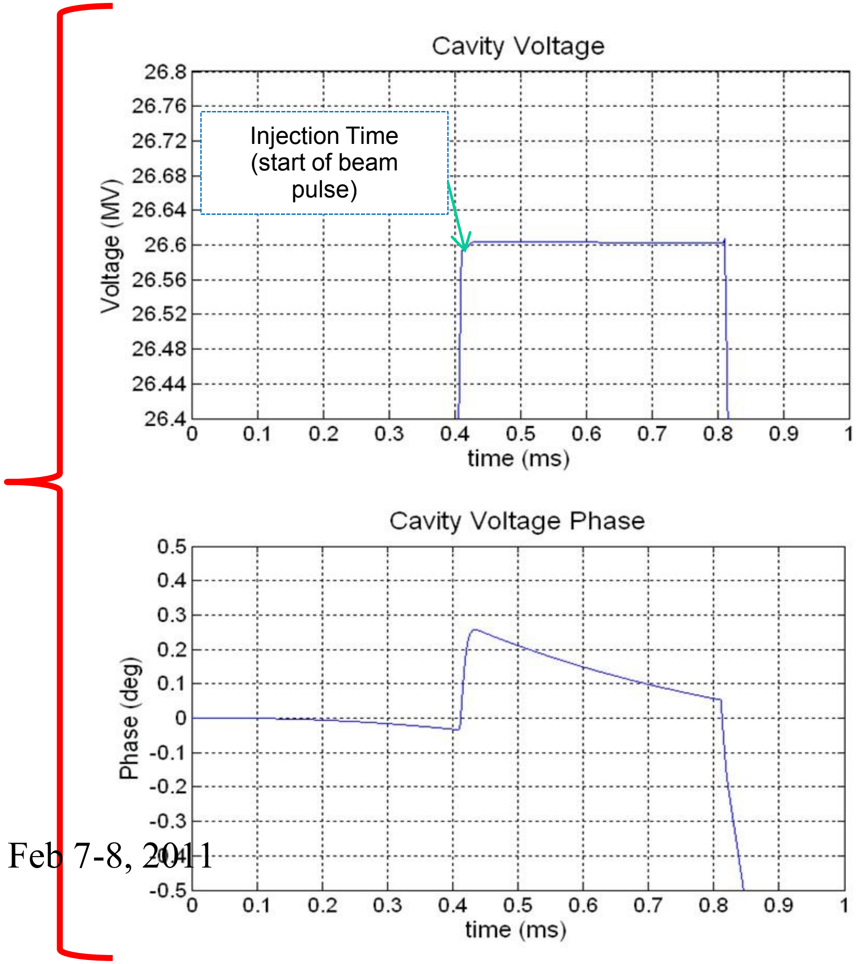
Full SPL: study of cumulative errors due to transients



246 cavities

Forward power needed along SPL



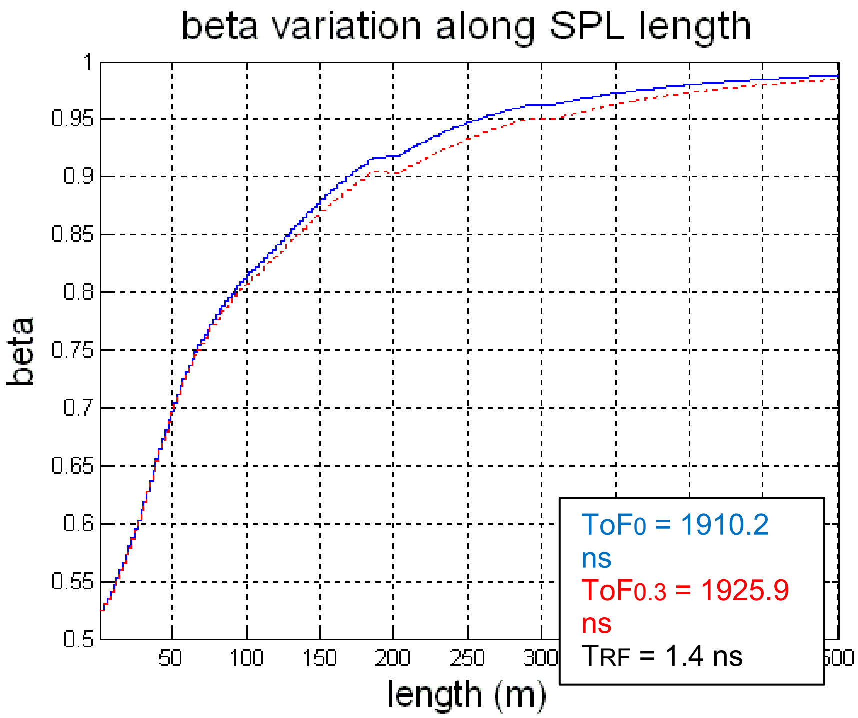


Cumulative error along full SPL due to transients

The SPL is comprised of 246 cavities with RF phases that are designed to fit the acceleration of the hydrogen ion beam as it traverses its length.

The cumulative effect of a 0.3 degree phase deviation on each cavity at beam arrival can result in merging of beam bunches.

The difference in "time of flight" (ToF) for a single charge that receives full acceleration as opposed to that which experiences a 0.3 degree deviation at arrival on each SPL cavity, would be an order of magnitude higher than the RF period of the cavity → needs correction

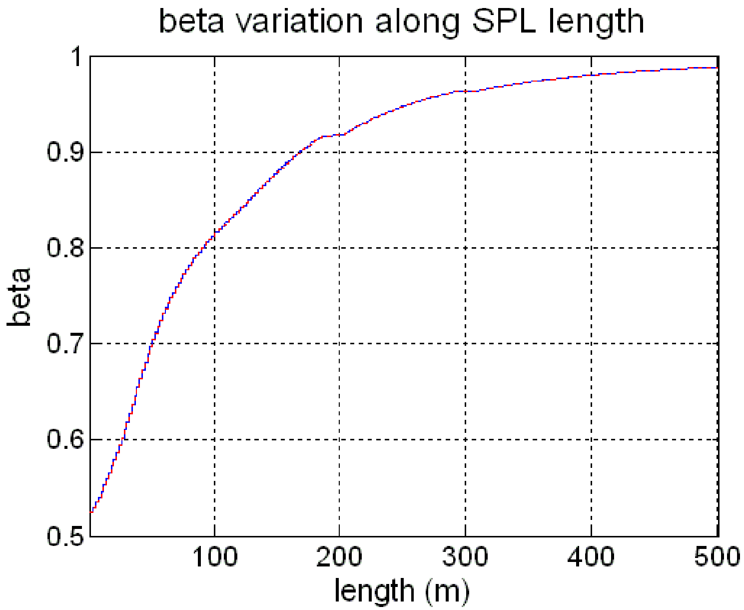


ToF_0 = 1910.2 ns
$ToF_{0.3}$ = 1925.9 ns
T_{RF} = 1.4 ns

Feed Forward Correction for Cumulative Error along SPL

Easiest solution is to intersperse slow feed-forward so that each SPL cavity will have the opposite error from the preceding one along the accelerator

In this way, particles travelling along the LINAC will not experience an accumulated deviation

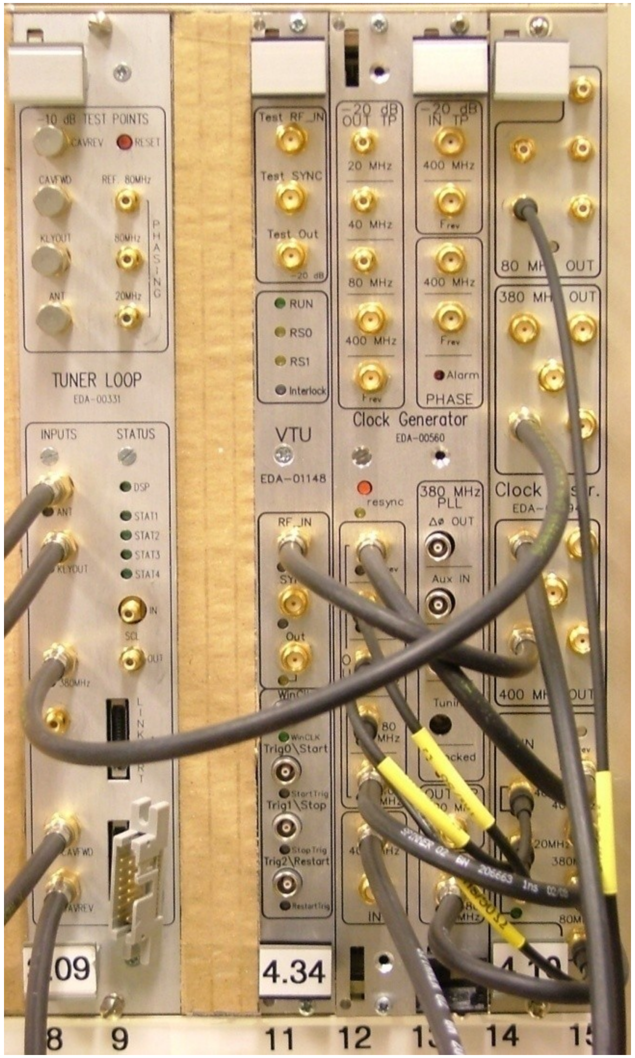


→synergy with ESS, regular updates presented at SPL collaboration meetings 2009-2010

Summary of effects addressed in simulations

- single cavity / klystron, no issues, straightforward, 3 us loop delay acceptable → important for option of SPL in a tunnel with RF sources on surface
- Q_{ext} variation with two cavities / klystron → vector sum OK but adjacent cavities exercise opposite excursions in amplitude and phase
- Lorentz Force detuning factor variation with two cavities / klystrons → individual control of piezo tuners to keep cavities on tune
- klystron power specification: beam current variation gives an important contribution, assume 5% variation for final report; overhead in power when used with unmatched current (note coupler Q_{ext} assumed fixed; 20 mA/40 mA beam currents in original LP-SPL and HP-SPL); overhead required for LP-SPL
- stable operation in simulations → high power vector modulator not needed
- systematic transient effects along linac dominate over statistically errors and need attention, strategy for their compensation
- layout proposed: one cavity / klystron with option of two cavities per klystron in all or part of the high β section

Contribution of CERN: LLRF Measurement set-up for tuner characterization and control



modified LHC hardware:
four channels analog down conversion to IF

f_{RF} = 704.4 MHz

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

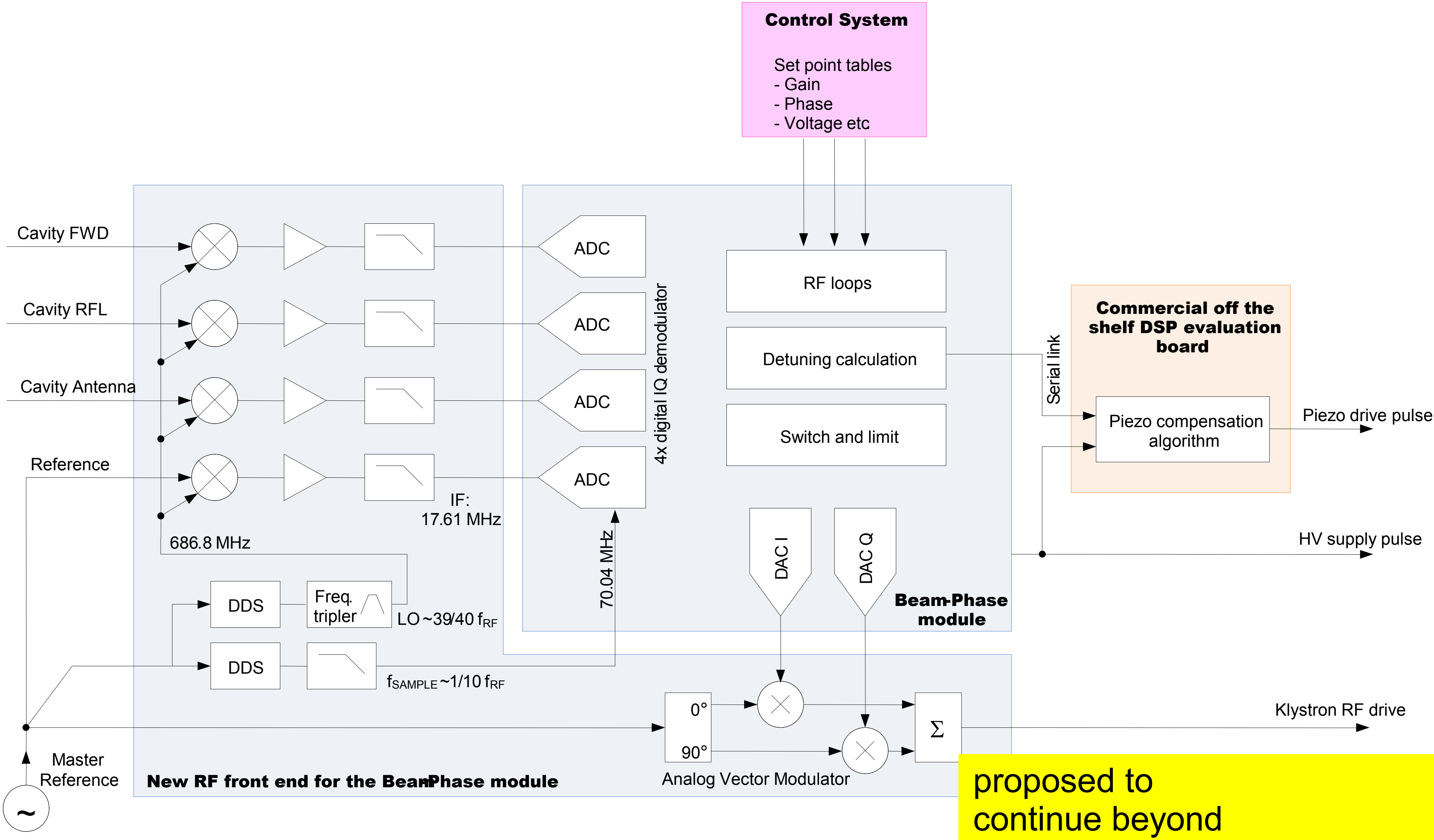
f_{IF} = f_{RF} - f_{LO} = 17.61 MHz

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

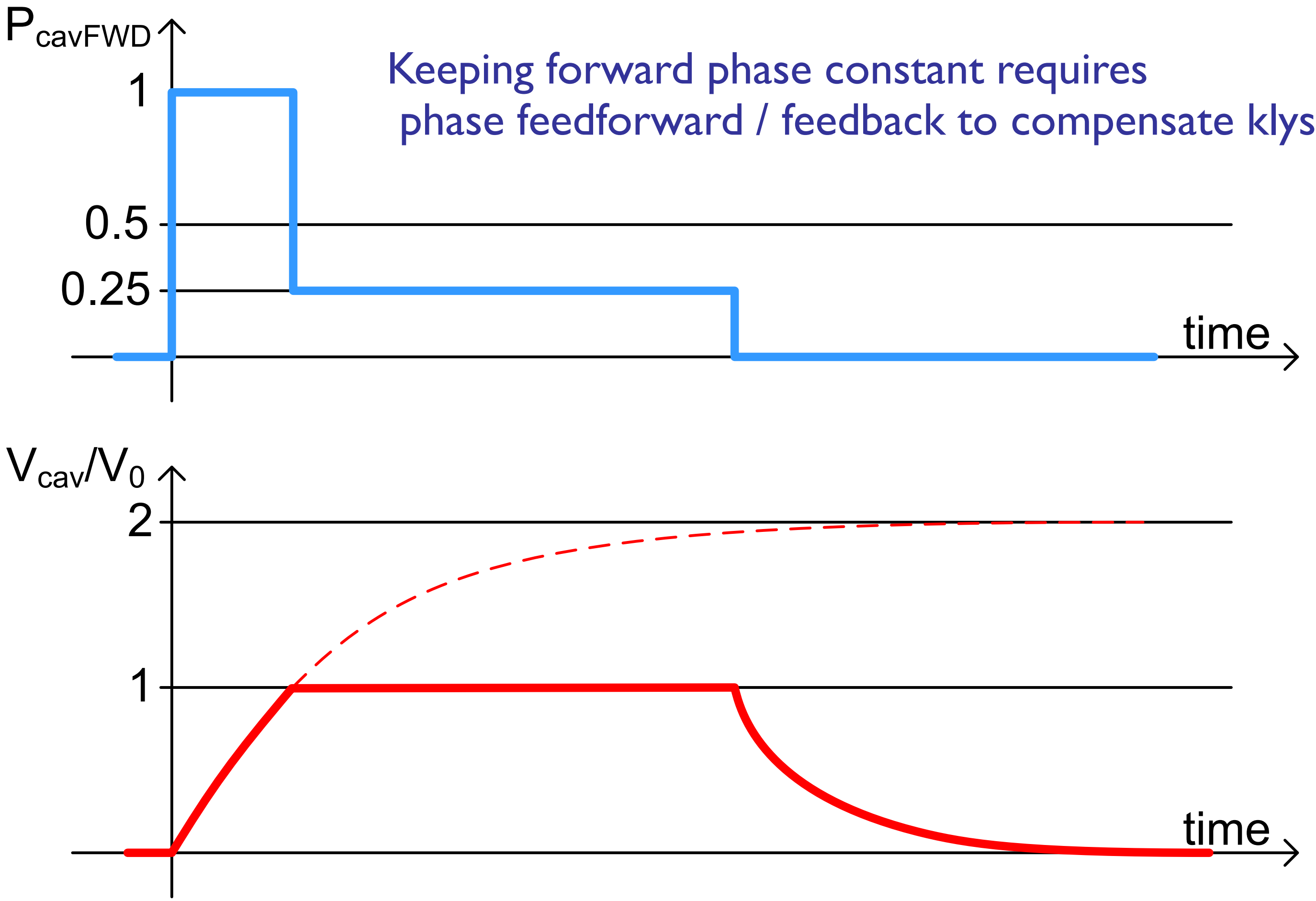
Future evolution of LLRF system



proposed to continue beyond sLHCpp project synergy also with ESS needs

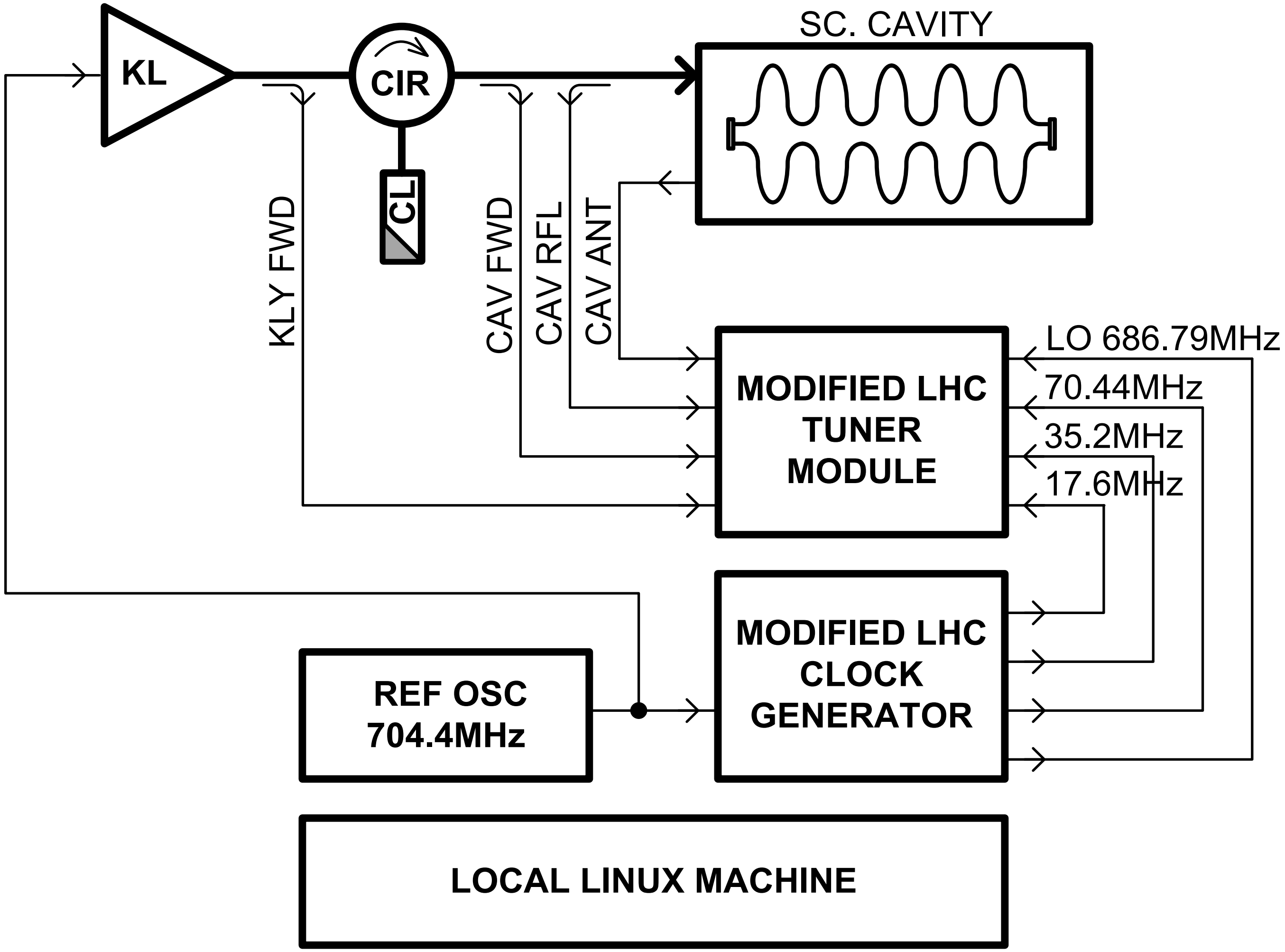
Typical waveforms for the cavity tests

No beam in test stand → situation in actual LINAC always different
→ some aspects of field stabilization only accessible by simulation



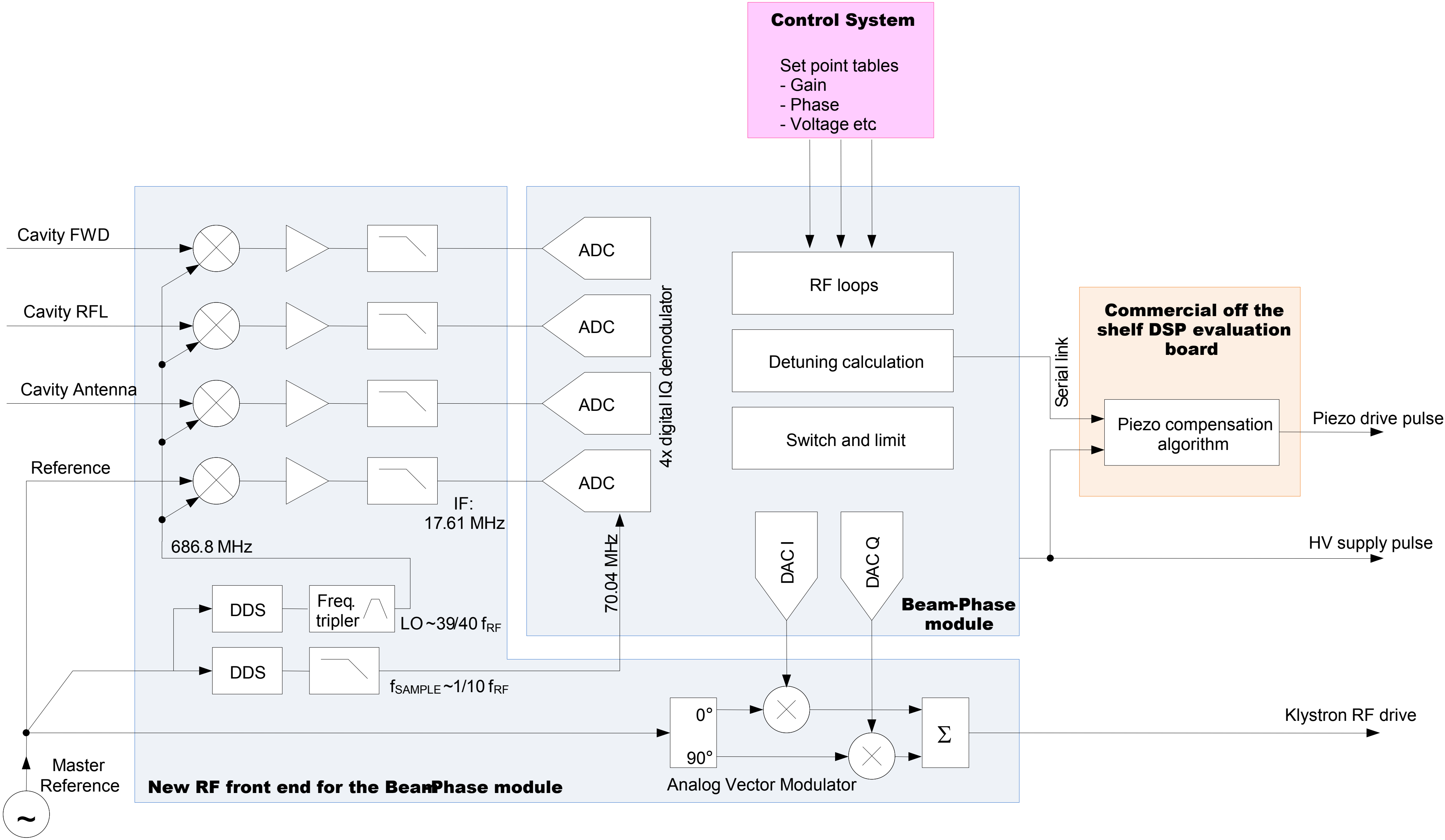
Keeping forward phase constant requires
phase feedforward / feedback to compensate klystron phase change

LLRF setup



LO frequency 39/40*RF
Observation memory 128k data points for each of the four channels
Max. observation rate 35.22 MSps and decimation in powers of two
full rate→ resolution 28.4 ns/point, record length 3.7 ms
down to a resolution of 0.93 ms/point, record length 122 s

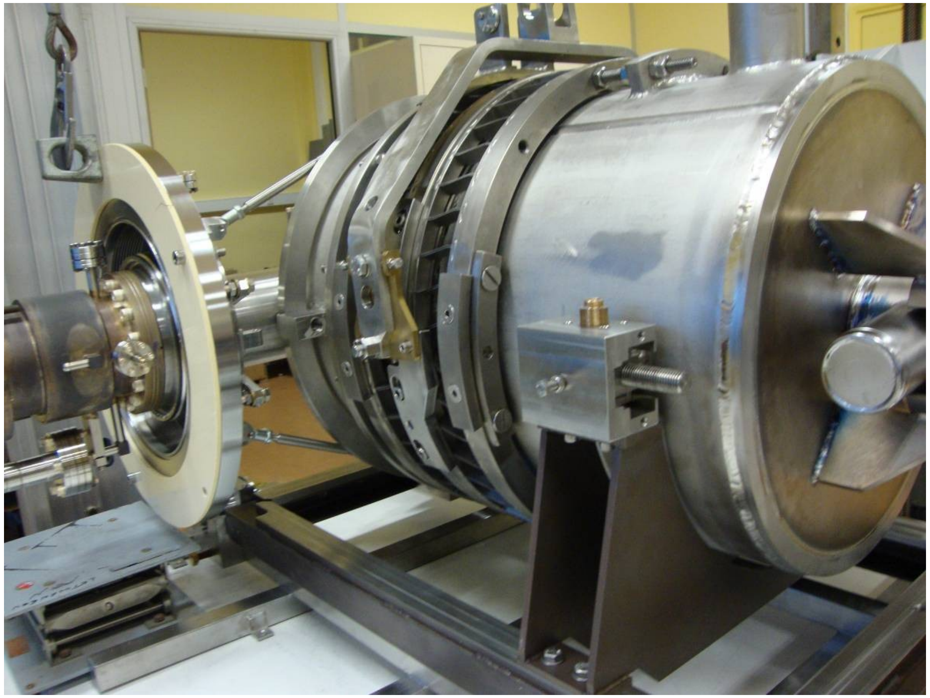
Future evolution of LLRF system



Contribution of INFN to WP7.2

β=0.5 cavity, He tank, blade tuner (from FP6 program)

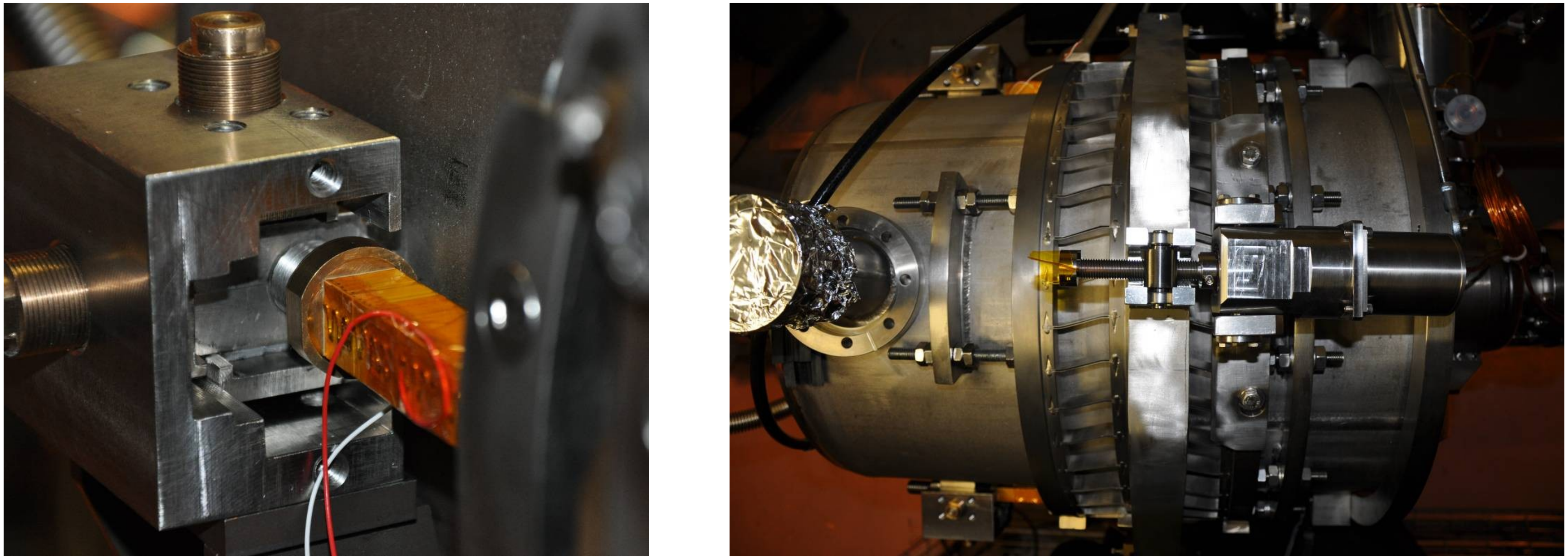
sLHCpp: participate in preparation for cold testing at CEA Saclay, assembly tuner, participation in tests



Contribution of INFN to WP7.2

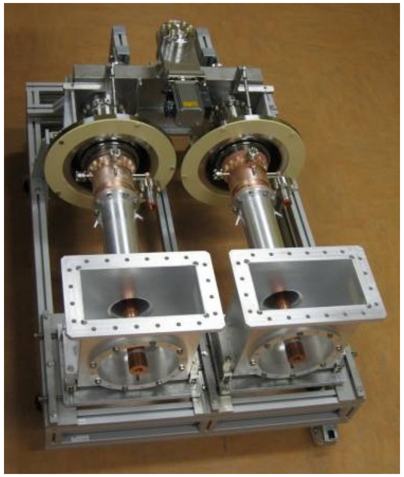
Details of INFN blade tuner with piezo

cold testing at CEA Saclay in Feb / March 2011



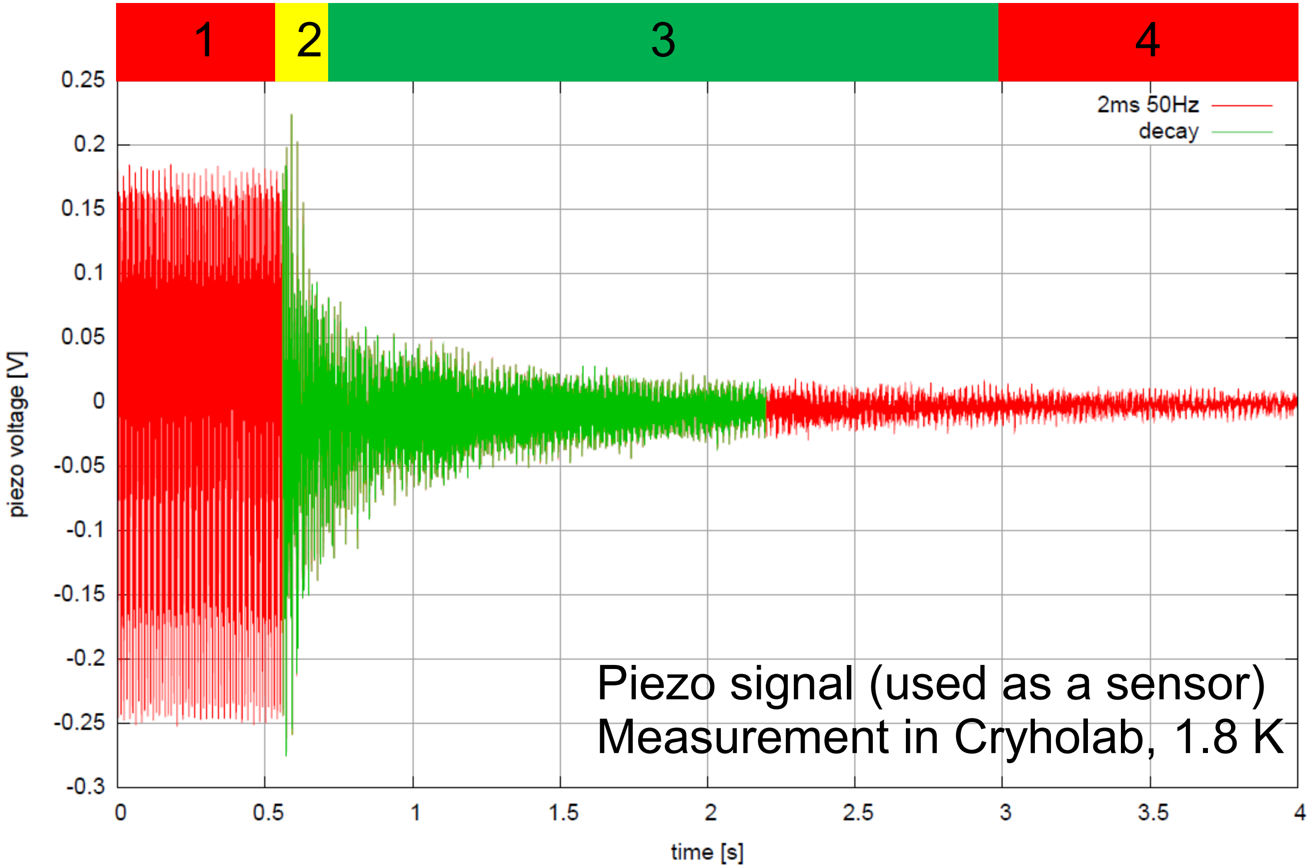
Contribution of CEA Saclay to WP7.2

"The CEA team will provide, operate and manage the test stand for superconducting cavities, with its 700 MHz high power RF system and one cavity/tuner ensemble. They will also contribute to the simulation of the RF system and of the Linac beam dynamics." (Final contract document)

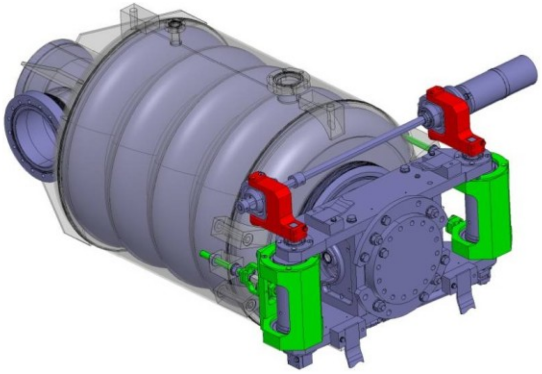


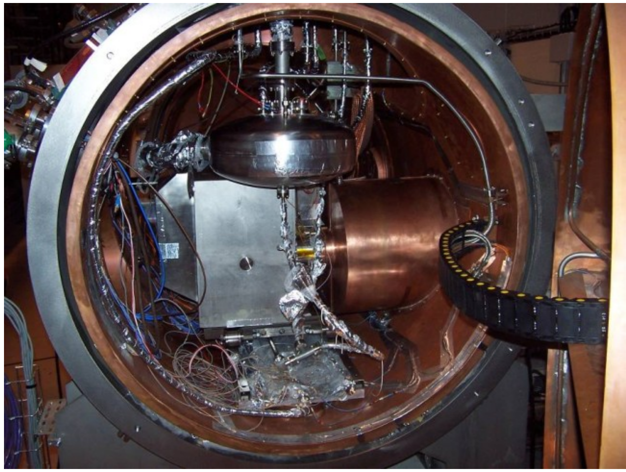
1MW RF power coupler pair in the conditioning configuration

Pulsed tests on the 704 MHz beta 0.5 CEA cavity



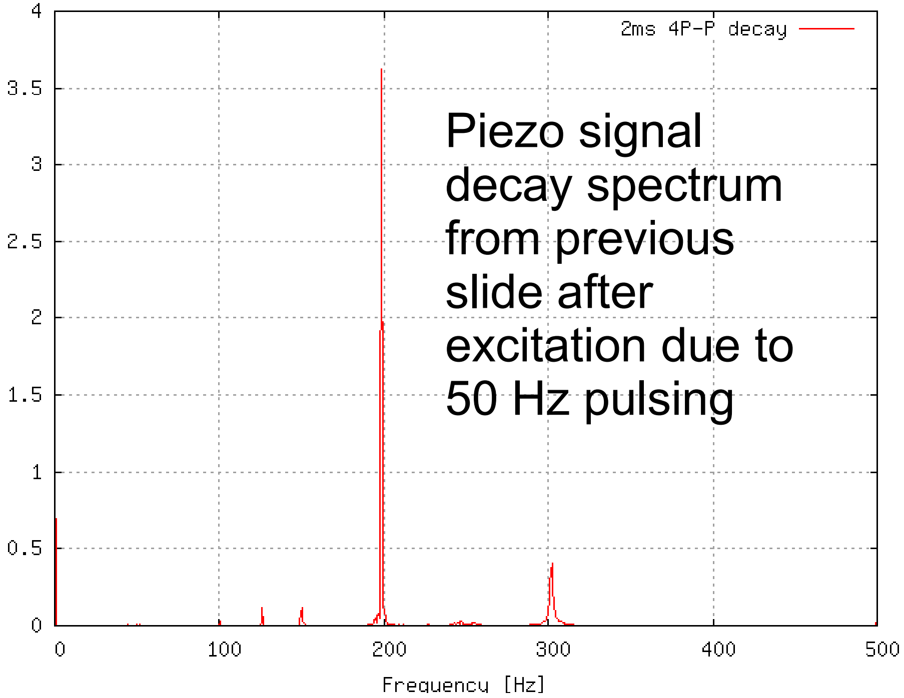
Piezo signal (used as a sensor)
Measurement in Cryholab, 1.8 K





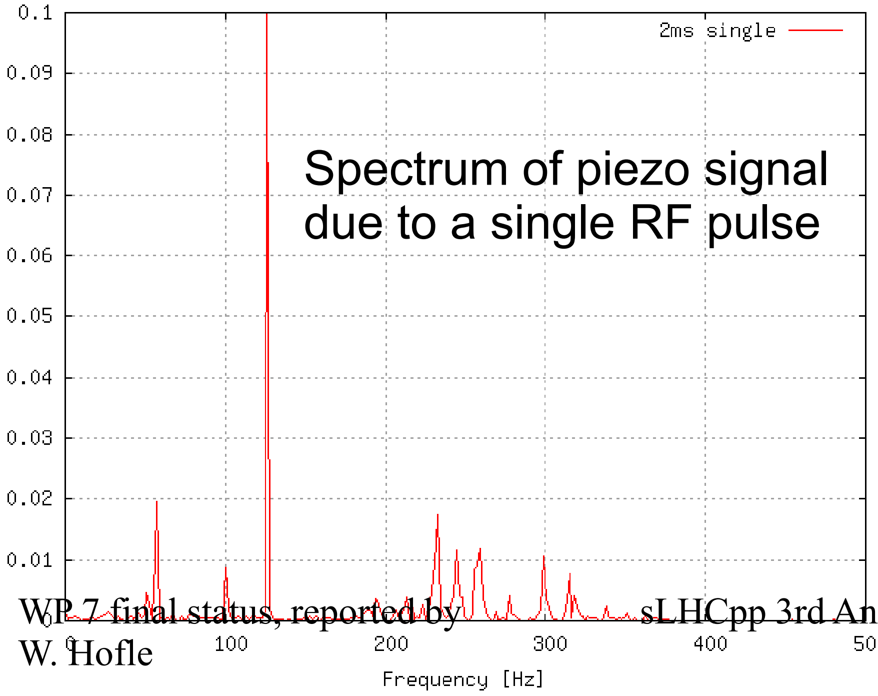
1 : Mechanical excitation due to Lorentz force detuning RF pulses 50 Hz, 2 ms, Eacc = 14.5 MV/m. Only stable oscillation observed. 20 ms between pulses is too short for the modes to decay.
2 : RF is switched off
3 : mechanical modes decay for approx. 2 s
4 : mechanical vibration due to the environment (the source of microphonics)

Pulsed tests on the 704 MHz beta 0.5 CEA cavity

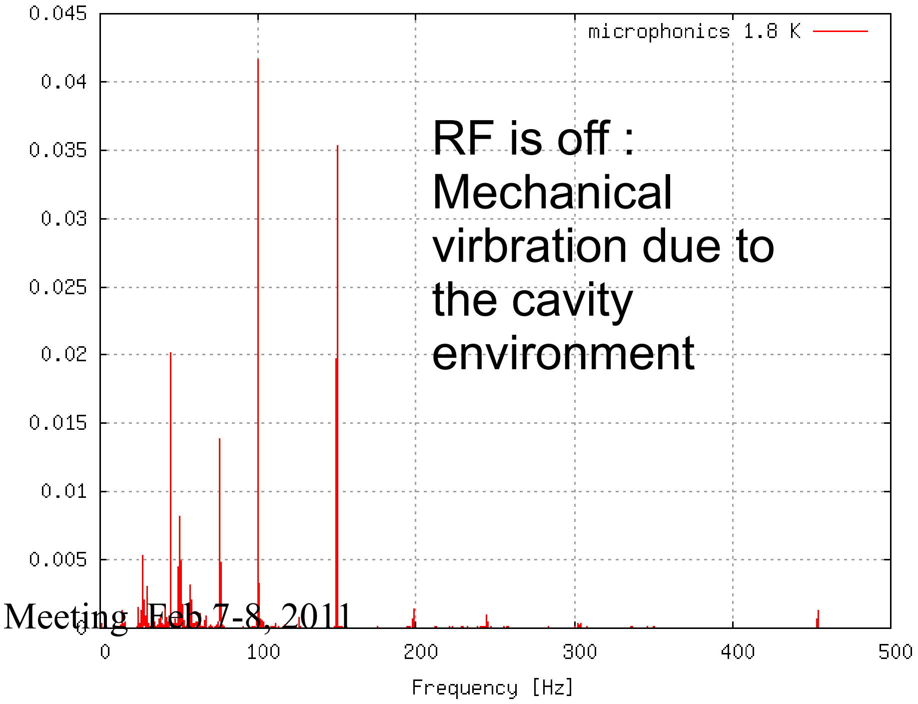


Piezo signal decay spectrum from previous slide after excitation due to 50 Hz pulsing

Q estimates : 400 for 198 Hz mode, 300 for 301 Hz mode



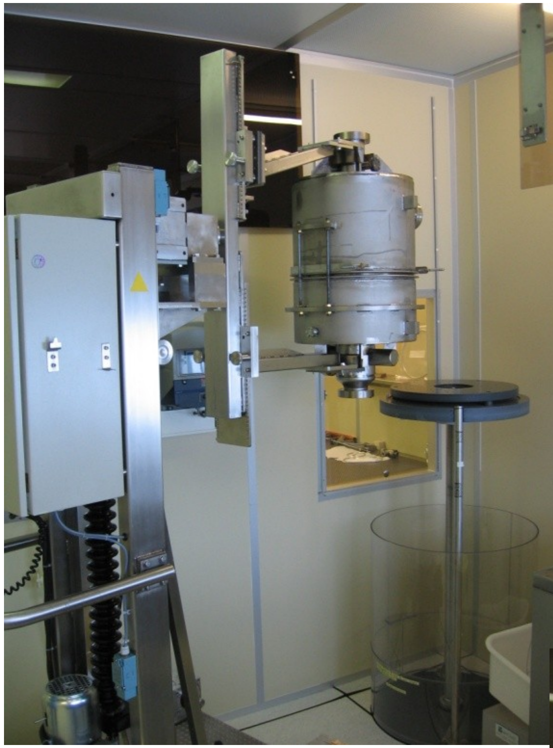
Spectrum of piezo signal due to a single RF pulse



RF is off : Mechanical virbration due to the cavity environment

Surface preparation and clean room assembly

BCP

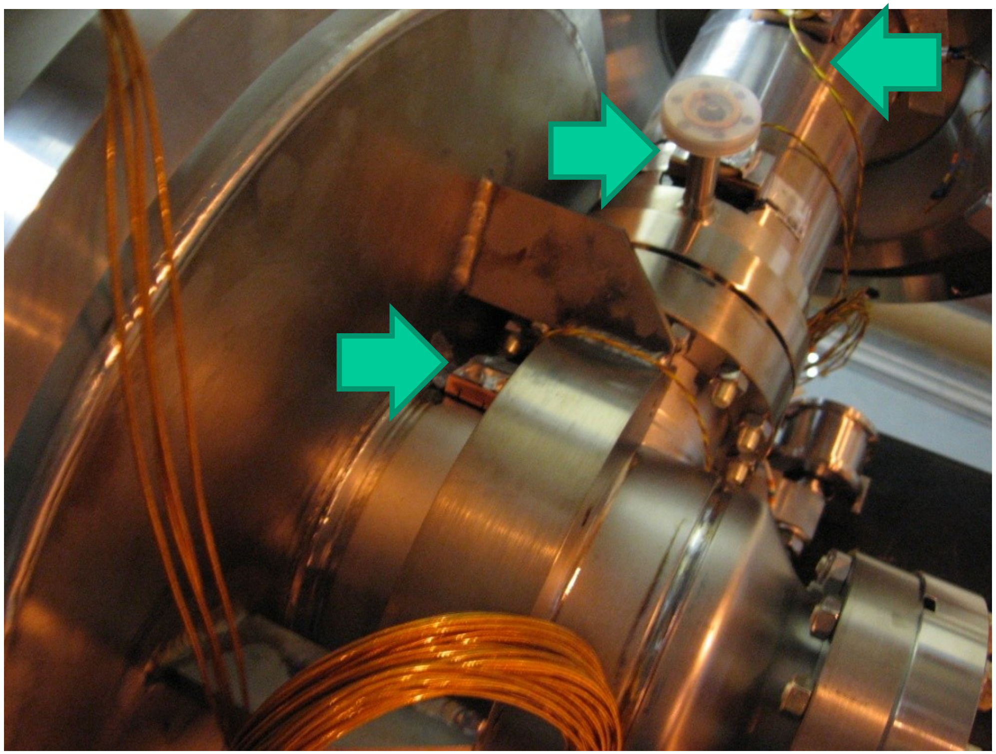


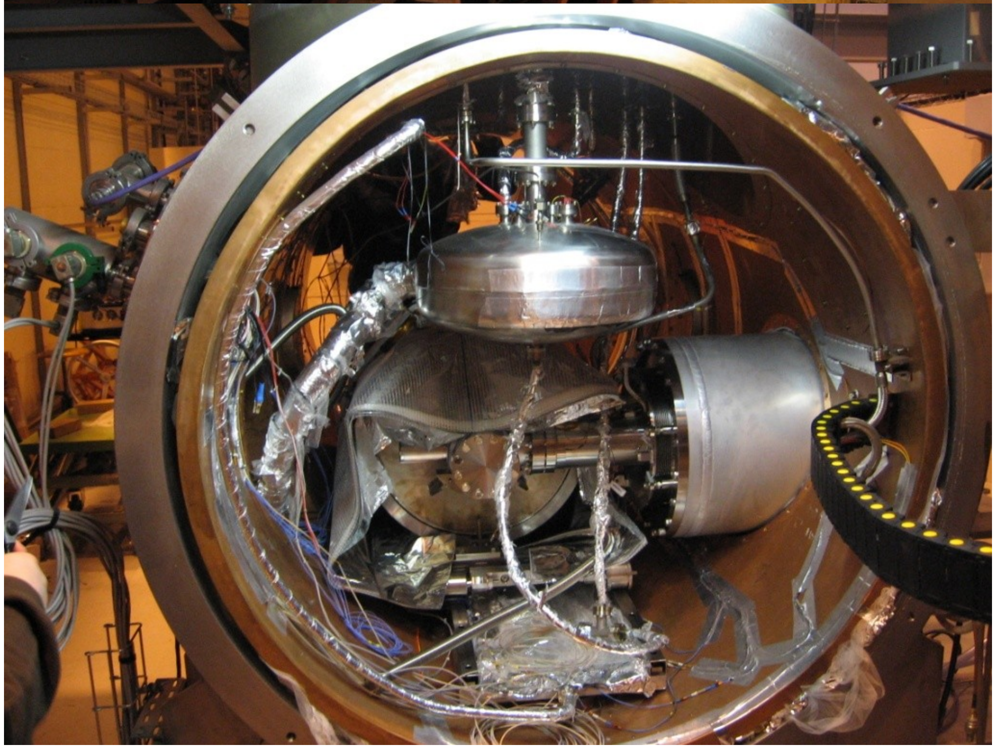
Installation on HPWR
inside clean room

drying

Power coupler
installation

Installation in horizontal test cryostat





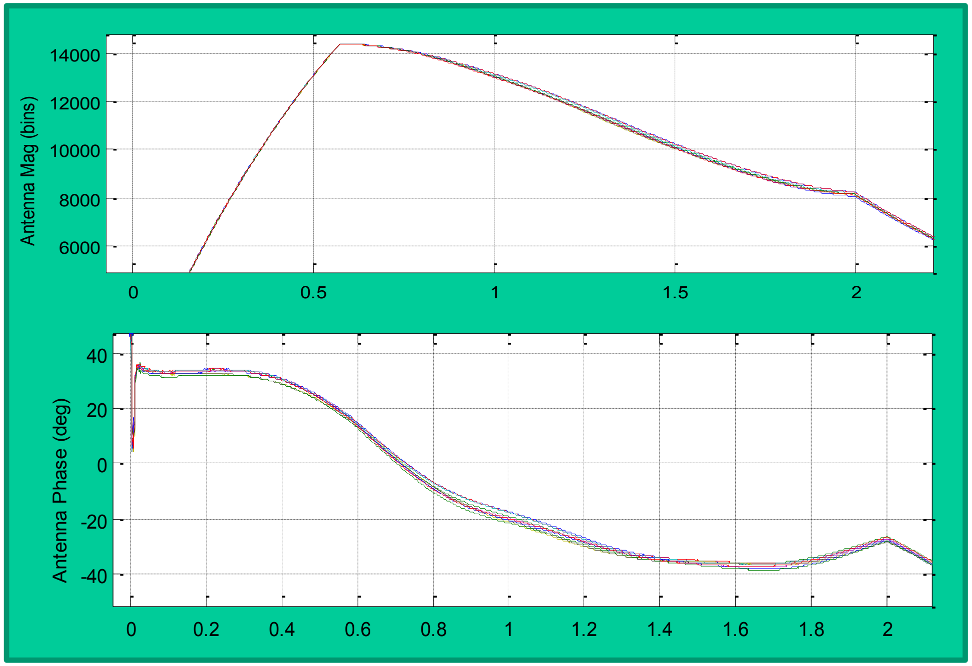
Th. sensors at critical location (coupler, coupler end group)

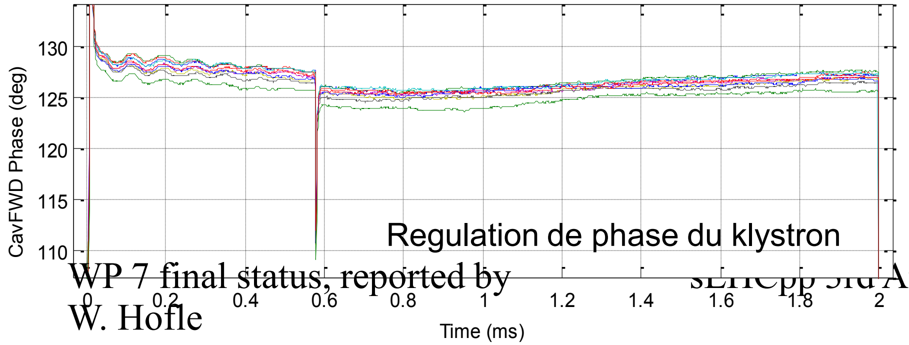
WP 7 final status, reported by
W. Hofle

Lorentz force comensation (Eacc = 13 MV/m)

Compensation piezo OFF

45% cavity voltage drop during the flat top due to Lorentz detuning
50° variation during flat top

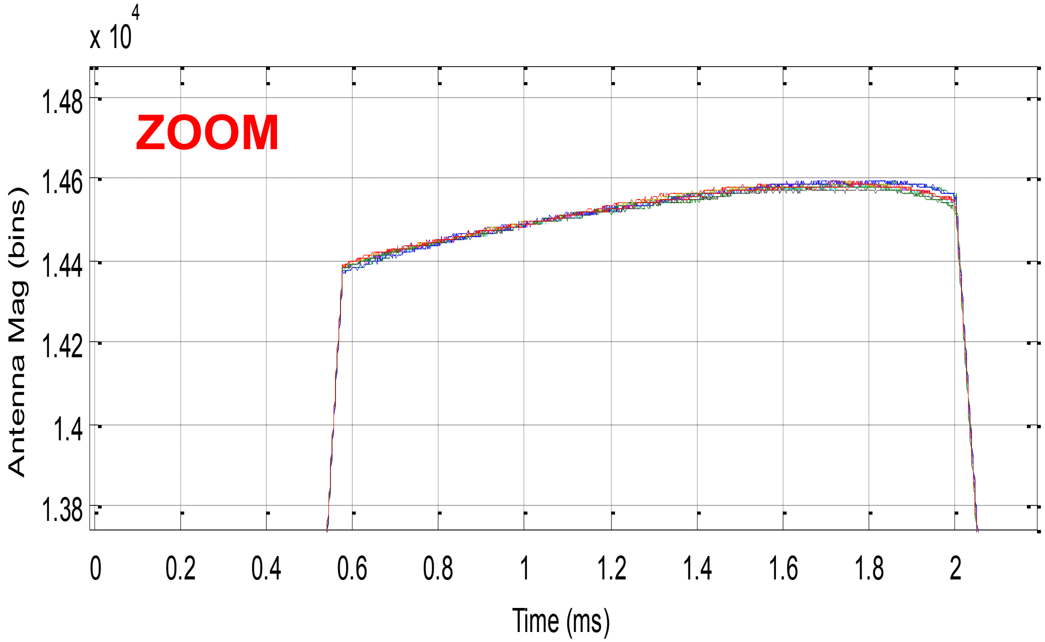




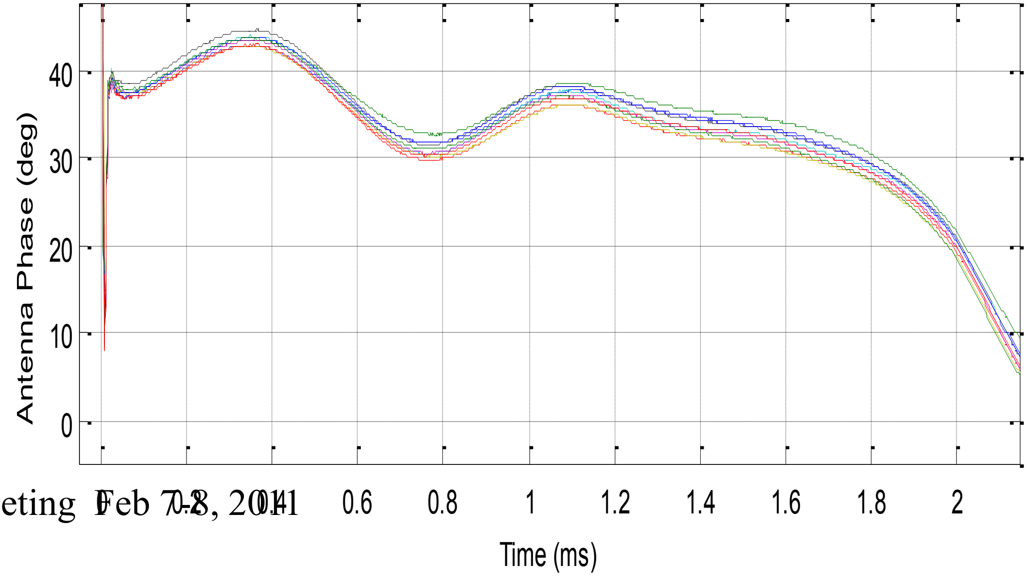
Regulation de phase du klystron

Compensation piezo ON

Amplitude excursion now reduced to 1.4% and phase shift within ± 8 deg.



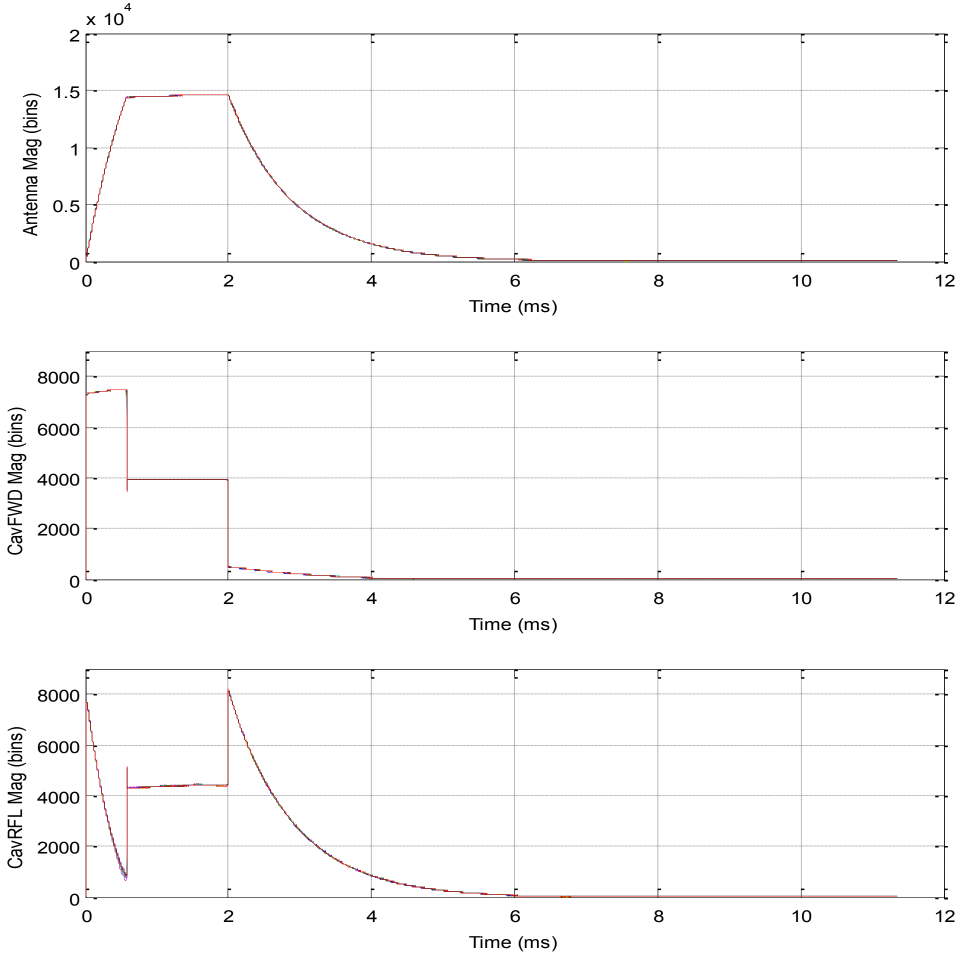
ZOOM



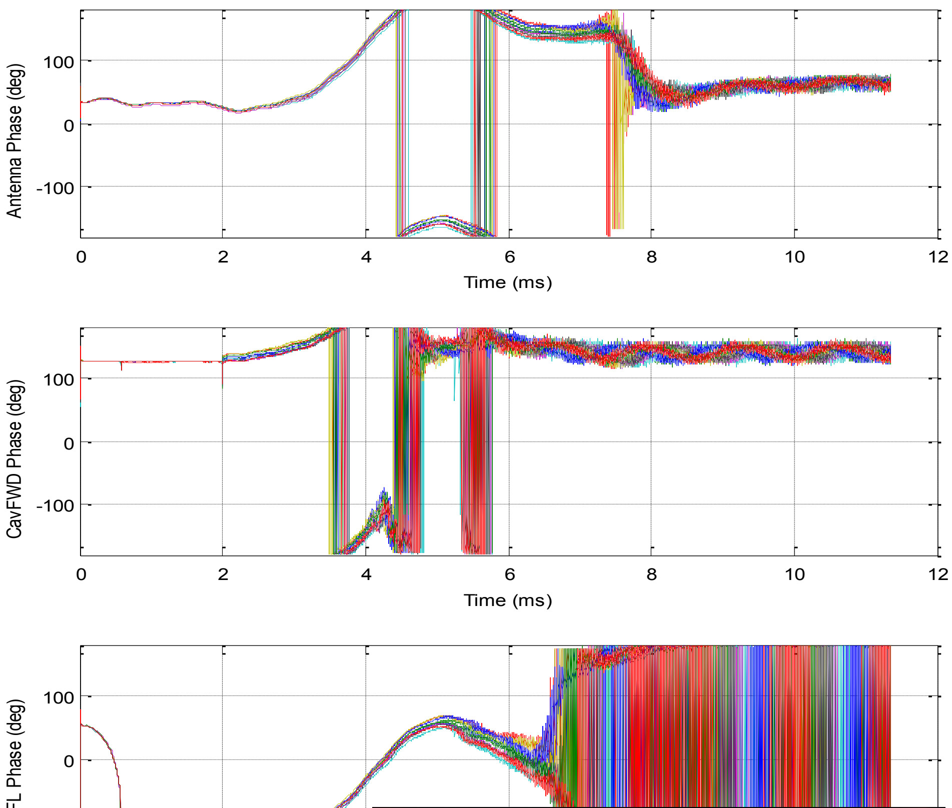
sLHC Lorentz force compensation with Saclay piezo tuner

Piezo ON

amplitude



phase



LFD Compensation achieved setting manually signal generators driving the piezo actuator. The piezo drive signal starts 940 μs before the RF pulse

Conclusions and outlook WP 7.2

- ☐ Cold testing of cavities and tuners → CEA cavity / tuner completed
  INFN cavity → March 2011
- ☐ Simulations: Progressed well, assembling into full SPL string of cavities ongoing, multi-parameter space, report to be completed by March 2011
- ☐ Field stabilization with Lorentz Force detuning compensation demonstrated experimentally on CEA Saclay cavity / tuner ensemble
- ☐ LLRF prototype hardware used in CEA Saclay test stand, plan for an evolution of this hardware exists, duplication for test stand at CERN possible

CEA Saclay and INFN cavity / tuner assemblies as completed at CEA Saclay