RF baseline, options & open issues

(200 MHz, 400 MHz, 800 MHz, possible wideband feedback system, crab cavities …)

Erk Jensen

CERN, BE-RF

3rd Joint HiLumi LHC-LARP Annual Meeting, 12-Nov-2013, Daresbury Lab.

Gratefully acknowledging: P. Baudrenghien, R. Calaga, W. Höfle, T. Mastoridis, E. Shaposhnikova for preparing this presentation … **and many other contributors!**

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Outline

- LHC Main RF System, ACS400:
  - power limitations
  - the solution: phase modulation
- Crab Cavities, "ACF400"
- High harmonic system (800 MHz)
- Wideband transverse damper system (HBTFB)
- ACN200 – the originally planned NC capture system
- A new fundamental RF system? ("ACS200")

The Main RF System, ACS400

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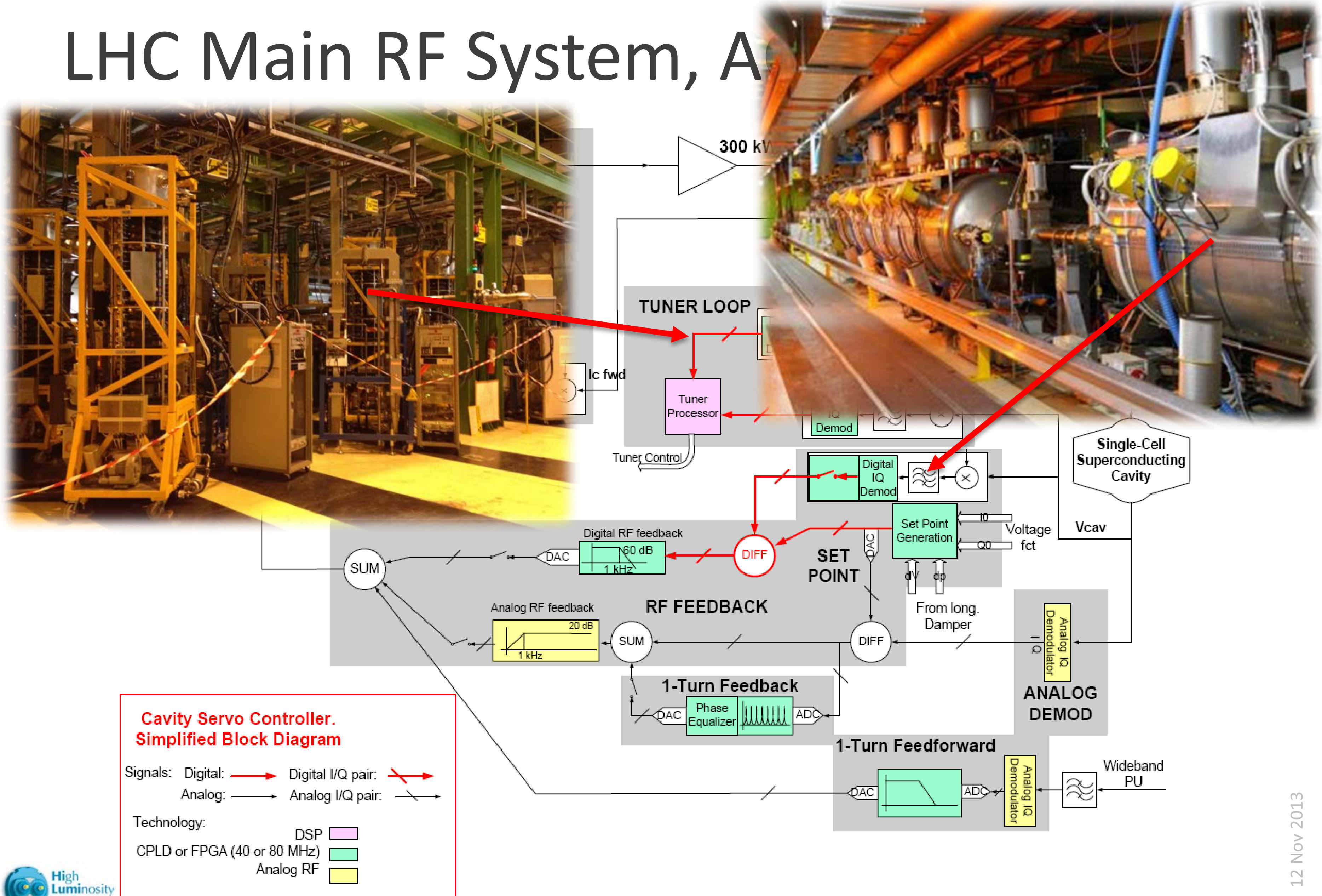
LHC Main RF System, A



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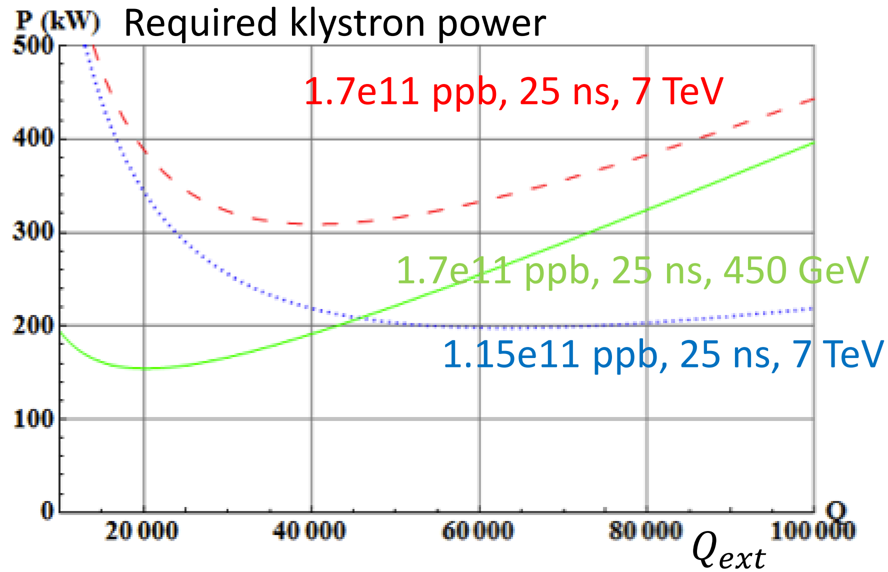
ACS400, **power limit** of present scheme

- The problem is transient beam loading excited by beam batches and gaps.
- System is currently setup for extremely stable RF voltage (minimizing transient beam loading effects, "half detuning"). Result: $< 1°$ RF phase variation ($7\ \mathrm{ps}, 2\ \mathrm{mm}$) with $0.35\ \mathrm{A\ DC}$.



- This scheme needs a lot of power – we reach the klystron absolute power limit of $300\ \mathrm{kW}$ at $0.86\ \mathrm{A\ DC}$ ($1.7 \cdot 10^{11}$ ppb, 25 ns)
- We must stay well below this limit for reliable operation, RF manipulations – with present DC settings, the klystrons saturate at $200\ \mathrm{kW}$.
- The present scheme **cannot be extended much beyond nominal**.

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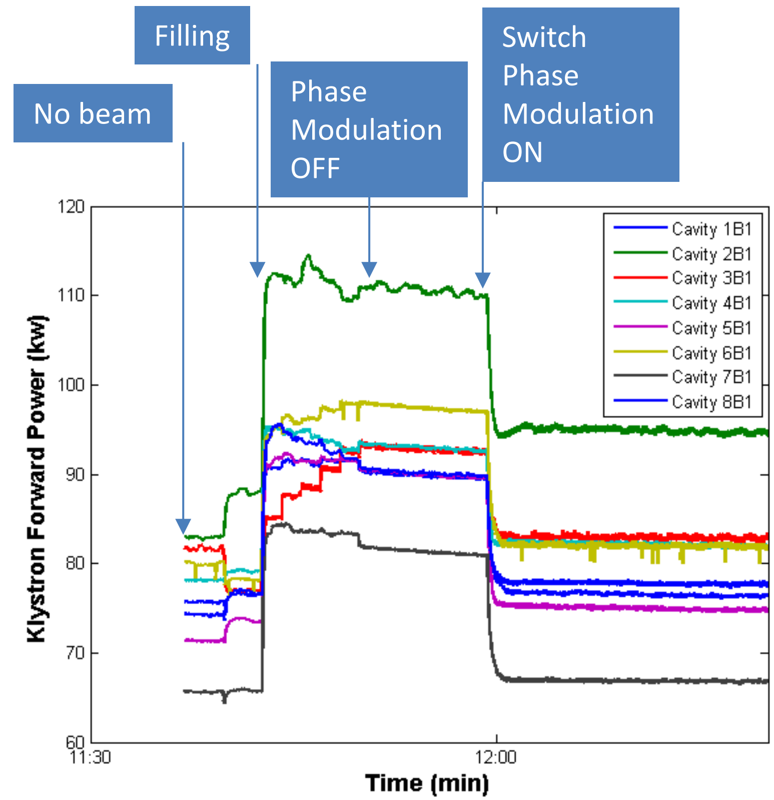
The idea: accept RF phase modulation

- Since the beam loading is mainly reactive, the beam loading transients will result in a variation of the cavity phase.
- If one accepts this phase variation and adapts the voltage set point for each bunch accordingly, the klystron drive is kept constant in amplitude and phase. (Proposed by D. Boussard in 1991)
- The gain is drastic: For $Q_{ext} = 6 \cdot 10^4$, the needed klystron power for 1.5 MV (12 MV total) is only 105 kW, almost independent of beam current.
- Beam stability is not compromised!
- Symmetric filling schemes will ensure that the luminous region is not displaced.
- This was tested in MD's – result see right.



Klystron power (8 stations)

- This has an important impact on **crab and harmonic cavity** operation!

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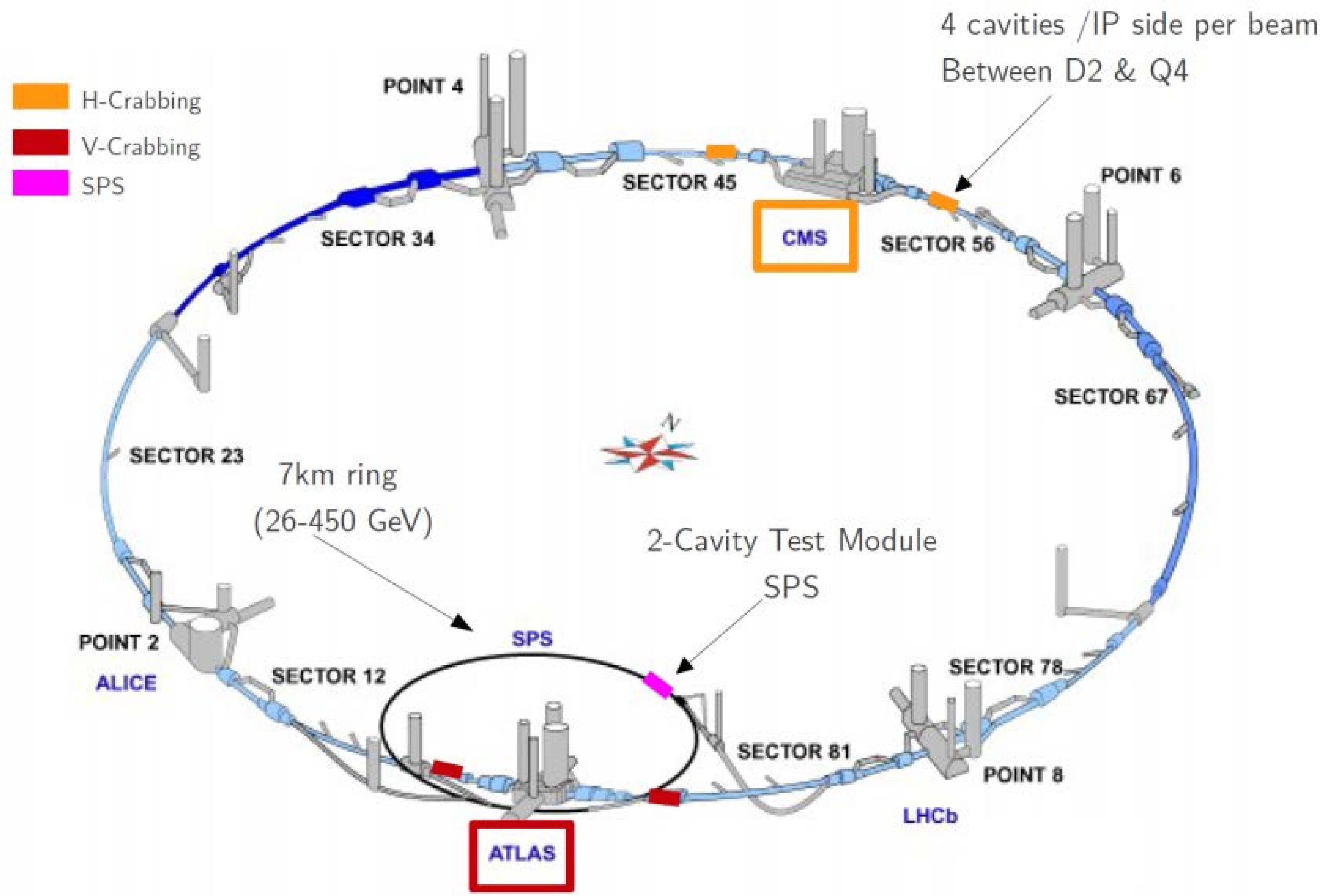
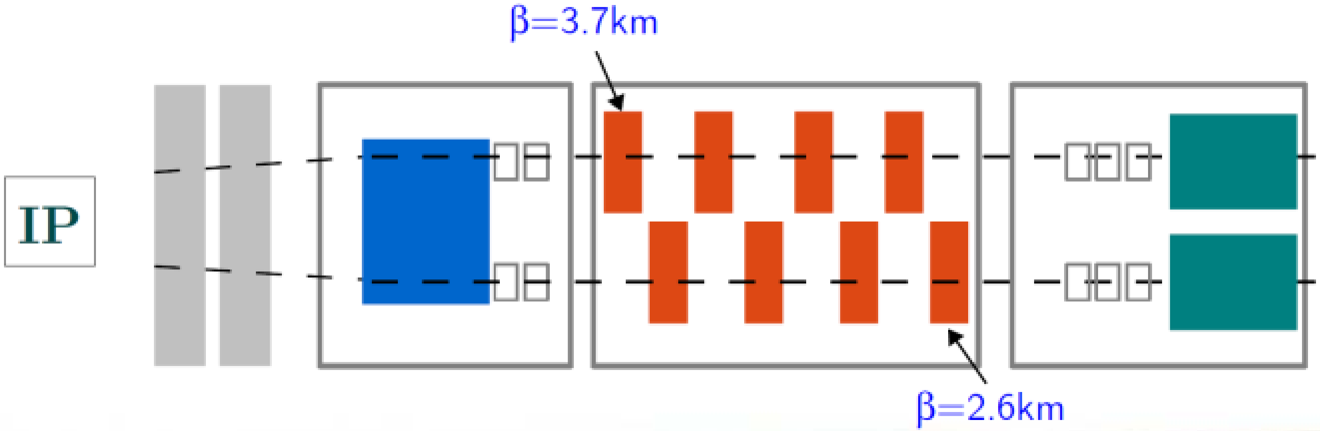
Crab Cavities

The LHC Crab Cavity Scheme



Some Basic Parameters

Operating frequency	400.79 MHz	
Kick voltage/cavity	3.4 MV	
Total kick voltage	13.6 MV	4 cavities! recent change!
Beta function β_{CC}	$(2.6 \div 3.7)$ km	
Number of cavities	$4 \cdot 2_{(IPs)} \cdot 2_{(sides)} \cdot 2_{(beams)} = 32$	
Q_{ext}	$5 \cdot 10^5$	
RF power/cavity	80 kW	
Cavity tuning range	± 1.5 kHz	

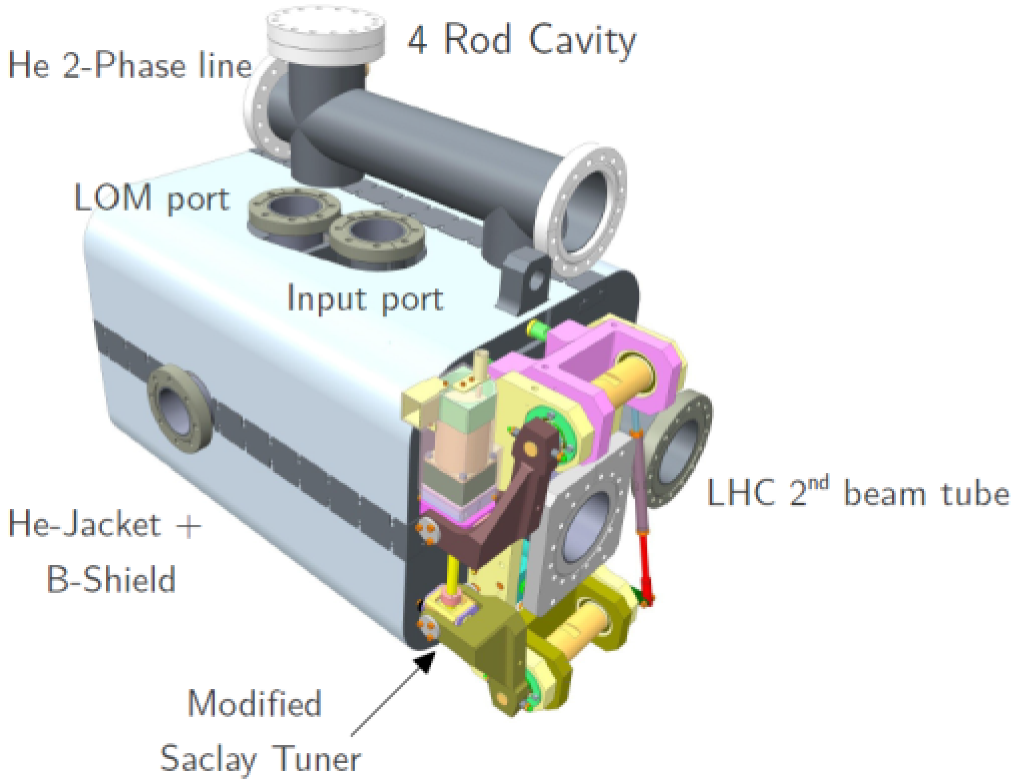


Technology Choice

- Three valid Nb prototypes exist – very compact concepts to allow for their integration in LHC

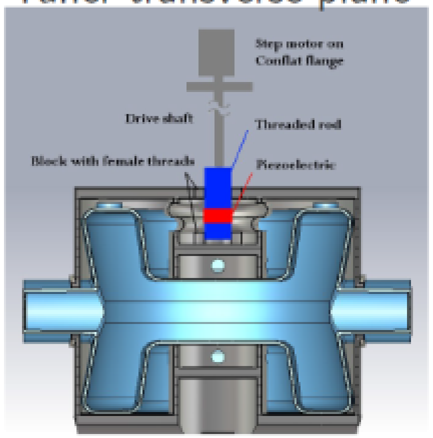
Double ¼-wave	RF Dipole	4-rod

Dressed Cavity Concepts – well advanced



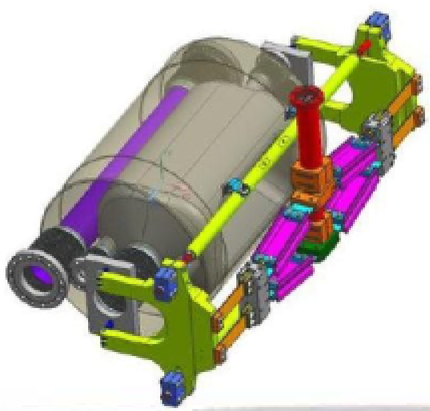
Double Quarter Wave

Tuner transverse plane

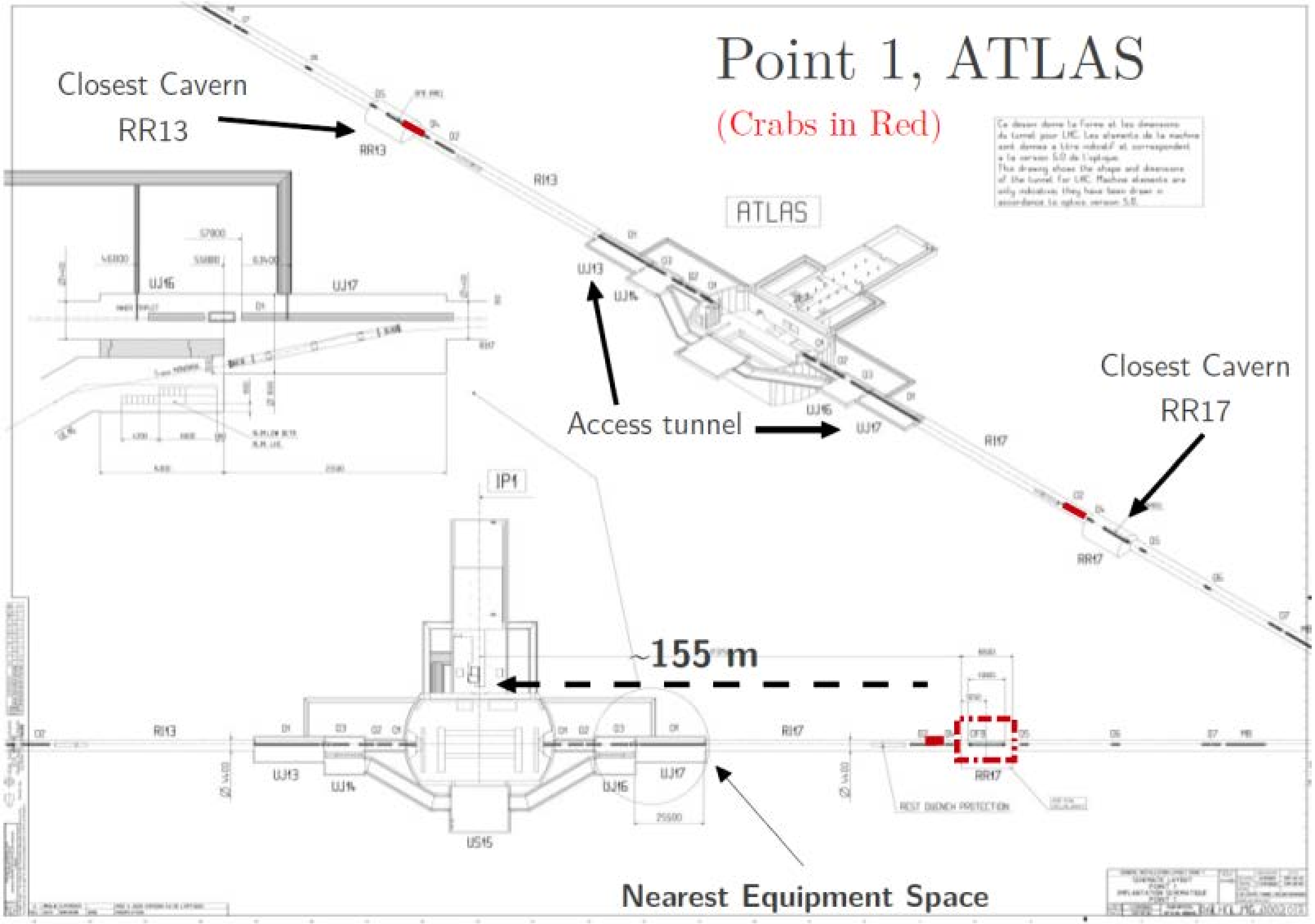


RF Dipole

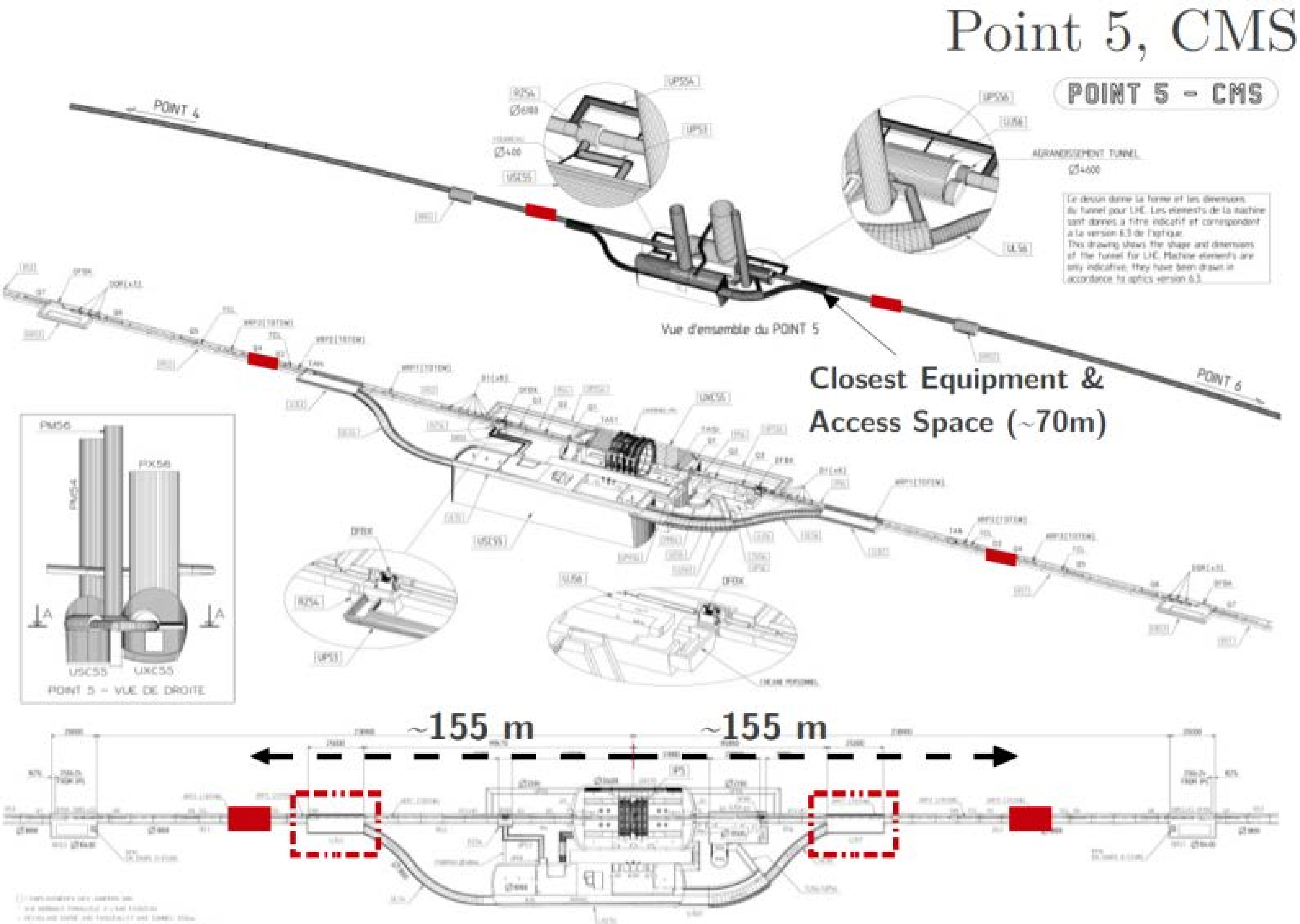
Longitudinal tuning



Integration in LHC IP1

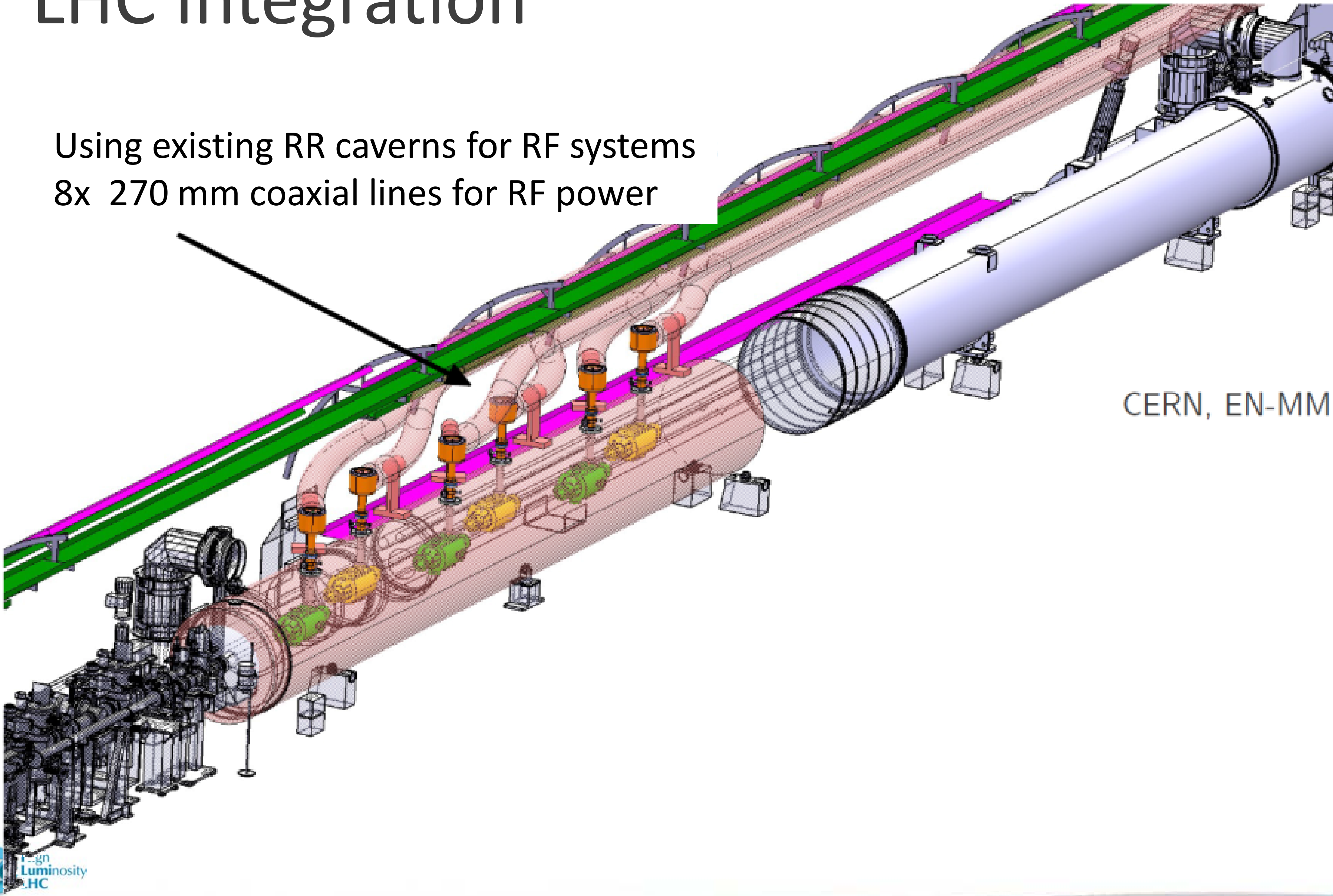


Integration in LHC IP5

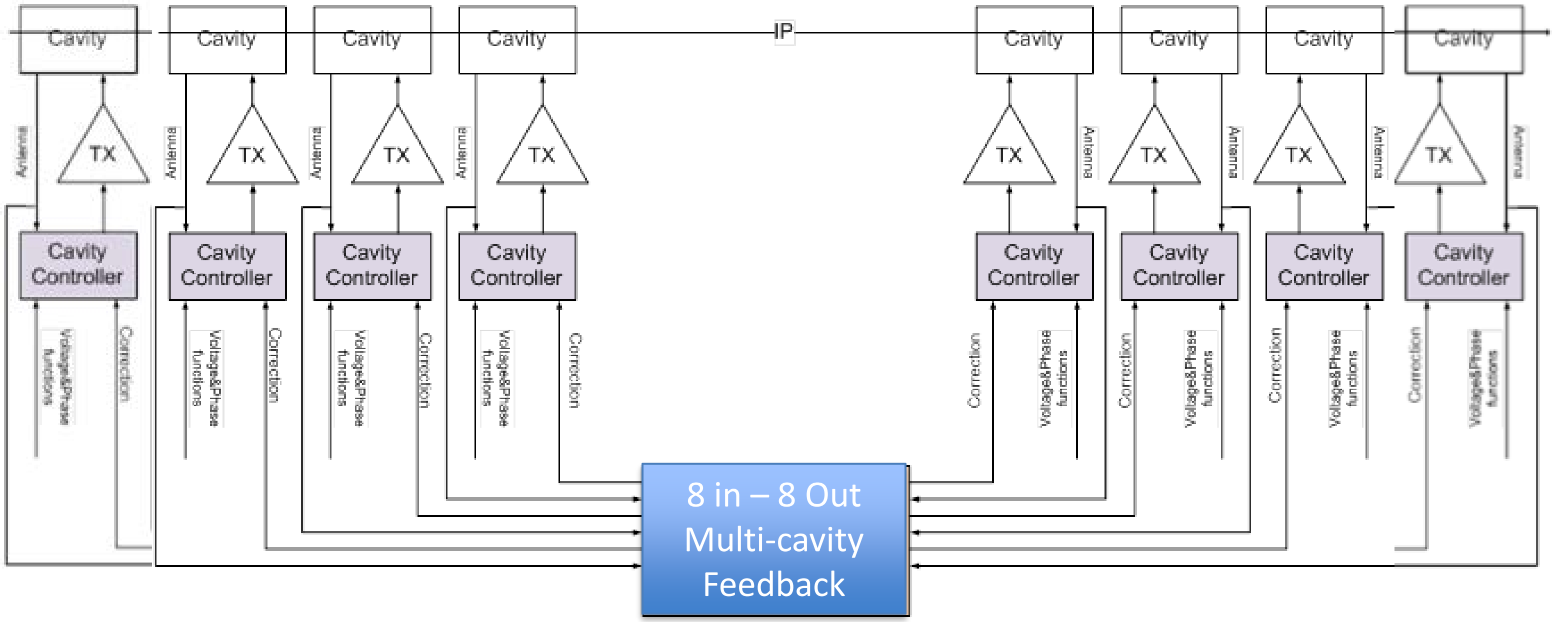


LHC Integration

Using existing RR caverns for RF systems
8x 270 mm coaxial lines for RF power



RF system conceptual layout



Cavity Controller	Strong RF feedback (< 1 μs loop delay) regulating the individual cavities
8 in – 8 Out Multi-cavity Feedback	Global feedback regulating the relative crabbing-uncrabbing actions. Sligthly larger loop delay (< 5 μs loop delay?)

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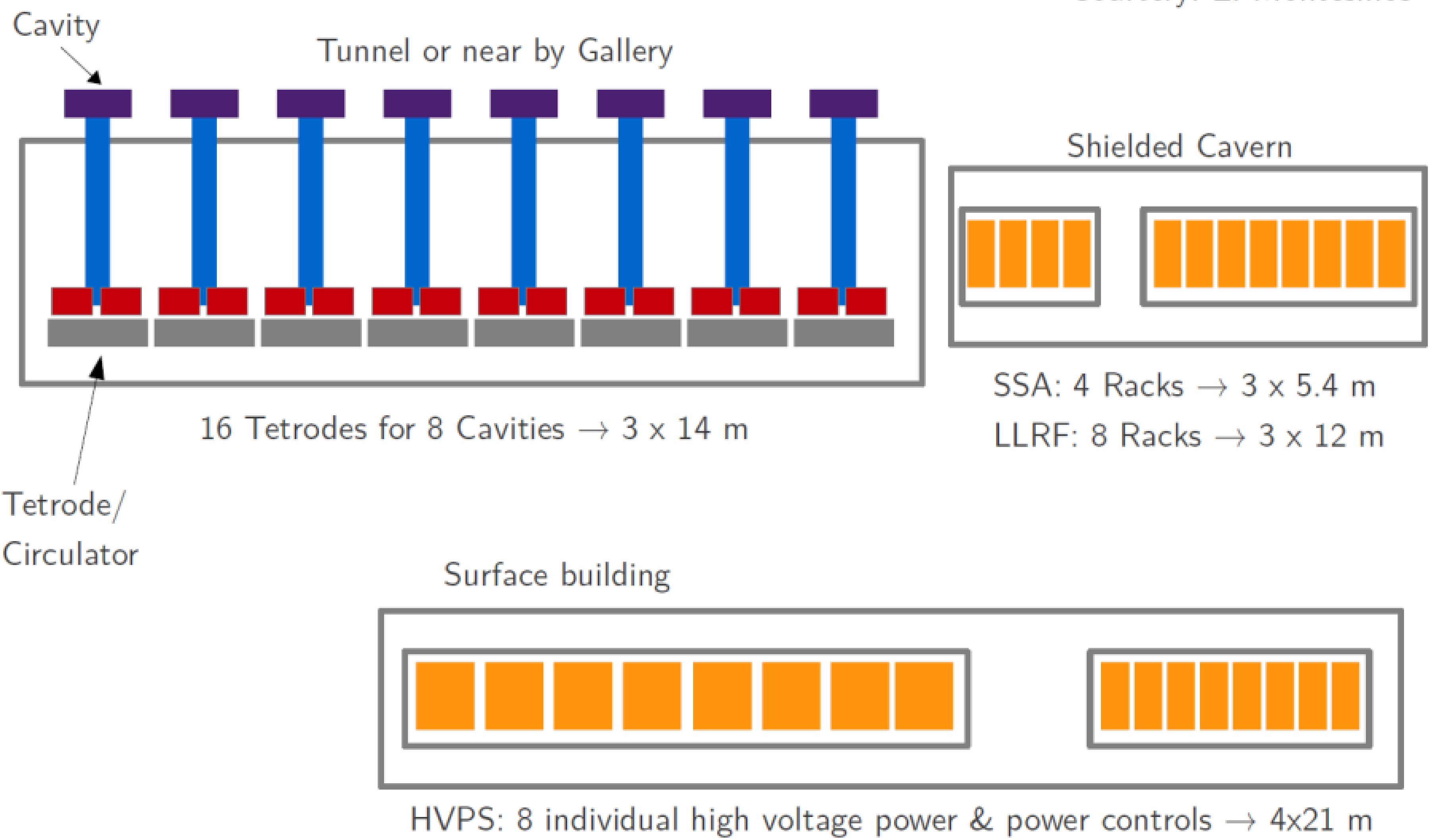
https://cds.cern.ch/record/1557219

Peripherals – space required

Courtery: E. Montesinos



More details on integration by P. Fessia later today

Required space: summary table

What?	Where?	Required space	# /IP /side
Cryomodule	tunnel	10 m /IP/side	8 cavities
Cryo jumpers	tunnel	integrated with QRL	8 jumpers
RF amplifiers	tunnel/cavern	3 m x 14 m	8 tetrodes
Circulators & loads	tunnel/cavern	included above	8
Drivers & controls	shielded cavern	3 m x 5.4 m	8 racks
LLRF racks	shielded cavern	3 m x 12 m	8+1 racks
LLRF central rack	exp. cavern	3 m x 10 m	5+1 racks
Slow controls	exp. cavern	3 m x 5 m	3 racks
Remote alignment	exp. cavern		
HV supply	surface building	4 m x 16 m	8

Crab Cavern: Nearest shielded location to the crab cavities ($< 1\ \mu s$ round trip, including tetrode-circulator-driver-cable group delay, LLRF latency 100 ns)
Therefore only ~ 40 m cabling max.!

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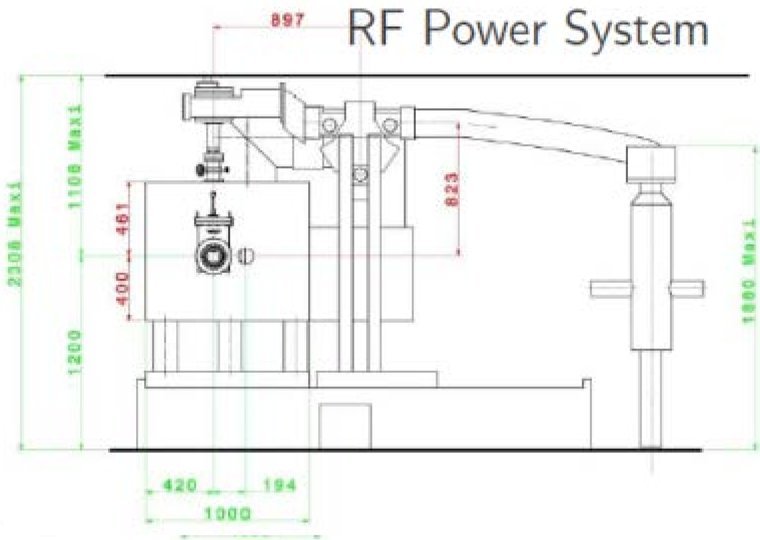
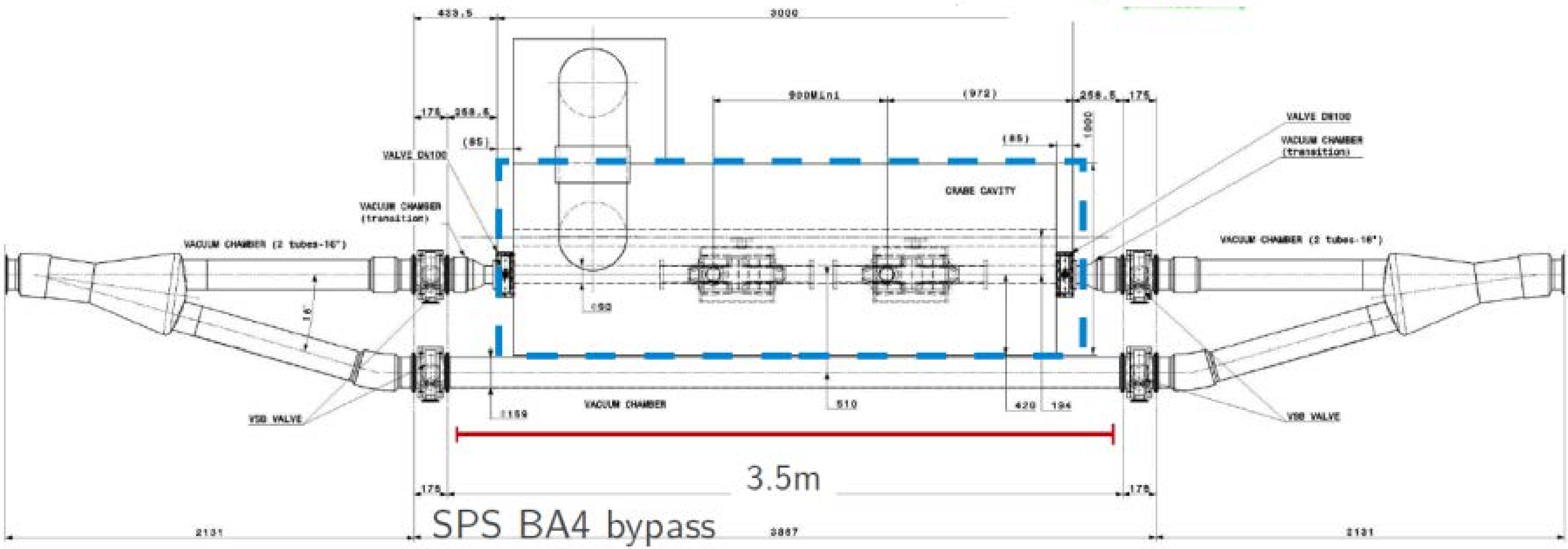
SPS Test Module

Proof of principle demonstration with protons

Important beam tests:

- Technology validation, performance, stability,
- Effects on the beam, cavity failure modes, radiation

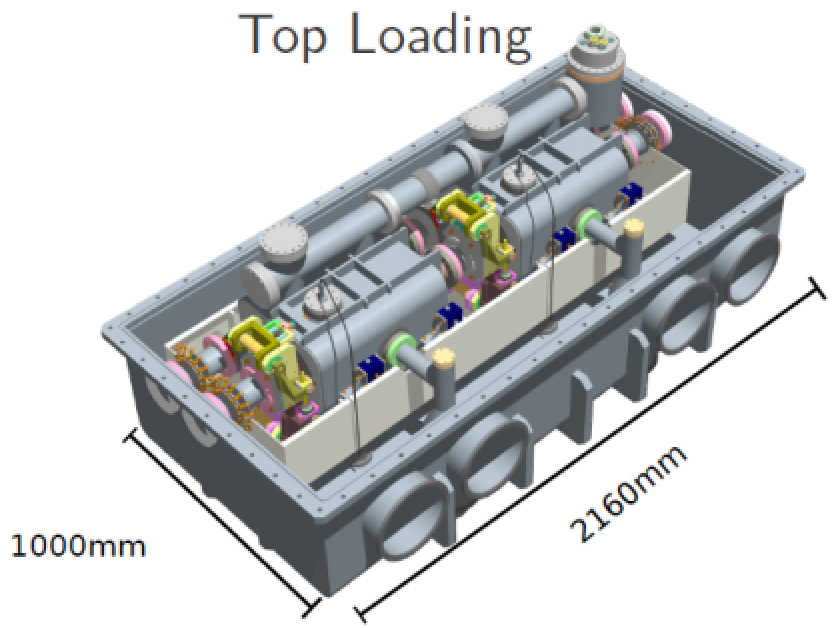


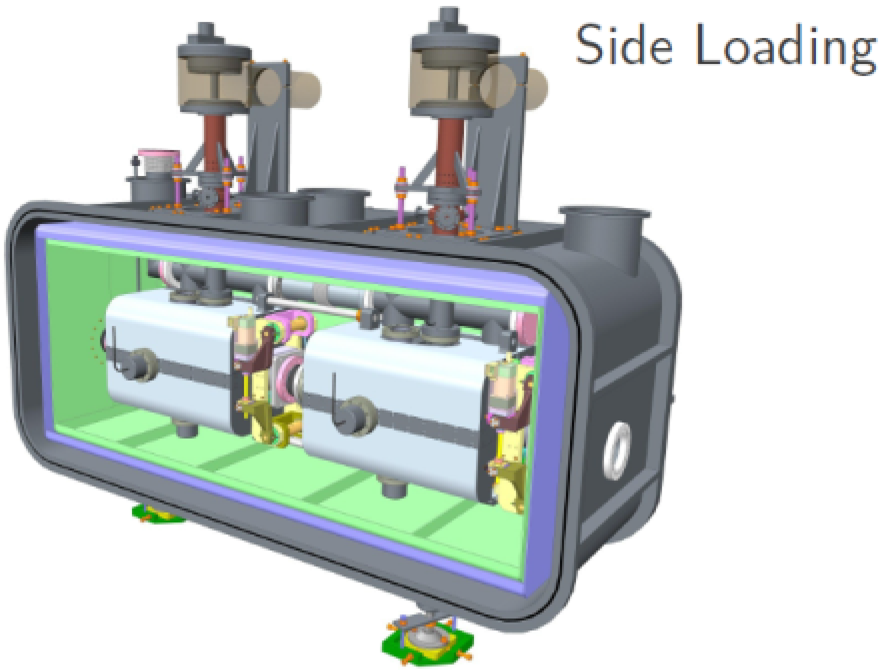


Preparation/integration in full swing – more details by A. Macpherson tomorrow.

Cryostat proposal for SPS tests (4-rod)

S. Pattalwar, T. Jones

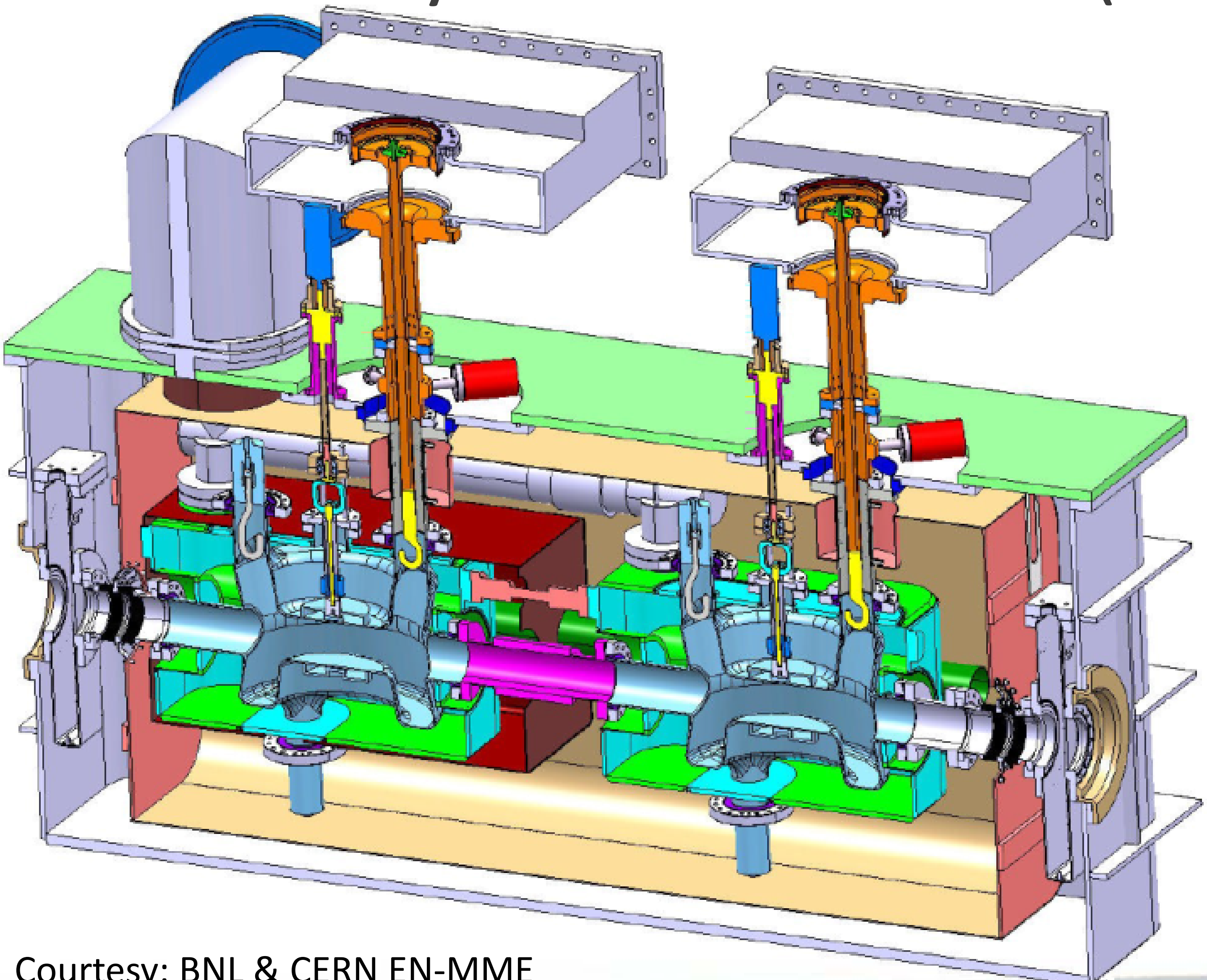




Simplified cryostat for easy assembly/access/maintenance,
but with relevant features of the LHC system (2 cavity cryostat, alignment, 2nd beam tube …)

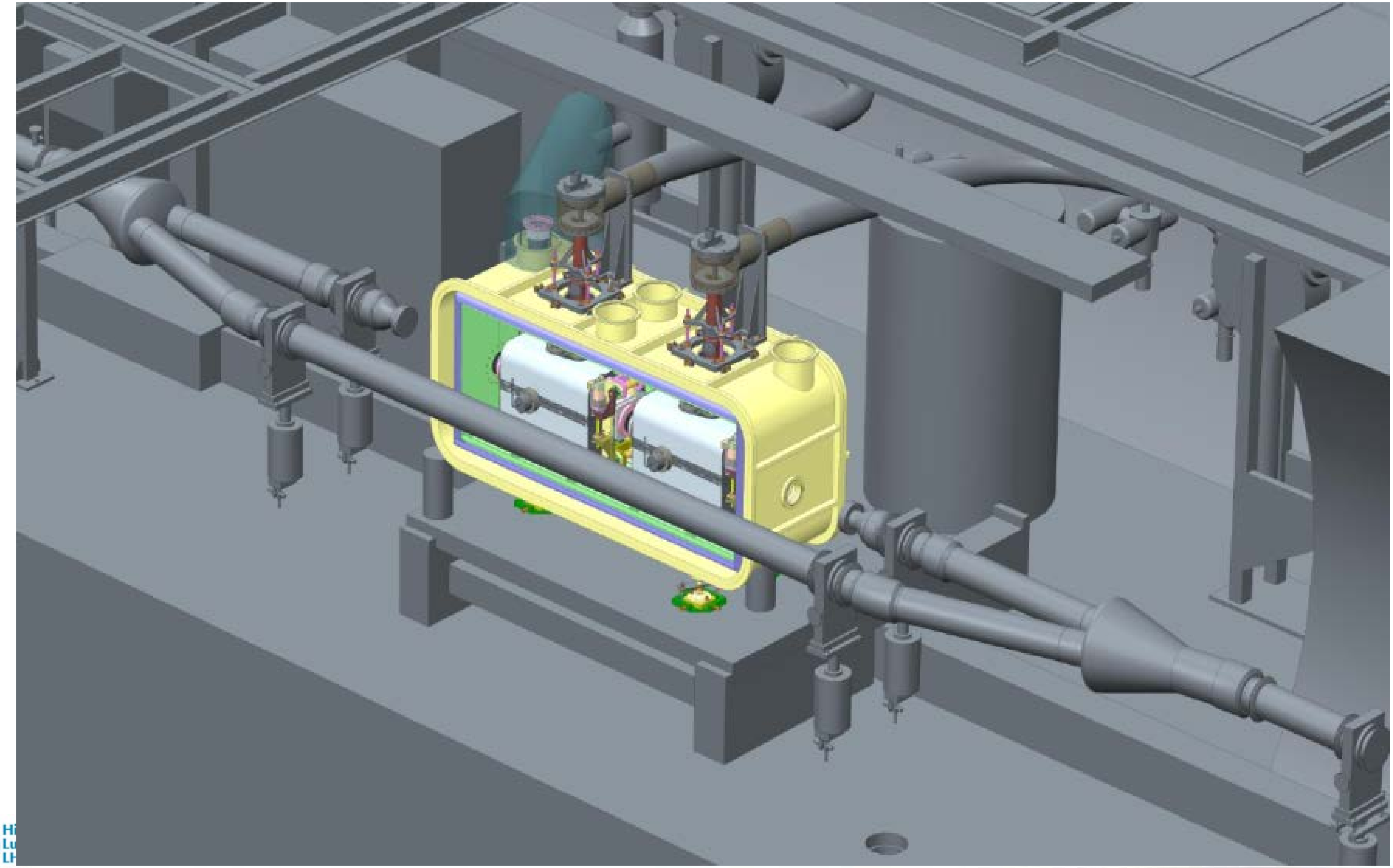
Very advanced! - more details by S. Pattalwar tomorrow

Alternative Cryostat for SPS test (DQW)

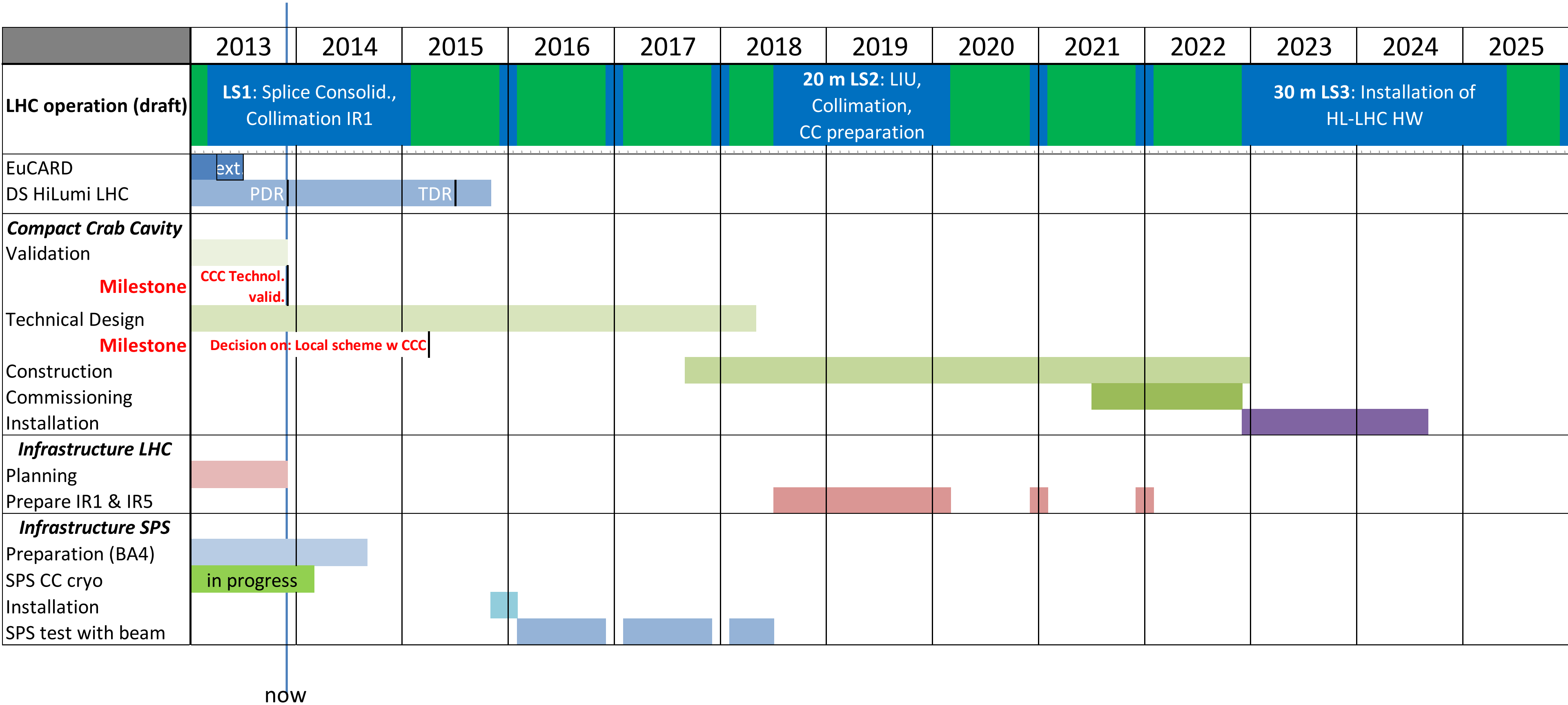


Courtesy: BNL & CERN EN-MME

SPS Integration (e.g.: 4-rod



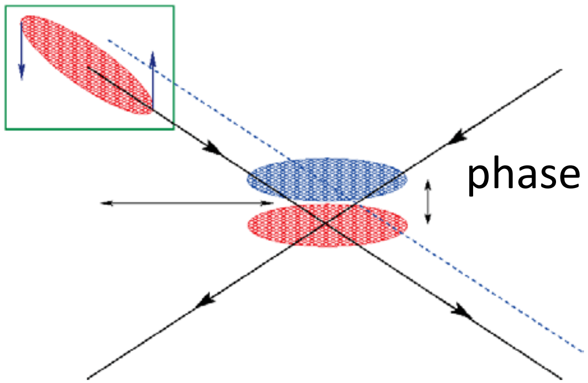
Draft of an updated schedule *)



*) Attention: This is assumed – not approved

Phase modulation and crab cavities

- If the crab cavity phase is kept constant, The phase modulation would offset the bunch centres by $\Delta x = \frac{c\theta}{\omega}\Delta\varphi$.
- With a phase error of $8°$ (realistic) and a half crossing angle of $295\ \mu\mathrm{rad}$, this offset would be $5\ \mu\mathrm{m}$, so roughly the transverse beam size.
- For symmetrical filling patterns, this would not lead to luminosity loss.



- In principle, also the crab cavities could be phase modulated to track the beam phase modulation resulting from beam loading transients. First studies indicate however that this would require a drastically reduced Q_{ext} and increased power.

High Harmonic RF System

High harmonic RF system

- **Voltage** in a double RF system:

$$V = V_1 \sin\varphi + V_2 \sin(n\varphi + \Phi_2)$$

(stationary bucket above transition):

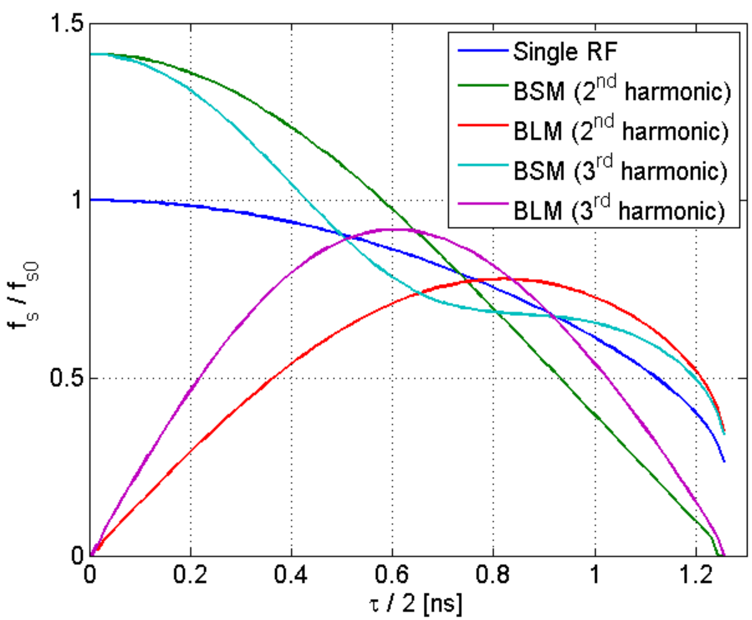
$\Phi_2 = 0$: bunch-lengthening (BL) mode

$\Phi_2 = \pi$: bunch-shortening (BS) mode

Purpose: Usually used to

- modify line density distribution ("flat" bunches in BL-mode) – can also be achieved in a single RF system but for a limited time (IBS, RF noise, SR)
- increase synchrotron frequency spread for beam stability (BL- or BS- mode)
- increase bucket size (only BL-mode)

Synchrotron frequency distribution inside the bunch



LHC high harmonic system studies:

- "LHC Luminosity and Energy Upgrade: A Feasibility Study", LHC Project Report 626, 2002, O. Brüning et al.
- LHC Luminosity upgrade scenario with short bunches (F. Zimmermann et al., 2002; S. Fartoukh, 2011)
- LHC Luminosity upgrade scenario with flat long bunches (F. Zimmermann et al.)
- Beam stability (T. Linnecar, E. Shaposhnikova, 2007)
- Reduction of beam induced heating and e-cloud effect (C. Bhat et al., 2011)
- Reduction of the IBS effect and beam losses on FB (T. Mertens et al., 2011)
- Decrease of luminosity pile-up density (S. Fartoukh, R. Tomas)

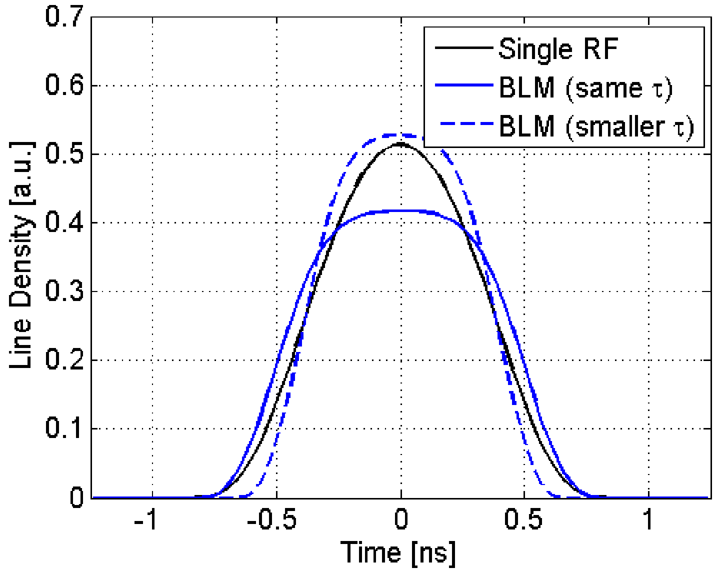
→ Preliminary cavity design of the 800 MHz RF system for LHC exists (L. Ficcadenti, R. Calaga, J. Tückmantel; M. Zobov et al.)

→ Tests of effect of “flat” bunch distribution in a single RF system on beam induced heating was performed in LHC in 2012

High Luminosity LHC

400 MHz (V) + 800 MHz ($V/2$)

Bunch profile

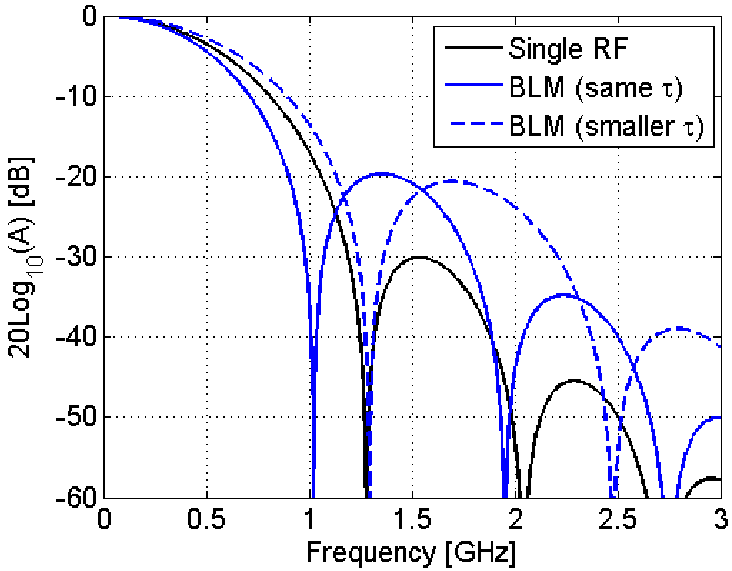


Single RF: $\tau = 1.5\text{ ns}, \varepsilon = 4\text{ eVs}$

Double RF: $\tau = 1.5\text{ ns}, \varepsilon = 3.2\text{ eVs}$

$\tau = 1.25\text{ ns}, \varepsilon = 1.65\text{ eVs}$

Power spectrum



At the same bunch length:

- improvement below 1.2 GHz
- degradation above

For shorter τ: larger values at all frequencies

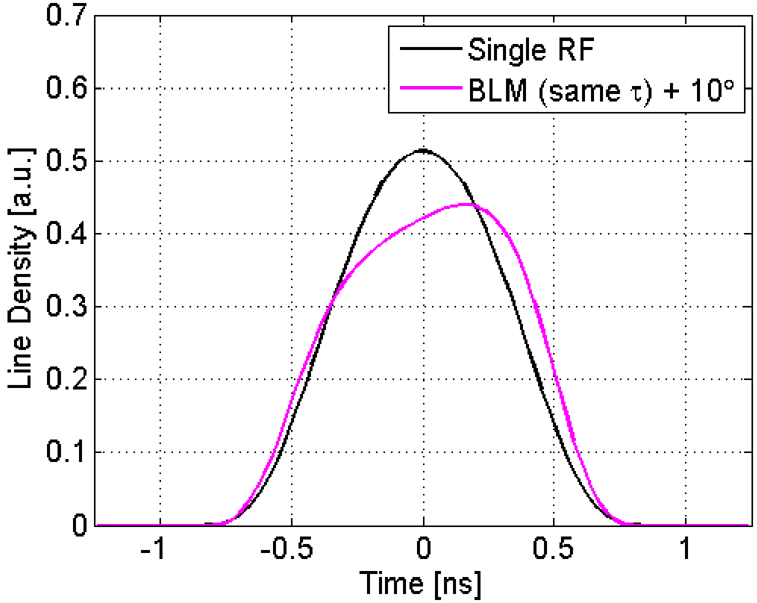
High Luminosity LHC

Phase modulation & harmonic cavity

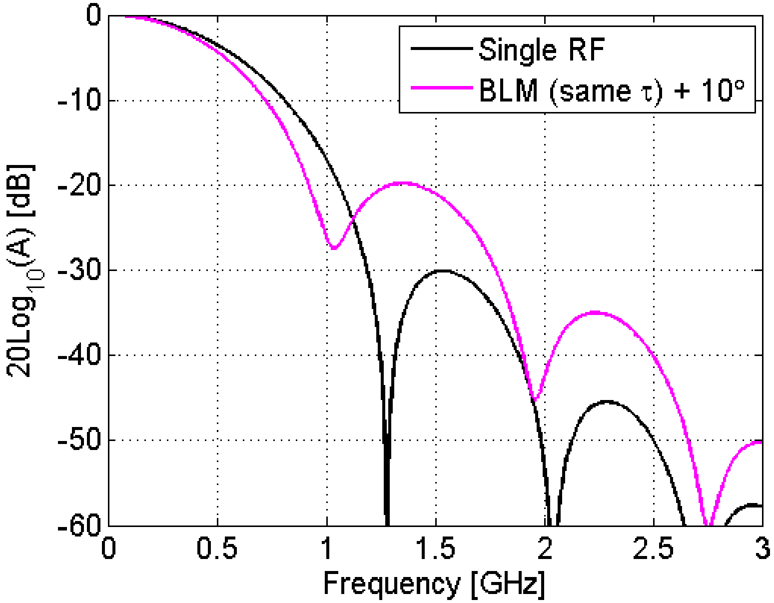
- In **bunch shortening mode** ($\Phi_2 = \pi$, 400 MHz and 800 MHz in phase at bunch passage), the φ modulation scheme can reduce the power requirement on the generators of the harmonic cavities, with a proper choice of the RF parameters: R/Q, Q_L and voltage. With this optimal choice a good part of the voltage is induced by the beam passage. This mode is of little interest in the LHC (heating).
- In **bunch lengthening mode** ($\Phi_2 = 0$, 400 MHz and 800 MHz in counterphase at bunch passage), the scheme will significantly increase the required RF power, while still keeping it manageable if the voltage per cavity is reduced. This mode is preferred.
- The optimal coupling differs between the two applications: high Q_L is needed in bunch shortening mode and low Q_L in bunch lengthening mode.
- With 3.2 μs abort gap, 1.11 A DC, bunch length 1 ns, 16 MV @ 400 MHz:
  - 8 MV @ 800 MHz require 55 kW/cavity, 5 cavities in bunch shortening mode.
  - 8 MV @ 800 MHz require 260 kW/cavity, 8 cavities in bunch lengthening mode.

Phase modulation leads to tilted bunches

Bunch profile



Power spectrum



Single RF: $\tau = 1.5 \text{ ns}, \varepsilon = 4 \text{ eVs}$

Double RF: $\tau = 1.5 \text{ ns}, \varepsilon = 3.2 \text{ eVs}$

No significant improvement for tilted bunches

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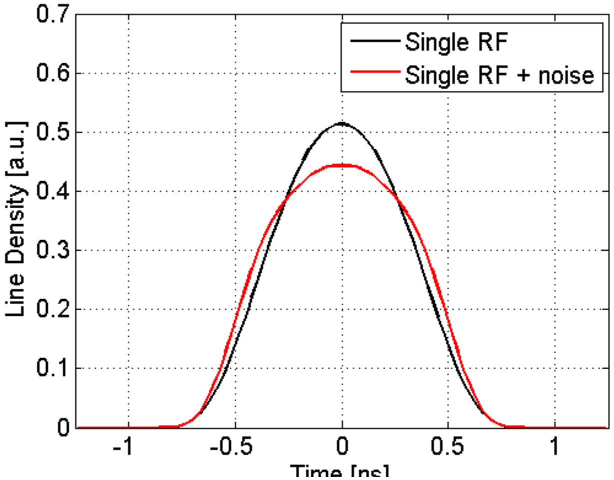
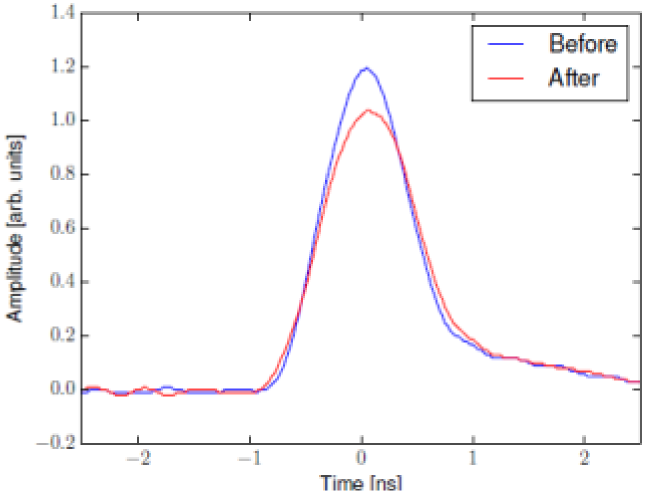
Flat bunches with a single RF system

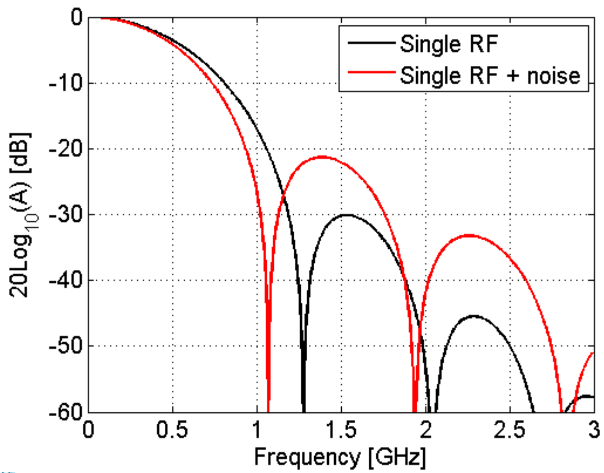
Simulations

Measurement (LHC MD 2012)

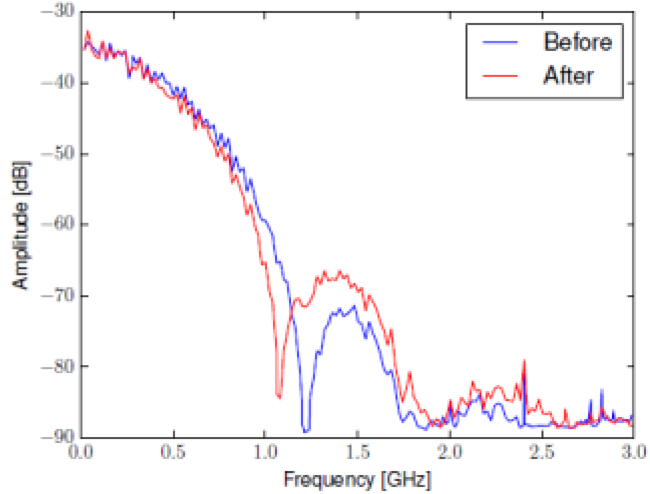


Bunch profile





Spectrum



High Luminosity LHC

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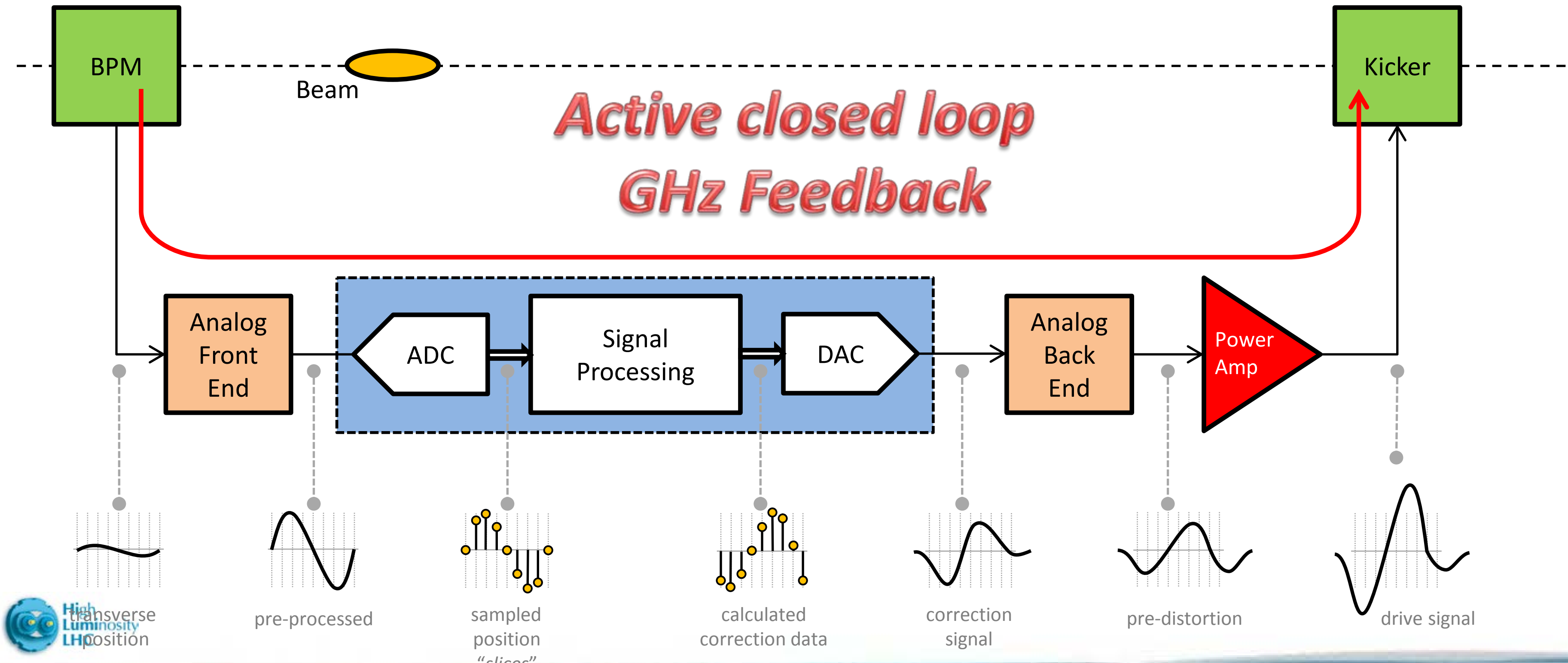
Wideband Transverse Damper (HBTFB)

Wideband Transverse Damper

- **Applicable to LHC injectors and LHC proper**
- Intra-bunch **GHz transverse feedback** system
- **stabilize beam** against e-cloud and impedance driven intra-bunch oscillations
- Proof of principle system being developed with **LARP for SPS**
- **Full SPS implementation included in SPS upgrades (US2)**
- **Complementary to existing rigid bunch transverse feedbacks**

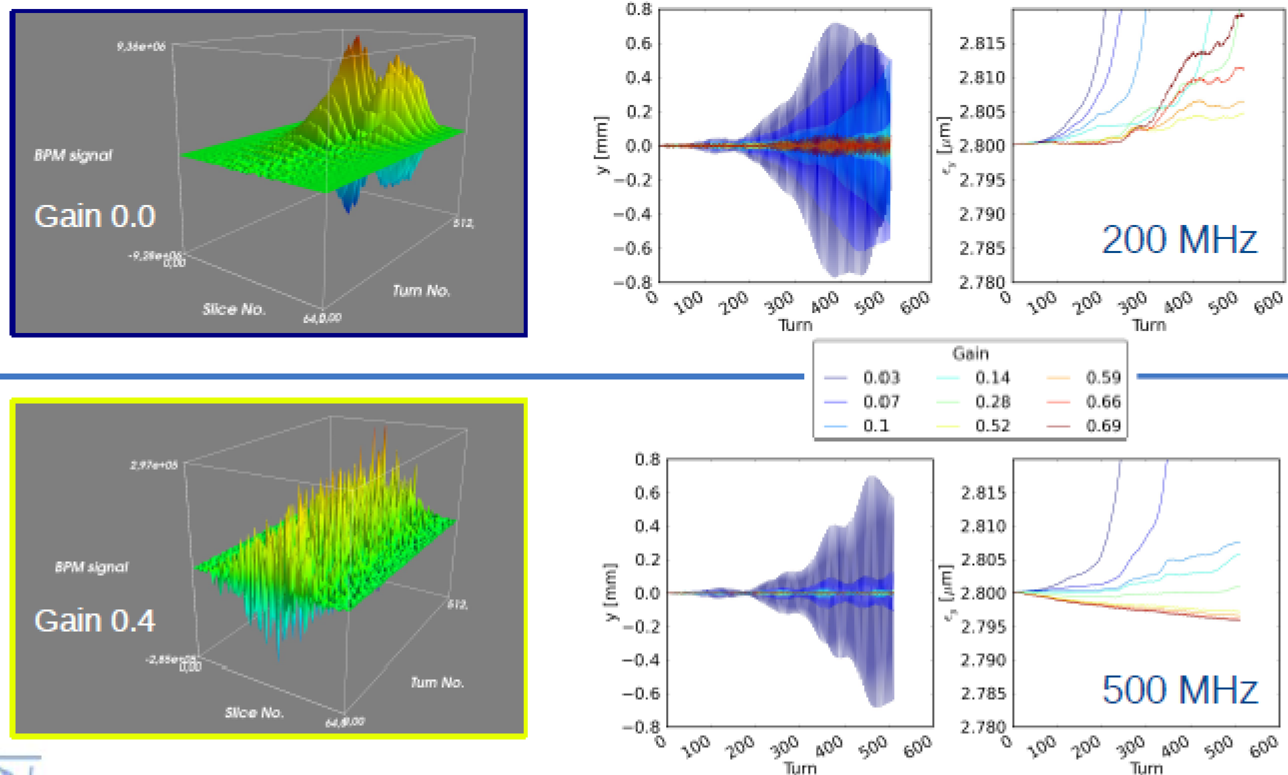
supported by:
US-LARP (SLAC, LBNL)
LNF-INFN (kicker study)
CERN SPS LIU Project

See also LIU review 2013: http://indico.cern.ch/conferenceDisplay.py?confId=260522



Ongoing work for SPS system - simulations

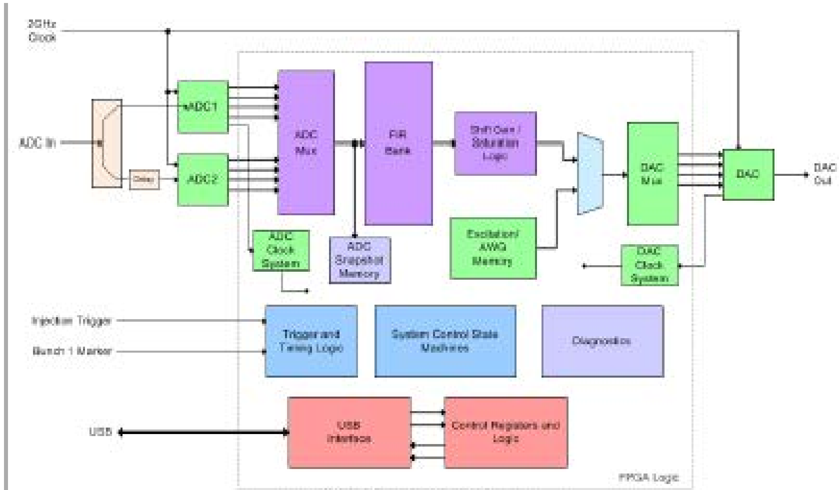
Q26 – $\rho_e \approx$ 6e11 m^{-3} – gain scan



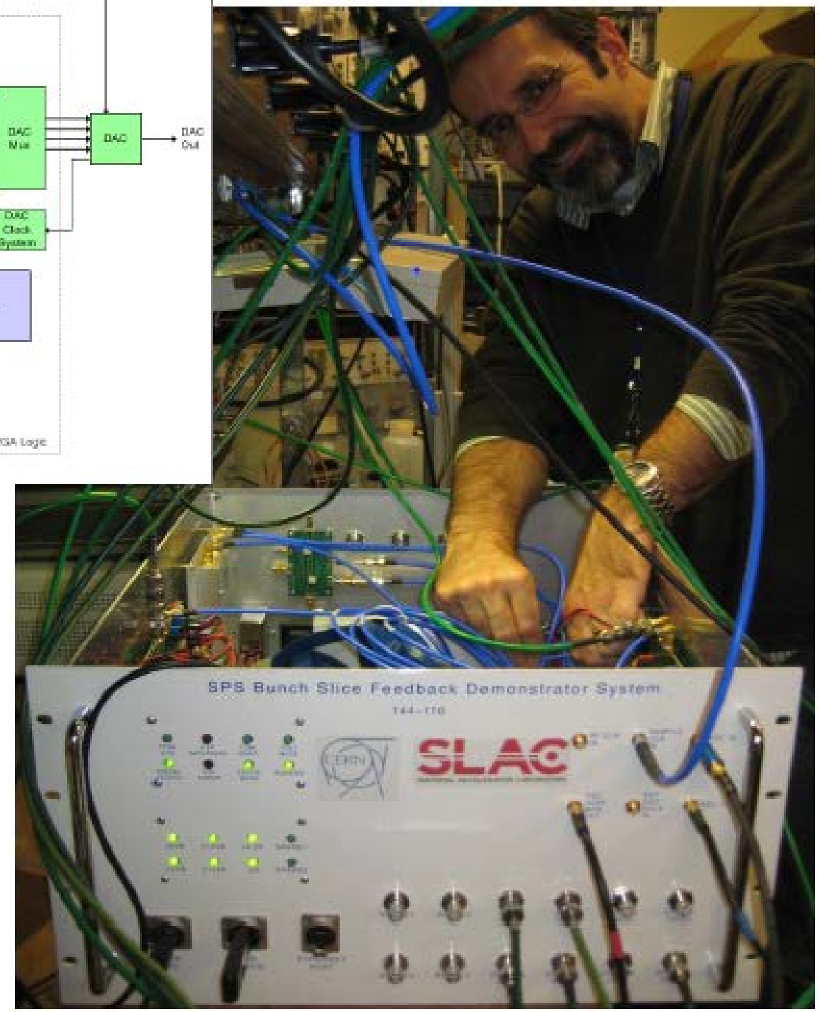
Kevin Li

Simulations for SPS during the ramp and Q20 optics ongoing (CERN-ABP)
Optimization of controller design (bandwidth, FIR filters) ongoing (SLAC)

SPS experimental demonstrator



Demonstrator Unit Block Diagram



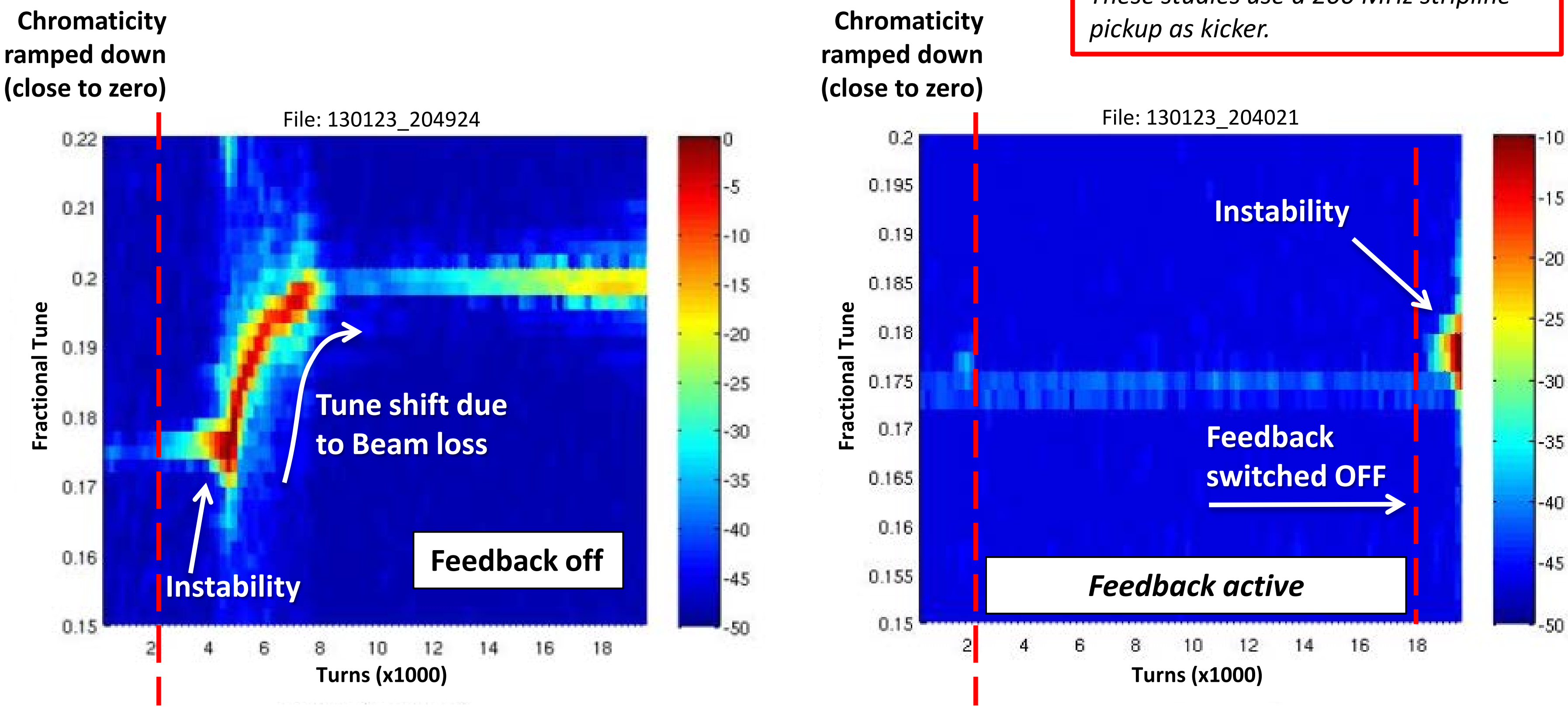
Features:

- Maxim MAX19693 12-bit 4 GSa/s DAC
- Two Maxim MAX109 2GSa/s 8-bit ADCs interleaved to get 4 GSa/s
- Xilinx Virtex-6 FPGA for all digital signal processing
- Multi-mode operation: Feedback channel -or- Excitation/AWG
- Timing and Trigger processing
- Diagnostics include:
  - ADC Snapshot memory
  - Trigger rate and missing trigger
  - DSP Saturation Indicator
- USB 2.0 Interface to host
- Suite of Visual Basic & Matlab SW

High Luminosity LHC

SPS single bunch tests

single bunch, 26 GeV, charge ~1E11
These studies use a 200 MHz stripline pickup as kicker.

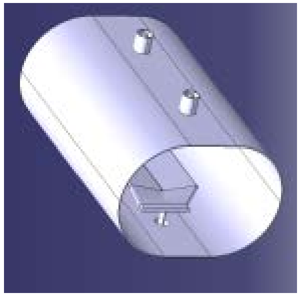


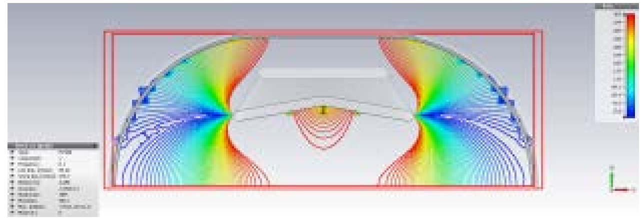
- **Feedback stabilizes the bunch** !
- clearly working for dipole mode, *limitation now is bandwidth of kicker*
- confirms high sensitivity of receiver circuit
- confirms feedback possible with the very small kick strength of ~1 kV [transverse]

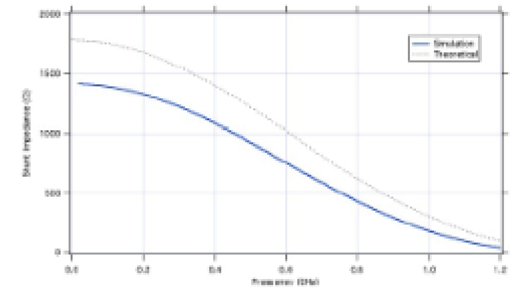
High Luminosity LHC

Kick design: Strip-line and Faltin Type

Strip-line



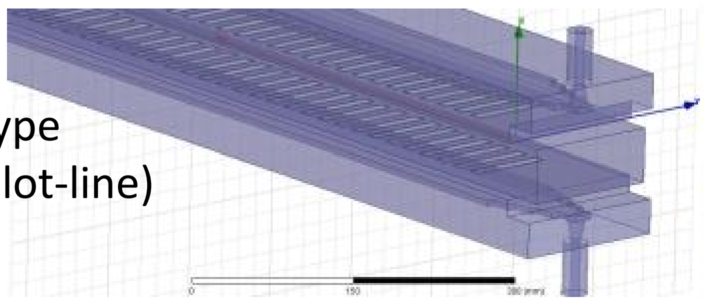


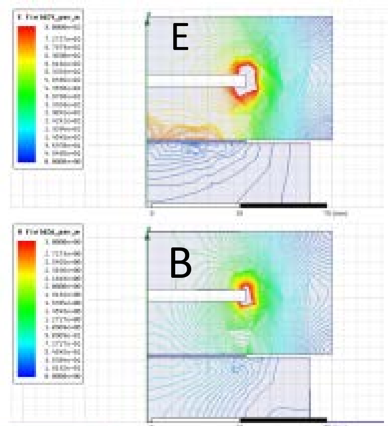


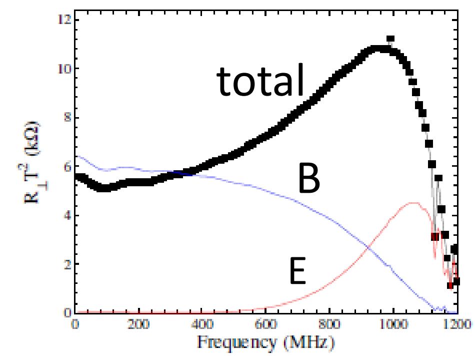
Installation of strip-line for SPS in LS1 !

Shunt-impedances → 1.2 GHz

Faltin type
(Strip/Slot-line)







	N_{mod}	N_{amp}	P_{amp} (W)	P_{tot} (W)	$V_\perp$ (kV) 100 MHz	250 MHz	500 MHz	750 MHz	1000 MHz
Striplines	4	8	500	4000	7.6	7.3	6.3	4.9	3.2
Striplines	44	88	100	8800	37.3	35.9	31.1	23.9	15.5
Slotline	1	2	500	1000	3.2	3.3	3.6	4.2	4.6
Slotline	1	2	2000	4000	6.4	6.6	7.2	8.4	9.3
Slotline	6	12	300	3600	14.8	15.3	16.7	19.4	21.5

J. Cesaratto (SLAC)
S. De Santis (LBNL)
M. Zobov (INF-LNF)
E. Montesinos (CERN)
et al.

Design Report: http://slac.stanford.edu/pubs/slacreports/reports18/slac-r-1037.pdf

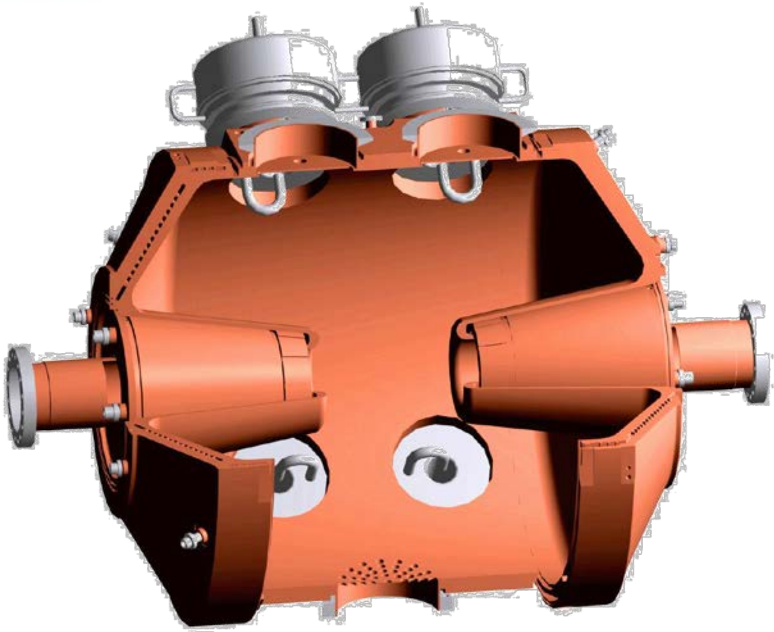
High Luminosity LHC

More details by J. Fox on Thursday & special FB session on Fri

ACN200

ACN200

- The 2004 LHC Design Report[1)] foresaw the staged installation of a capture cavity system, ACN200.
- J. Tückmantel estimated in 1999[2)] that injection of $\varepsilon > 1$ eVs, assuming beam phase and energy errors, would lead to unacceptable capture losses in LHC without the capture cavity.
- But even with ACN200, the recapture in 400 MHz would still be limiting.
- In real life we were lucky this time – the error estimates turned out to be pessimistic, RF systems of the SPS were improved (LLRF, 800 MHz), **SPS impedance was reduced** and the LHC capture voltage was increased and the 400 MHz system was used as longitudinal damper.
- With present experience we can firmly state that **ACN200 will not be used**.
- Should one reconsider one day to improve transfer SPS→LHC, other (further SPS improvement, larger SPS voltage, lower h in LHC)



1) https://edms.cern.ch/file/445835/4/Vol_1_Chapter_6.pdf
2) http://cds.cern.ch/record/397578

E. Ciapala in Chamonix 2010: http://indico.cern.ch/conferenceDisplay.py?confId=67839
P. Baudrenghien in Chamonix 2011: http://indico.cern.ch/conferenceDisplay.py?confId=103957

preliminary

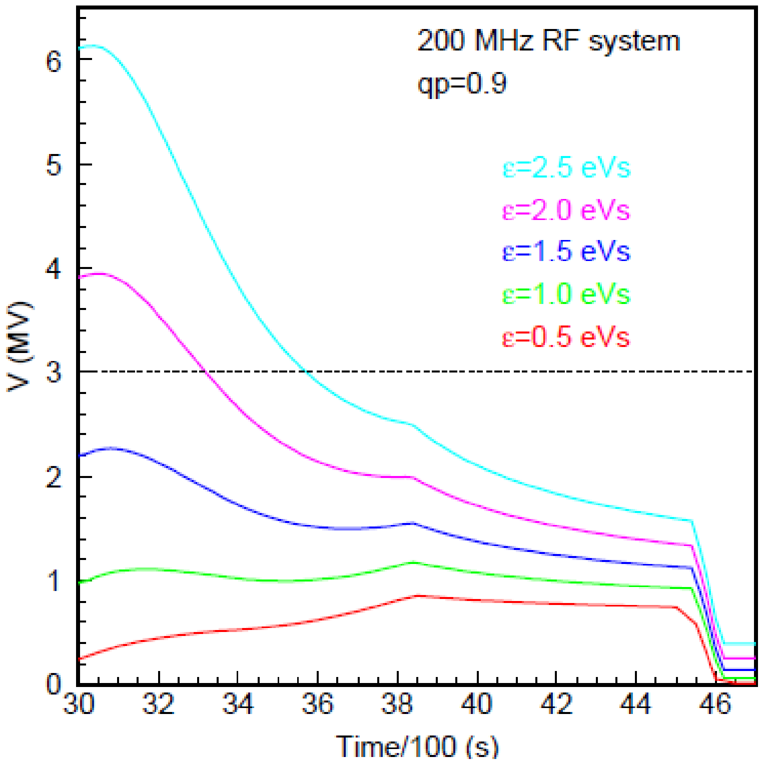
A 200 MHz Main RF System?

Motivation for a 200 MHz Main RF system

- It would soften the present limit of injected intensity
- It would provide longer bunches
- Together with the existing 400 MHz, RF, it can be used for luminosity levelling
- It would improve IBS, beam induced heating and e-cloud effect.
- It could be beneficial for ions and an envisaged momentum slip-stacking scheme in the SPS.

200 MHz main RF system (ACS200)

Ramp



Flat top

1. 3 MV is enough to accelerate 1.5 eVs and
2. 3 MV is also enough to transfer 3 eVs to 400 MHz @ 7 TeV

Bunch length @ 7 TeV:

Reference: in 2012, we had 1.25 ns with 2.2 eVs and 12 MV.

To have the same bunch stability, we would need

3 eVs with a single 400 MHz system,

4 eVs with a single 200 MHz system,

→ one could use both harmonics for future higher intensity

High Luminosity LHC

ACS200: beam parameters at 7 TeV

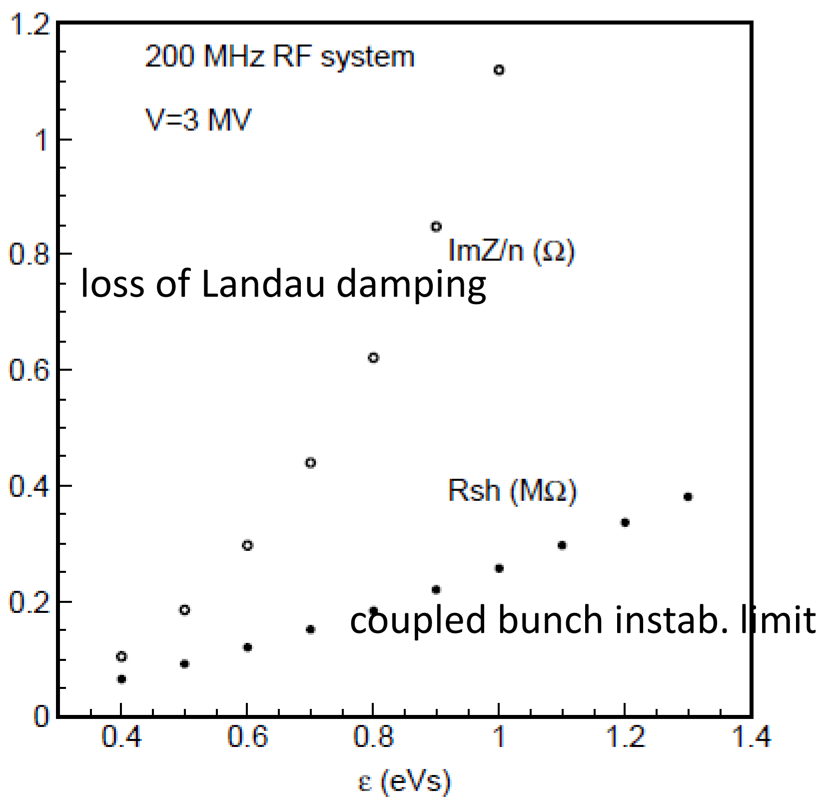
ε_{long} [eVs]	V_{acc} @ 200 MHz [MV]	V_{acc} @ 400 MHz [MV]	double RF operation	bunch length [ns]	
3.0	0.0	16.0	-	1.17	present scheme
3.0	3.0	0.0	-	2.1	
3.0	3.0	1.5	BSM	1.83	
3.0	3.0	1.5	BLM - flat	2.41	
3.0	16.0	0.0	-	1.34	
3.0	16.0	8.0	BSM	1.14	
3.0	16.0	8.0	BLM – flat	1.8	
2.0	6.0	0.0	-	1.68	
2.0	6.0	3.0	BSM	1.44	
2.0	6.0	3.0	BLM	2.07	

High Luminosity LHC

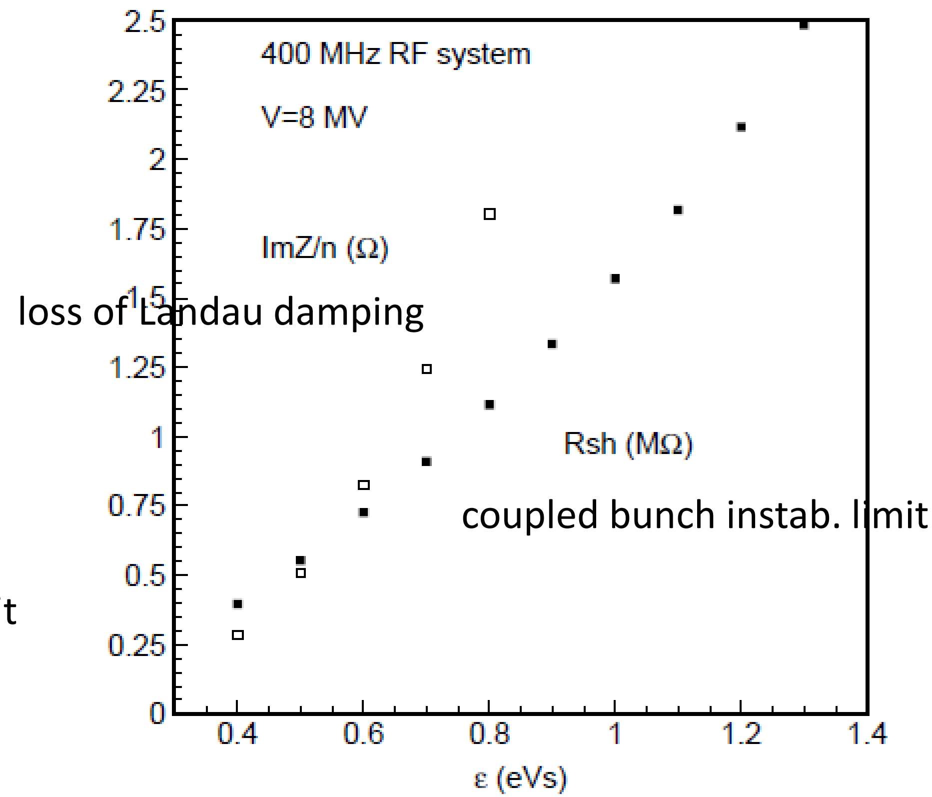
12 Nov 2013

ACS200 vs. ACS400: beam stability

200 MHz RF



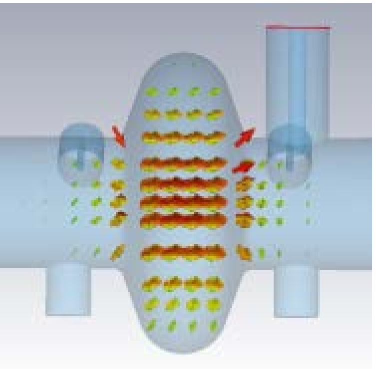
400 MHz RF

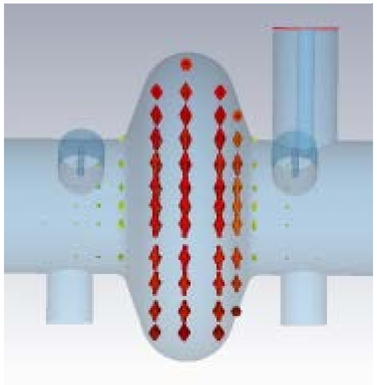


for nominal intensities

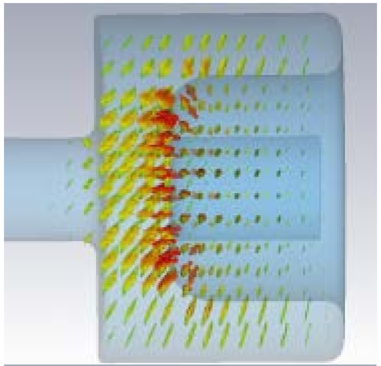
ACS200 – A possible cavity shape?

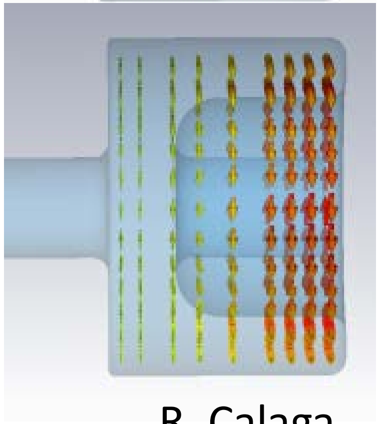
existing ACS400





possible ACS200





R. Calaga

	ACS400	ACS200
Voltage	2 MV	2 MV
Frequency	400.79 MHz	200.4 MHz
Gap length	377 mm	134 mm
R/Q	43.4 Ω	45 Ω
E_{pk}	12.5 MV/m	29 MV/m
B_{pk}	30 mT	68 mT
Aperture	300 mm	168 mm
Cavity envelope	344 mm	284 mm

- These are just first ideas, details need study (FPC, HOM, MP, tuning)
- The power source at 200 MHz may be simpler (Diacrode?)
- Synergy with other 200 MHz systems (SPS, ICTF, LANL…)

ACS200, possible issues & concerns

- Very low synchrotron frequency – susceptible to noise
- Should be used together with the ACS400 system (as a high harmonic system) to preserve beam stability (for the same longitudinal emittance, the stability threshold scales as h^2, so it would be 4x lower)
- In a double RF system (BL-mode): limit on the bunch length (3.4 ns) to avoid loss of Landau damping
- Full-detuning scheme most probably would also be needed → tilted bunches (if required bunch positions are not the same) and reduced beam stabilisation
- Crab cavities at 200 MHz (?)

Conclusions

- ACS400:
  - At present power-limited at slightly above nominal beam current; could be remedied by
    - klystron power increase, phase modulation, a combination of the above
- Compact crab cavities:
  - Prototypes of 3 geometries exist, tests ongoing – promising results
  - LHC Integration:
    - RR caverns (baseline) result in large waveguides through tunnel, large τ_g limits performance, limited shielding
    - Option: New caverns! This would allow for requested $\tau_g < 1\ \mu\text{s}$, reduce radiation and ease maintenance
- LHC high harmonic system:
  - Would allow bunch longitudinal profiling, reduce heating, improve pile-up density
  - not really compatible with phase modulation (tilted bunches) – need more study!
- Wideband transverse damper:
  - Could alleviate e-cloud problem!
  - Good progress in SPS with demonstrator
- ACN200: history!
- New 200 MHz main RF system? Looks very interesting – requires more study!

High
Luminosity
LHC

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.