Crab Cavities: SPS test Scope

SPS-BA6 Status
Test Overview w.r.t performance
Foreseen machine development time

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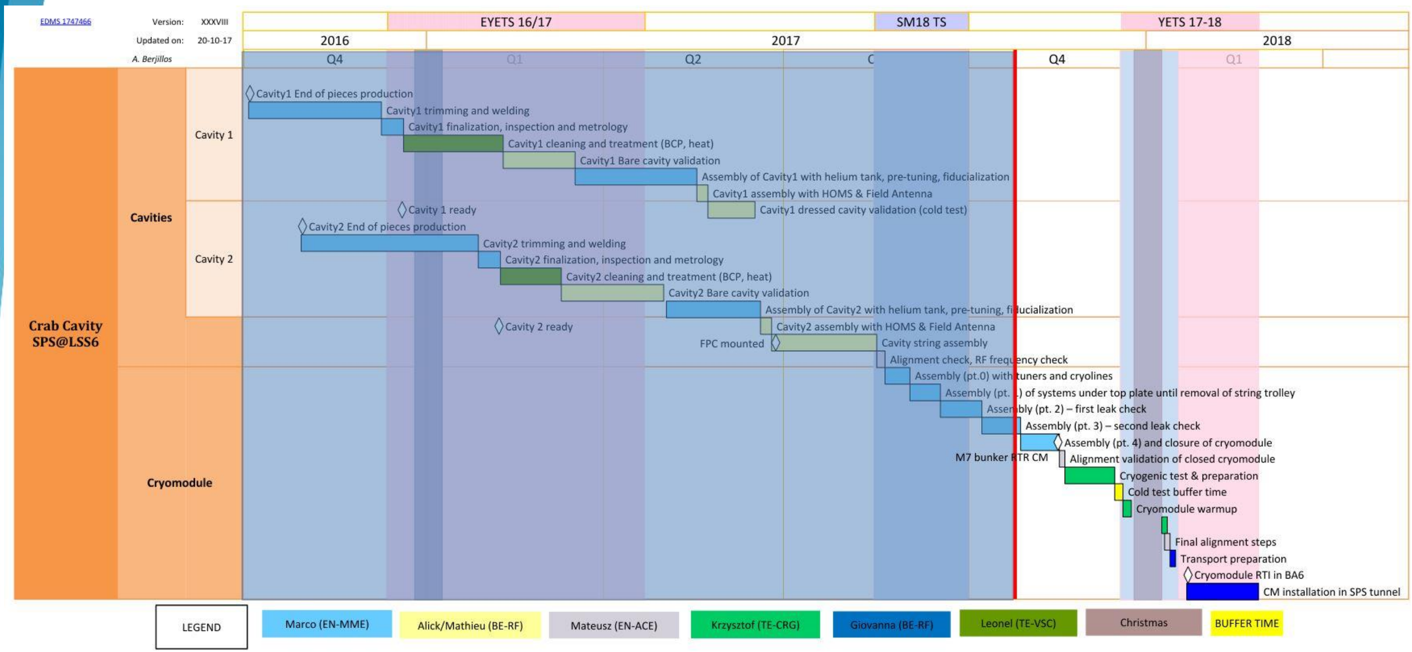
on behalf of WPs 2/4/9/12/13
CERN

7th HL-LHC Collaboration Meeting, Madrid – 15 Nov 2017

Recap SPS-CM Schedule



CM cooldown start ~Dec 4, 2017 (2 wk)
CM at SPS-BA6 – Jan 22, 2017

RF Performance Expectations

- A minimum of 1 MV/cavity was put as a threshold for installation into SPS tests

- The operable voltage will be **~2.5 MV/cavity** (vertical) to not to exceed 5 W cryo-load
  - At 3.3 MV, dynamic heat load from 5 W → 12 W
  - The cause of voltage degradation from 5 → 3.3 MV not fully understood, tests ongoing at Jlab

- Due to RF feedthrough non-conformity, a replacement low power feedthrough was used. HOM power interlock from 1kW → 200 W

Overview SM18/SPS Installation

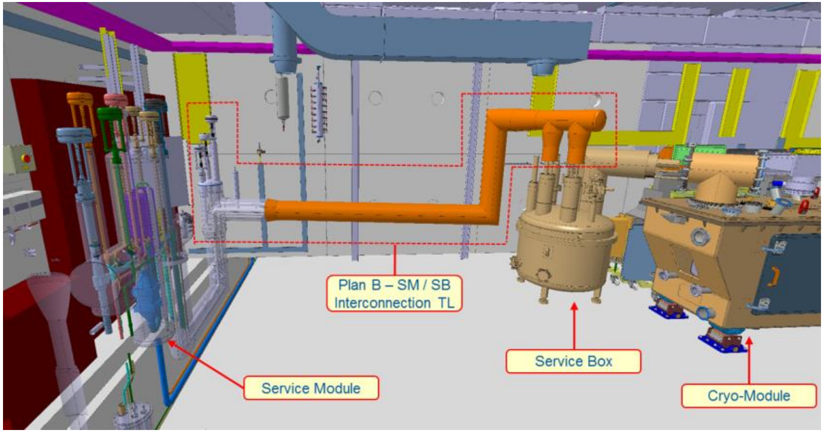
Week: 47-48 SM18 Installation	Week: 49-51 SM18 Cool-down	Xmas TS	Week: 02-04 RF/Align Checks, Transport	Week: 4-7 SPS Installation	Week: 8-9 SPS Cool-down

- Cryomodule tests in SM18
  - Main goal is to perform a cool-down cycle
  - Limited RF tests (cavity tuning & conditioning)

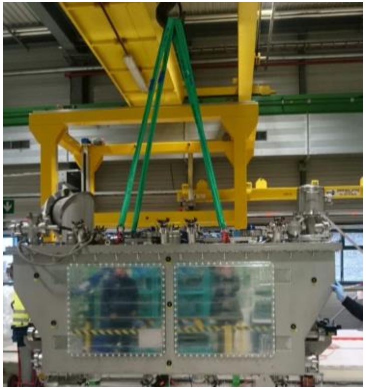
- SPS installation
  - Very detailed YETS planning (2-shifts/day + nights)
  - Reduced time (-1 wk) + additional safety cabling

SM18 Bunker Preparation

- Service box and infrastructure in its final steps

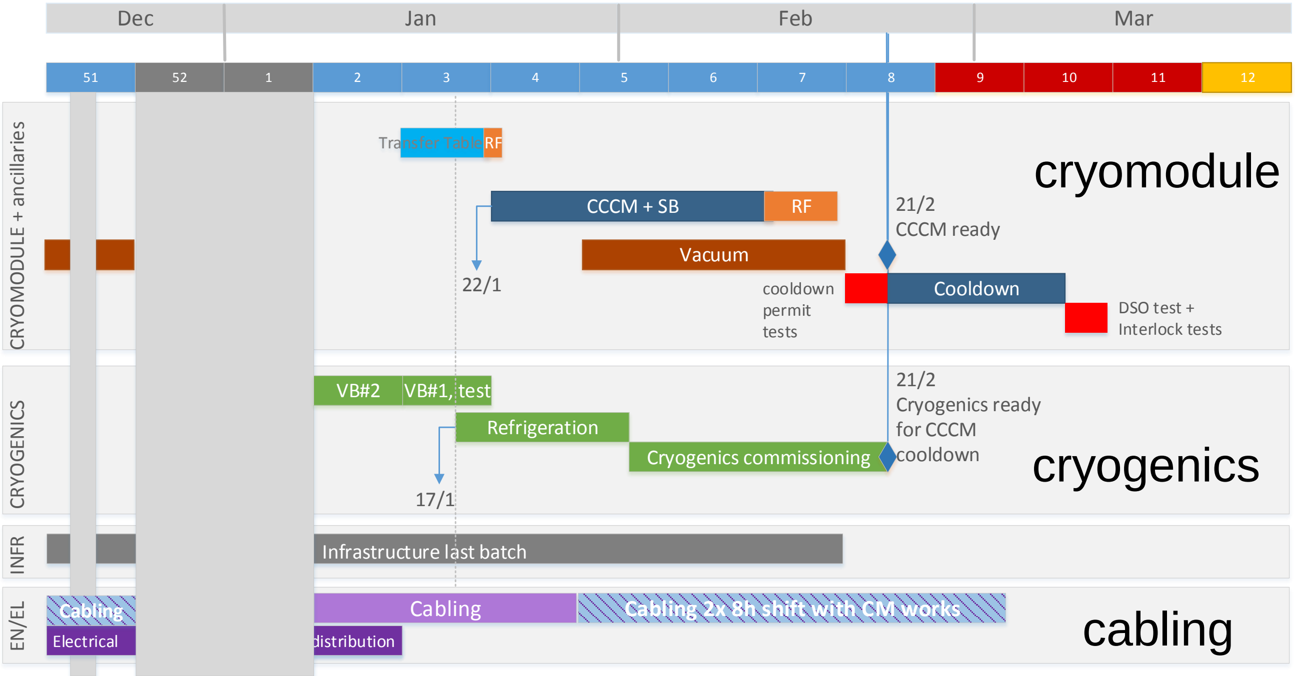


Courtesy
TE-CRG



Courtesy
EN-MME

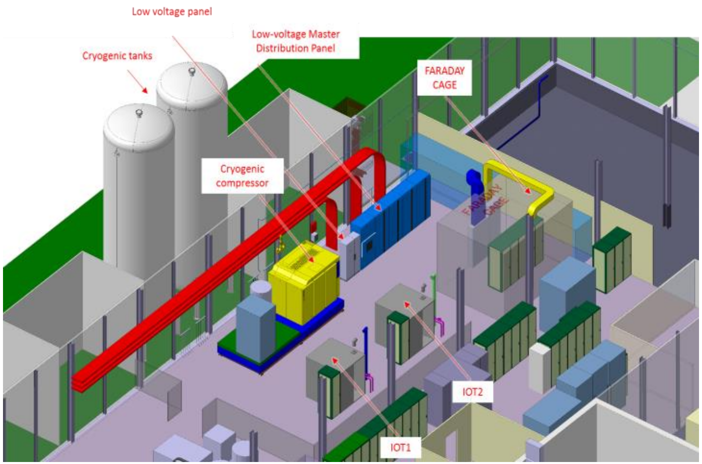
SPS Infrastructure (YETS)



Effective duration now 7 weeks

First week (51) only partial access, extra cabling

BA6-Surface Installation



Transformer and GHe tanks

Low Voltage distribution

IOT RF Amplifier

Faraday cage

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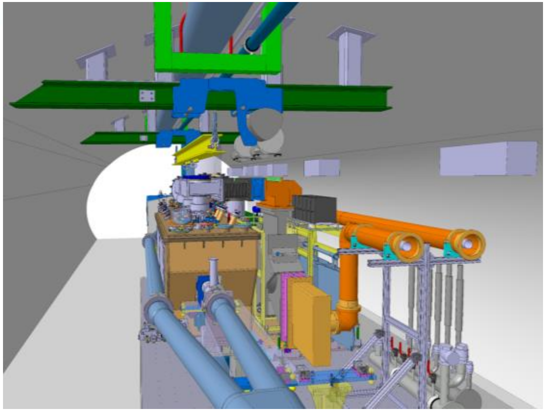
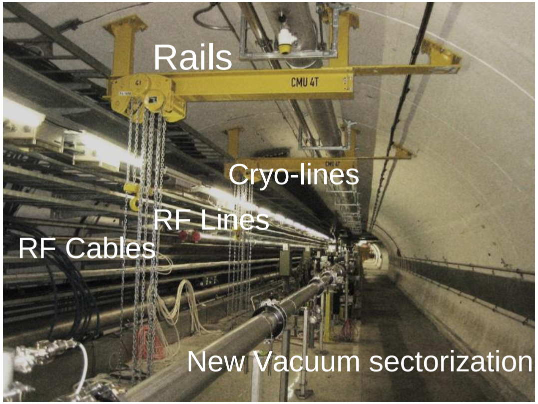
SPS-LLS6 Tunnel Installation





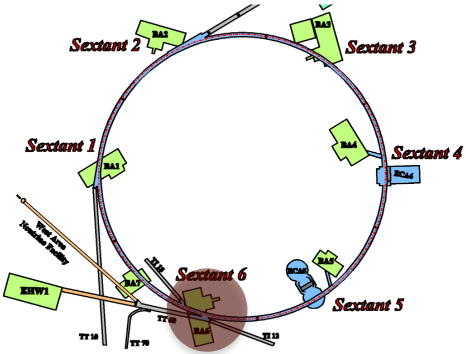
Transfer Table

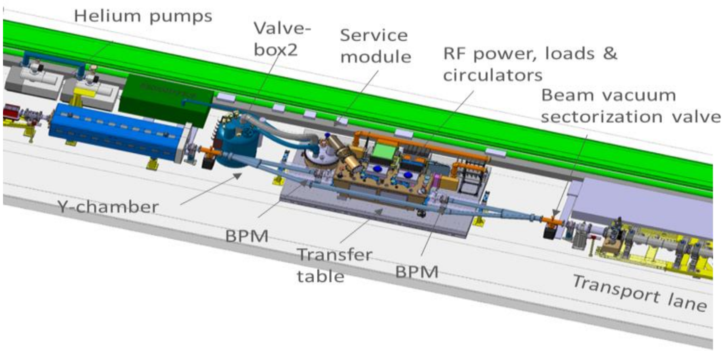
Cryogenic distribution line

Valve Box

Why do SPS tests ?

- Decided in 2011 that beam tests with protons are a pre-requiste before going into LHC (SPS obvious choice). After a long campaign, SPS-LSS6 chosen to insert a new SCRF test stand





- The SPS tests will be first stepping stone not only for technology-beam validation, but also establish the robustness. This will be one of the main workhorses for luminosity production in the HL-LHC

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What do we Validate ?

- Some critics ask, is it necessary ?
- Cavity validation with beam is vital, but it is only part of the story. It be the first time to circulate high energy/current protons, the RF gymnastics needed to operate in LHC was never done before!

- Three major systems (cost drivers)
  - A complex RF system with 16 high power systems
  - The 2K sub-atmospheric cryogenics in LHC & its proper dimensioning for stable operation
  - The crab vacuum system including coatings

SPS Beam Parameters for Crab Tests

	Units	Value
Energy	GeV	$\mathbf{26 - 450}$
Coast Energy	GeV	$\mathbf{55, 120, 270}$
Intensity	p/bunch	$0.05 - 1.3 \times 10^{11}$
RF Voltage	MV	$3.0 - 7.0$
Bunch Length	ns	< 2.0
Longitudinal Emittance	eVs	$0.35 - 0.5$
Betatron Tunes		$26.12, 26.18$
$\beta_{x,y}$	m	$40, 80$
Dispersion	m	-0.5

Some concern at 55 GeV with machine protection for low voltages under investigation with machine protection team

Expected SPS Test Sequence

	What	When	MD slots
0	RF commissioning (no-beam)	Mar-Apr	~ 4 weeks
1	RF-beam synchronization	Apr-June	2 x 24h
2	Transparency to beam	Jul-Aug	2 x 24h
3	Performance & Stability	Sept-Oct	2 x 24h
4	High intensity RF operation	Nov-Dec	≥2 x 24h

- Steps 1) & 2) mandatory to declare success for the 2018 SPS tests (will be dedicated MDs)
- Due to the complex movement of "cold" cryomodule in the bypass and hardware setup, early beam commissioning is essential for MD program into 2018
- Crab-bypass is designed for full remote control: **no need for access** for MDs

How to synchronize Crab-RF ?

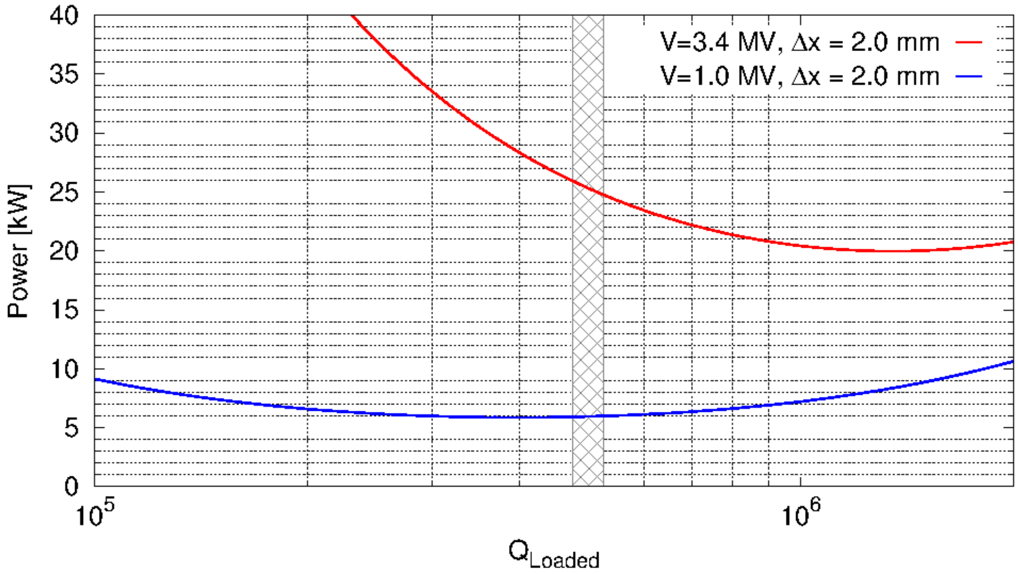
- Tuning range verification at 2K
  - Freq (400.53 – 400.78 MHz): 26 – 450 GeV

- At Injection: LSS6 – LSS3 RF synchronization
  - Beam capture with at ~10% of the voltage (26 GeV)
  - Closing of RF loops at injection plateau
  - Beam centering, crab-RF phase & RF power calibration

Cavity Parameter	Units	Value
Resonance frequency	MHz	400.6 ± 200 kHz
V_T/ cavity (cw)	MV	**2.5**
R/Q	Ω	420
Low field Q_0	-	4×10^9
Dynamic Load at 2.5 MV (3.4 MV)	W	5 (12)

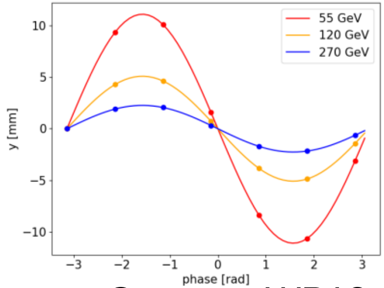
Sizing of RF Power (in SPS)

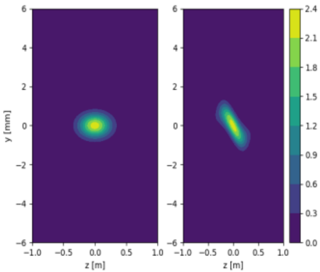
- Maximum required power with $I_b = 350\ \mathrm{mA}$ (200 bunches, $N_b = 1.7 \times 10^{11}$p/b)
- Available maximum is 40 kW including in LHC



Is the Instrumentation Sufficient ?

- At $26\ \mathrm{GeV}$, orbit response of $\pm 20\ \mathrm{mm}$ and implies $\pm 2\ \mathrm{mm}$ at $270\ \mathrm{GeV}\ (2.5 + 2.5\ \mathrm{MV})$
  - **BPMs**: Orbit mode resolution $\pm 0.1\ \mathrm{mm}$, and trajectory mode $\pm\ 0.4\ \mathrm{mm}$. Effect of RF non-linearity under investigation
  - **Head-tail monitor**: $\pm 100\ \mu m$ orbit resolution, we can observe a pk-to-pk $\pm 600\ \mu m$ oscillation at 270 GeV
  - **Wire-scanners**: Change in the projected emittance from $1\ \mathrm{\mu m}$ to $1.5\ \mathrm{\mu m}$ should be easily seen
  - **Synchrotron light monitor**: Non-destructively measure the projected emittance as a function cavity voltage





Courtesy WP13, Simulations: A. Alekou

What is the preferred Energy ?

- Available "coast" energies (55, 120, 270 GeV)
- SPS energy ramp $(26 - 450\ \mathrm{GeV})$:
  - Time for Energy ramp $\sim 2\ \mathrm{s} \rightarrow 250\ \mathrm{kHz}$ in freq. swing
  - Fixed crab cavity freq with beam re-tuning

- The crab kick (or tilt) inversely proportional to γ
- Effect more visible at injection, but beam better behaved at higher energies (shorter bunches & natural emittance)
- Beam-crab commissioning majority at **injection** and use $\mathbf{270\ GeV}$ coast for long term stability

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*LHC ramp: ~20min, 1kHz

Transient Effects ?

- Injection & beam centering
  - Injection oscillations (mm over ? turns)
  - RF power calibration between the two cavities

- Cavity alignment strategy for LHC (+ FSI)
  - Realize (measure) the ± 0.5 mm cavity-to-cavity offset
  - Implication of large orbit shifts in LHC (~ 5 mm)

- Counter-phasing & re-phasing
  - The fastest feedback is limited to RF roundtrip delay ($1.3\ \mu s$ loop delay with $R_{\min} = 1\ \mathrm{M}\Omega$)
  - Counter-phasing for a “invisibility” (ex: $\pm 90^0$) including transient phase of energy ramp & squeeze
  - Re-phase the cavities adiabatically

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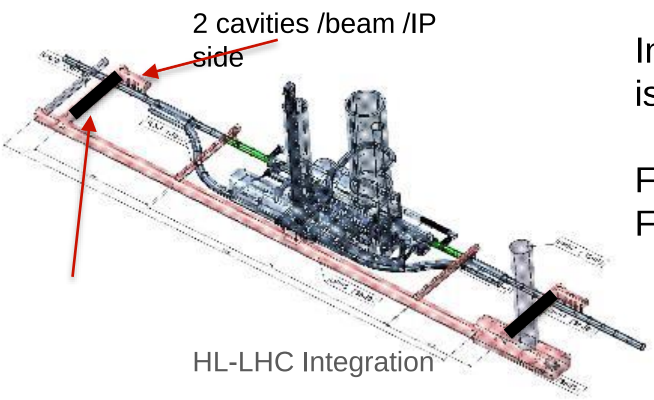
LLRF with Long Distances

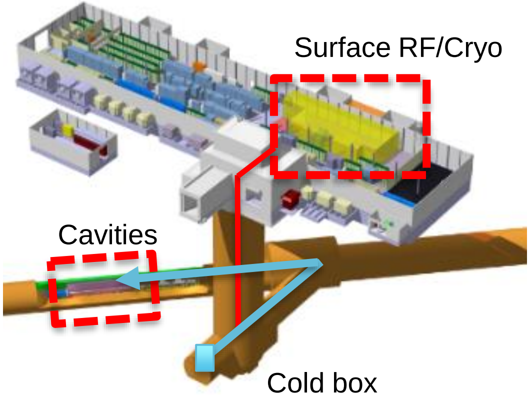


In the LHC, the local round trip delay time is ~ 1 μs & cross IP ~ 2 μs

Field stability determines impact on lumi
Failures mitigated by cross IP regulation

The LLRF in SPS has a roundtrip delay time ~ 1.3 μs – validation of field stability and reaction time to be very similar to LHC

Self excited loop (already tested in SM18) for locking the crab cavity frequency



What about SPS Optics (Q26, Q20….)

- For the primary scope of SPS tests, mainly single bunch (or few) with low intensity ($1 - 2 \times 10^{10}$p/b)
- Energy “coast” cycles (120 & 270 GeV) are well established including SPS instrumentation with **Q26**

- For latter part with highest intensity operation, Q20 optics will be needed, but there is no observable difference the point of view of crabs
- Some local optics changes near the “crab-zone” were discussed but would required a special wiring of the quads (if needed post LS2)

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Where are we with Emittance Growth ?

- After numerous MDs over the last years
  - The sweet spot for long term behavior is 270 GeV (or 120 GeV)
  - IBS explains only part of the growth, there is a natural residual growth similar in both planes ($\leq 0.5\ \mu/\mathrm{hr}$) – reproducible!
  - Chromaticity plays an important role, especially in the vertical plane
  - Identified source of de-bunching from RF feedback with low intensities

- Growth sensitive to beam energy but not to intensity, optics & initial conditions
  - A good candidate for the natural vertical emittance growth is the residual gas scattering
- Present estimate from existing crab electronics in SM18 (very noisy!)
  - Phase noise: $2 - 8\ \mu\mathrm{m}/\mathrm{hr}$ (bunch length: 1.0-2.0 ns)
  - Amplitude noise: $0.8 - 1.4\ \mu\mathrm{m}/\mathrm{hr}$ (bunch length: 1.0-2.0 ns)
  - This local oscillator will be replaced before SPS tests

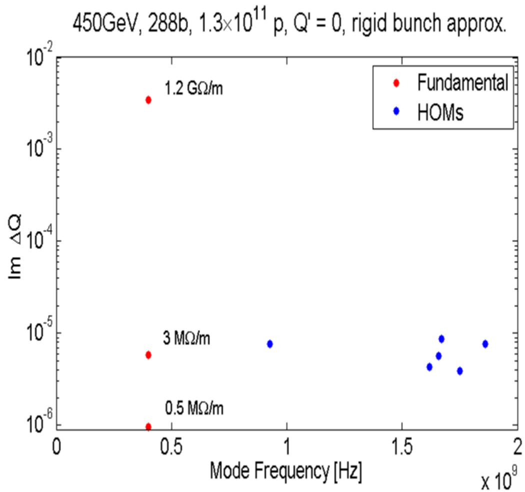
4) High Intensity Operation

- Beam induced failure scenarios as a function of bunch high intensity and number of bunches
  - Beam aperture near crabs needs some special attention (i.e. LHC extraction not possible)
- Cavity stability, trip rate, cavity quenches including fast transients to the beam
  - Trip scenarios are difficult to foresee, no obvious signs from SM18 until "quench field" ~ 3.3 MV
- Special attention to injection & ramp (parasitic impedance to beam)
- HOM power interlock at 200 W from any of the 6 couplers (RF feedthrough limit)

Can we measure Crab Cavity Impedance

- No significant impedance or HOM power is expected in SPS
- Will investigate the selective un-damping of fundamental mode & HOMs and it effect on stability and HOM power

Energy [GeV]	26	450
Intensity [p/b]	1.3×10^{11}p/b	
# of Bunches	288	
Bunch length [ns]	4.0	1.0
HOM Power [W]	**0.02**	**200**



Courtesy: WP2-Impedance

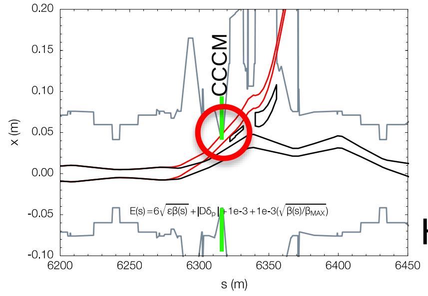
What about Collimation ?

- Like crabs, the LHC collimation system was first tested in the SPS
  - A full prototype & instrumentation present in SPS-LSS5
  - Was essential to validate the collimation system (design, alignment, impedance, software & studies)
  - Drawback 2018 – Horizontal collimators, vertical crabs

- The main driver is <u>machine protection</u> includes fast failures and loss vs. time, crab-dispersion leakage and **collimation hierarchy** optimization
- Studies: Longitudinal collimation, colored noise for halo scraping, crab kick for extraction (crystals)

How to Determine Robustness of Crabs

- The ideal robustness check would be to leave the crab cavities in “transparent mode” during SPS regular operation
  - Will asses the feasibility towards the end of the run after the first period of crab validation
- The main constraint is aperture restriction for LHC extraction at LSS6



H. Bartosik

- What is essential is an <u>extended program until LS3</u> to optimize the operational scenarios in the SPS

Recap of the MD Outline

	What	When	Approx time
0	RF commissioning (no-beam)	Mar-Apr	~ 4 weeks
1	RF-beam synchronization	Apr-June	2 x 24h
2	Transparency to beam	Jul-Aug	2 x 24h
3	Performance & Stability	Sept-Oct	2 x 24h
4	High intensity RF operation	Nov-Dec	≥2 x 24h

- Steps 1) & 2) mandatory to declare success for the 2018 SPS tests (will be dedicated MDs). Early beam commissioning is essential for very precise definition of the MD program into 2018
- For 3) & 4), if cavity is truly transparent during the SPS energy cycle, some parasitic MDs feasible but will restrict the beam to LHC

Thank you

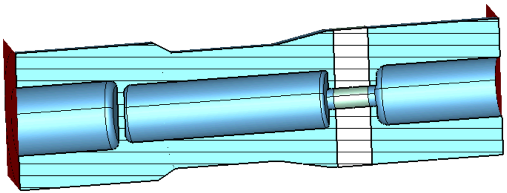
SM18 Test Plan

Week: 47-48 SM18 Installation	Week: 49-51 SM18 Cool-down	Xmas TS	Week: 02-04 RF/Align Checks, Transport	Week: 5-8 SPS Installation	Week: 8-9 SPS Cool-down

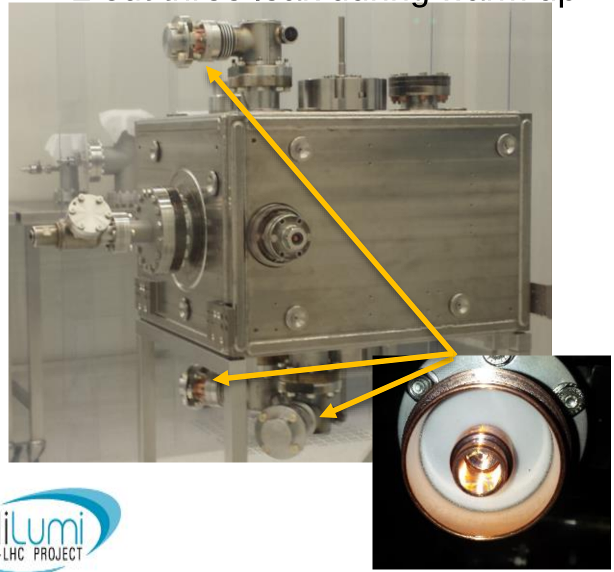
	Tentative date	Temperature	Comment
Warm Measurements, cabling, instrumentation	Ongoing	300 K	
M7 Service Module Pressure Tests	**16-17 Nov 17**		Infrastructure Prep
Cryomodule to Bunker & Connections	**20 Nov 17**		
Warm Coupler Cond.			1 kW, parasitic
CM Vacuum checkout & Cooldown	**4 Dec 17**	300-2K	SM18-M7 Bunker
Frequency Tuning, Interlock Checkout	**4-15 Dec 17**		VNA, Motor Control
Q_L at 400 MHz, Full HOM spec, B-field			All RF measurements at 2K subject to the availability of time
Calibration input power (P_f, P_r, P_t)		2K	
Coupler/Cavity Conditioning			
Kick voltage determination			
LLRF loops, phase noise, stability			
Dynamic heat load, Q_0			
Warmup	**18-22 Dec 17**		Min 3 days

HOM Feedthrough Replaced

Original feedthrough
1kW HOM power

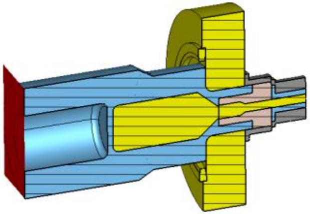


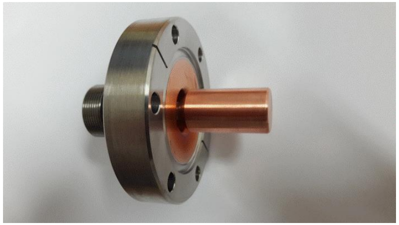
2 out three leak during warm up



Replacement feedthrough
~200 W HOM power

New interlock added to RF chain





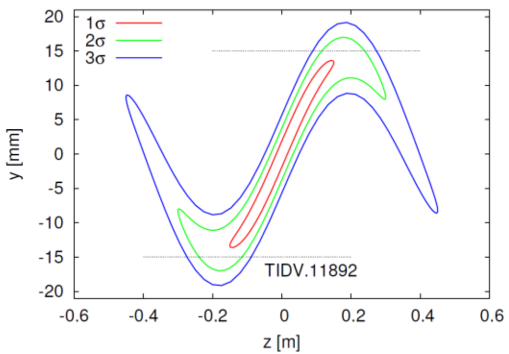
In the SPS with special filling and high current, 200 W is expected to be max

Status of SPS Tests

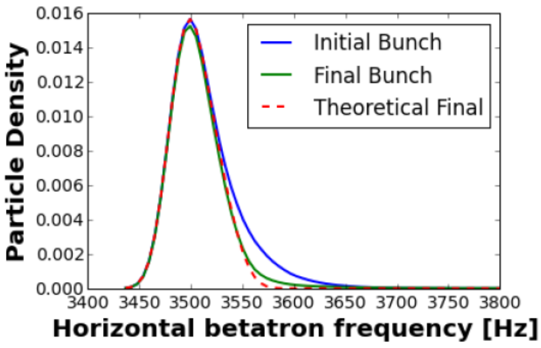
- Design and Documentation
  - Integration concluded on surface premises and underground
  - Electrical distribution layout designed and implemented
  - Safety review and follow-up with risk analysis for vessel, test stand, cryogenics
  - Layout of Oxygen Deficiency Hazard detectors worked out
  - Interlocking schemes determined by Machine protection and Personnel Safety
  - Modification to the Personnel Protection System (Access Safety)
- Preparatory work in EYETS-2016/17
  - Large part of infrastructure installation: cables, RF power lines, handling equipment, civil engineering, warm- and cold pipework
  - Beam line layout modified for new vacuum sectorization
  - Installation of equipment on surface premises: IOT RF amplifiers, Cryo storage tanks, electrical distribution equipment, Faraday cage for LLRF
  - Production of vacuum chambers, BPMs
- Procedures & Planning
  - Common procedures for surface (SM18) and underground activities
  - Operation scheme worked out
  - Planning in very challenging Year-End Technical Stop framework

RF Non-Linearity

- In the SPS, the bunches are almost twice longer ($2\ \mathrm{ns}$), the effect of RF non-linearity is more pronounced and visible
- Longitudinal collimations “x-z” for bunch length manipulation & possibility of transverse tail cleaning with shaped noise
- Effect of crab dispersion & collimator hierarchy (during failures)



Courtesy R. Tomas



Courtesy T. Mastoridis

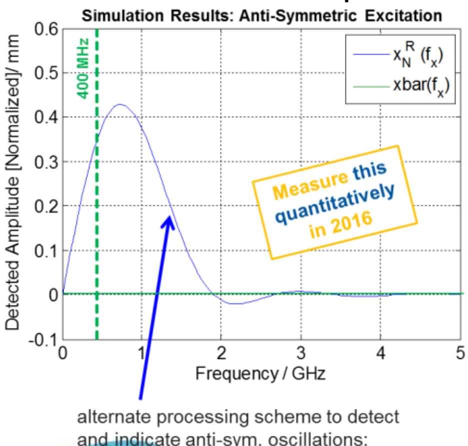
Can we Leave Crabs in regular Operation ?

- Crab cavity in beam is compatible with slow extraction to North Area with respect to aperture
- We need to make sure that the CC does not affect the fixed target operation, in particular because the fixed target beam has very high intensity and therefore can damage the machine.
- Mostly a machine protection issue.
- The high intensity fixed target beam might damage the CC in case of beam loss.
- The critical point is the protection of the CC.
- Both aspects are quite critical, therefore for the moment no plan to use the CC during fixed target operation, unless absolutely necessary (e.g. lack of dedicated MD time).

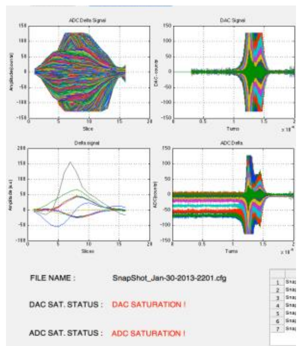
Additional Topics

- Interplay with the SPS transverse damper & use of damper instrumentation (including WBFS)
- Use crab cavities as an AC dipole for measurement of RF multipoles
- Impact of the bunch shape on the response of the BPMs (1.0 – 2.0 ns)
- Alternative methods for CC phase measurements

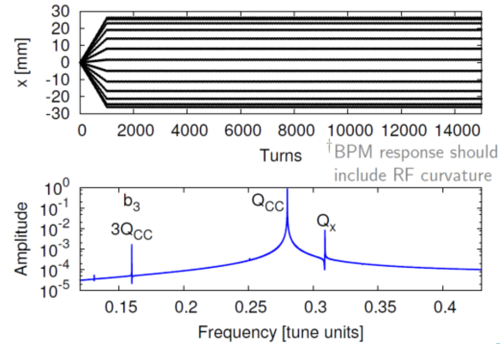
Present Damper



Wideband FB



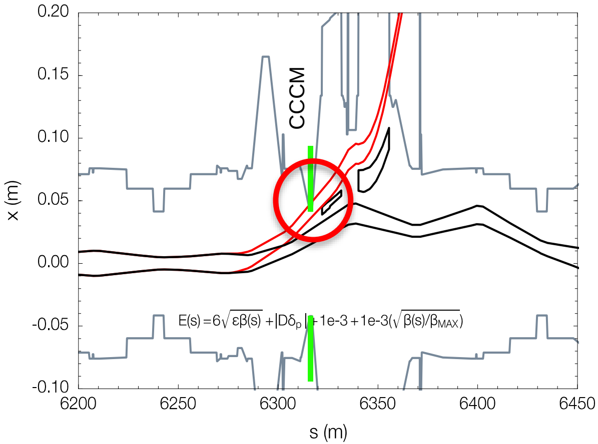
CC as AC-Dipole



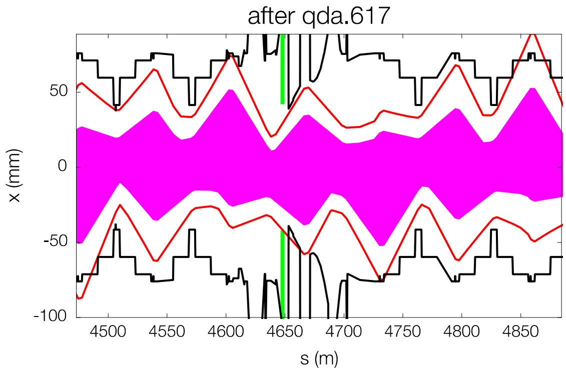
Courtesy: G. Kotzian, R. Tomas et al.

Compatibility with SPS Operation

LHC Fast Extraction, LSS6



Slow extraction of fixed target beam



@400GeV, incl extraction bump
purple : raw beam envelope, red: beam envelope + tolerance

Courtesy: H.Bartosik