SPS crab-cavities - simulations and possible test program in view of reduced voltage

A. Alekou, F. Antoniou, H. Bartosik, R. Calaga
R. Appleby, G. Arduini, C. Welsch, Y. Papaphilippou

With input from: P. Baudrenghien, T. Bohl, R. Tomas Garcia, G. Iadarola, T. Lefevre, T. Levens, J. Luis Sirvent Blasco, G. Kotzian, T. Mastoridis, E. Metral, C. Pasquino, S. Redaelli, J. Repond, B. Salvant, E. Shaposhnikova, J. Storey, G. Trad

Many thanks to the SPS OP team

HL-TCC – 5 Oct 2017

Summary of SPS Test Strategy for 2018

	What	When	MD slots
0	RF commissioning	Mar-Apr	~ 4 weeks
1	RF-beam synchronization	May-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

G. Vandoni, R. Calaga,
214th IEFC meeting

Beam Parameters for Crab Tests

	Units	Value
Energy	GeV	26-450
Coast Energy	GeV	55, 120, 270
Intensity	p/bunch	$0.05\text{-}1.3 \times 10^{11}$
RF Voltage	MV	3.0-7.0
4^{th} Harmonic Voltage	MV	0.0
Bunch Length	ns	<2.0
Longitudinal Emittance	eVs	0.35-0.5
Betatron Tunes		26.12, 26.18
$\beta_{x,y}$ (CC location)	m	40, 80
Dispersion (CC location)	m	0.5

HiLumi HL-LHC PROJECT

1. Crab-RF synchronization

- Verification of the tuning range of ±300kHz (SM18 & SPS)
- At injection, synchronization between main and crab RF
  - Capture beam, injection oscillations, closing RF loops
  - Beam centering in crabs and RF power calibration
- For coast energies (55GeV, 120GeV, 270GeV)
  - Difficult to tune the cavities during ramp*
  - Fixed crab frequency for coast energy and retune at coast (only SPS)

Cavity Parameter	Units	Value
Resonance frequency	MHz	400.6 ± 300 kHz
V_T/cavity (cw)	**MV**	**2.5**
R/Q	Ω	420
Low field Q0	-	$4x10^9$
Dynamic Load at 2.5 MV (3.4MV)	W	5 (12)

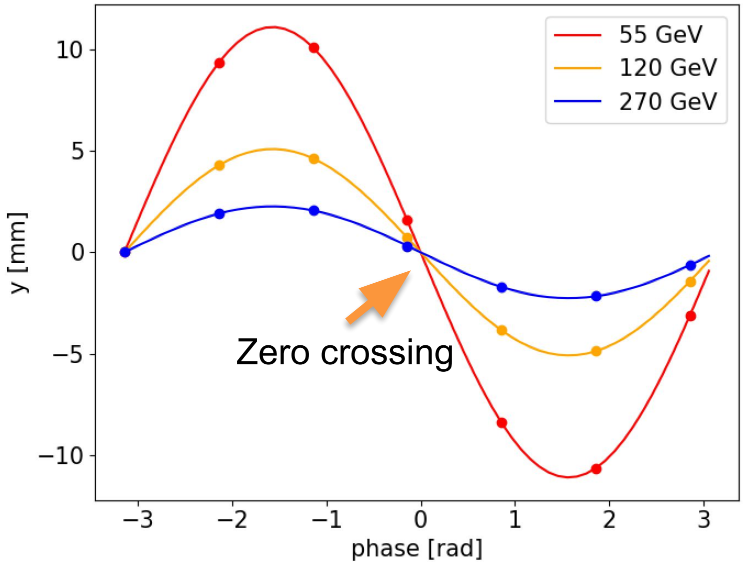
*SPS 2 sec ramp too fast for the cavity tuner to follow (**LHC ramp: ~20min**)

2. Transparency

- LHC energy ramp, cavities operated at 10% voltage and counter-phased
  - Precisely measure field/phase for fast feedback during the energy ramp
  - Counter-phasing (i.e. ±90^o) for the crab kick to be invisible
- The present RF pickup designed to extract 1W at 400 MHz for LLRF field & phase regulation
- Re-phase the cavities to full crabbing adiabatically

What can be Observed

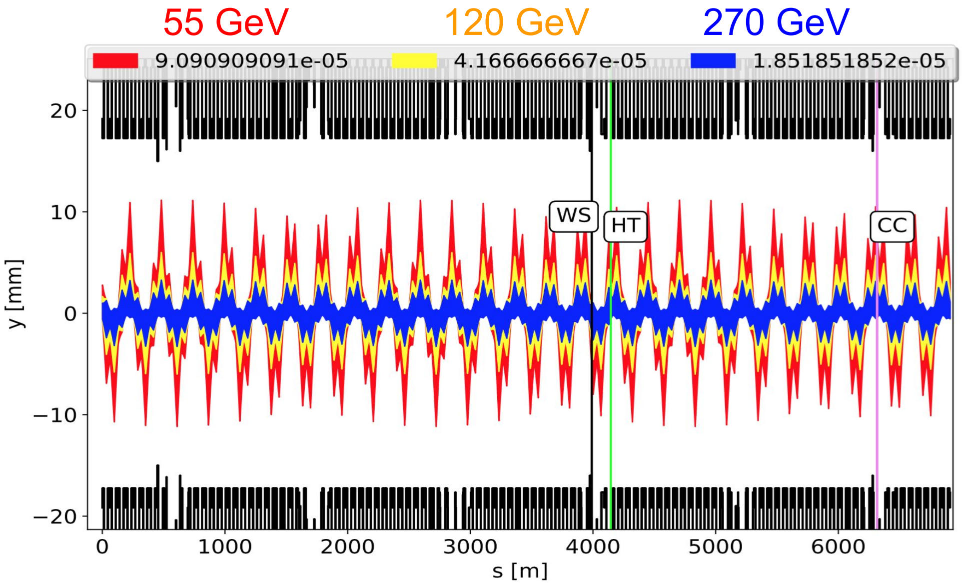
- Orbit measurement to determine crab-RF phase



A. Alekou

What can be Observed

- Orbit measurement to determine crab-RF phase
- At 55 GeV, orbit response (at crest) of ±10 mm with 2.5 MV times 2 cavities while ±2 mm at 270 GeV
- No aperture restrictions

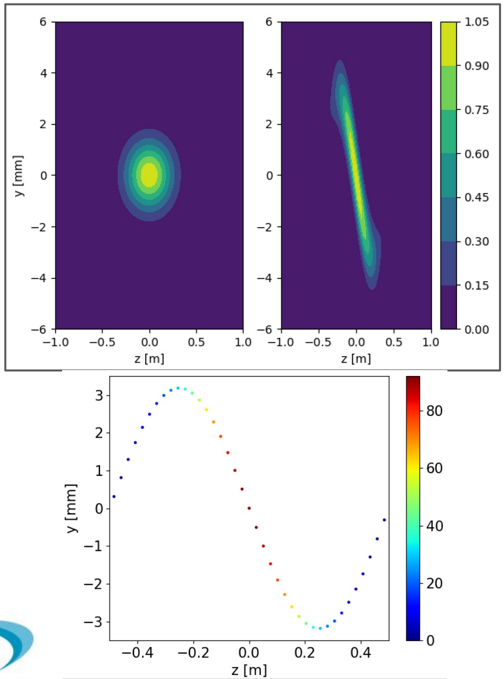


A. Alekou

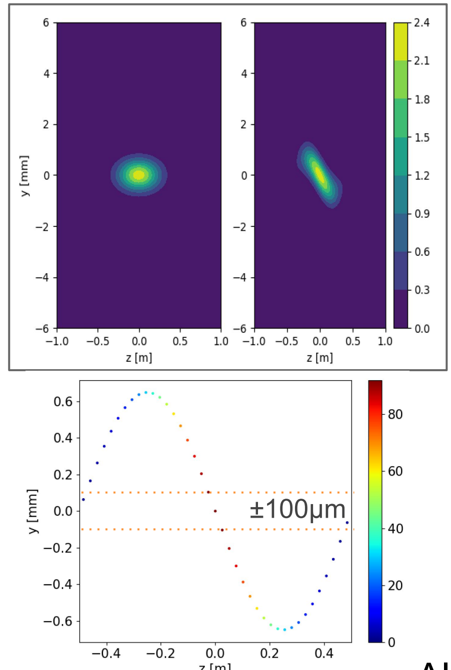
Validation of crabbing

- **Head-tail (HT) monitor**
  - Resolution of less than 100μm for 1.6sec
  - Also New EO-Pick-up and MIM under development

55 GeV

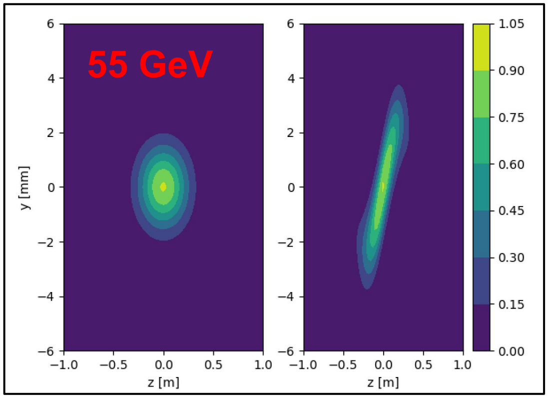


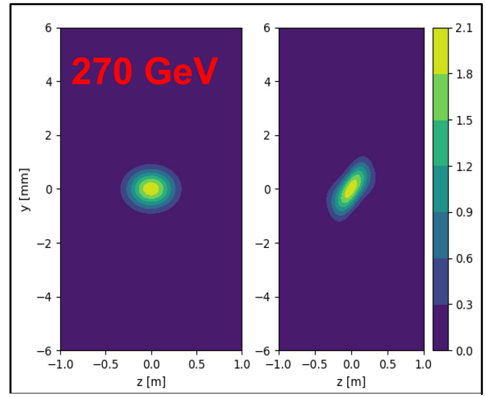
270 GeV

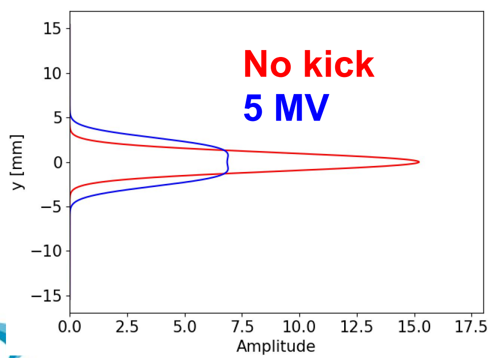


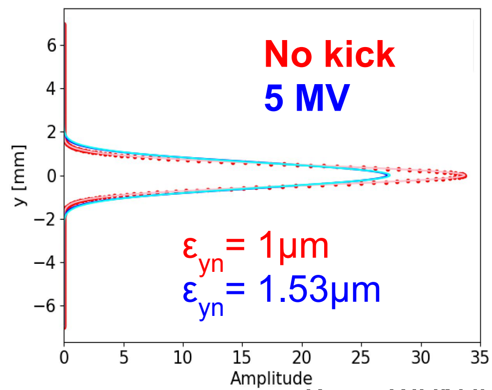
Validation of crabbing

- **Wire scanners (WS)**
  - Change of the bunch profile due to crabbing





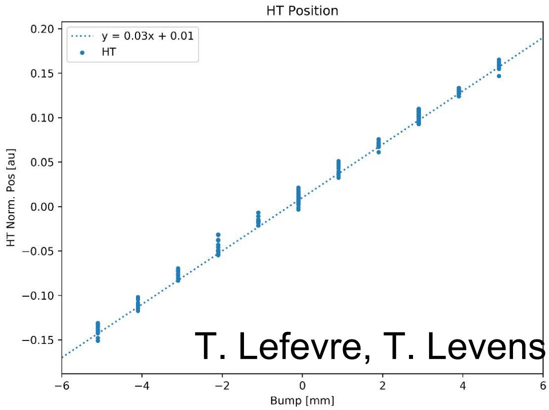




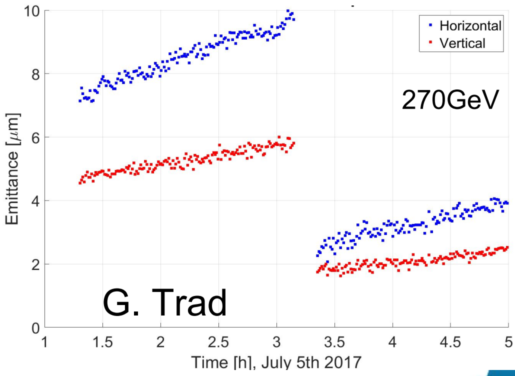
A. Alekou

Instrumentation validation studies in 2017

- **Head-tail monitor**
  - Calibration at low and nominal intensities
  - Source of ~3mm offset on MOPOS position not understood
    - check alignment of BPCL.421 during YETS and repeat measurements with more careful setup of MOPOS.

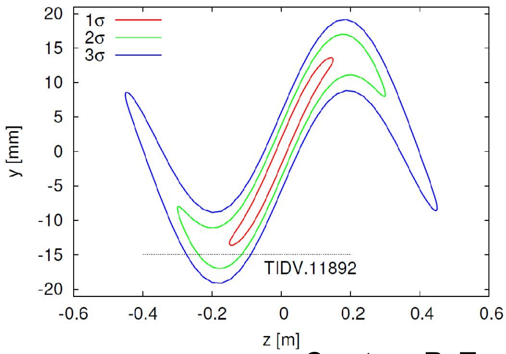


- **Synchrotron light monitor (BSRT)**
  - Non destructive with continuous measurements
  - Calibration was performed for coasting beams

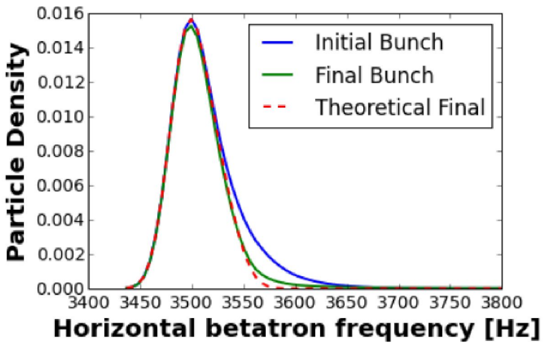


Other issues

- In the SPS, the bunches are almost twice longer (2ns)
- Effect of RF non-linearity more pronounced and visible
  - Impact on the BPM reading is under investigation
  - Simulations for short bunches in the SPS to follow
  - Longitudinal collimation “y-z” for bunch length manipulation & possibility of transverse tail cleaning with shaped noise
- Validation of effect of crab dispersion
  - Important for collimator hierarchy (during failures)



Courtesy R. Tomas



Courtesy T. Mastoridis

3. Performance and long term stability towards the HL-LHC

- Cavity performance
  - Maximum (and minimum) stable voltage with beam
  - Cryogenic heat load (with beam) & degradation with time
  - Cavity vacuum (aC-coating on either side of the cavity)
- RF gymnastics
  - Adiabatic ramping of voltage
  - Phase manipulation (anti-phasing, re-phasing…)
- Long term stability
  - Emittance growth, RF non-linearities (2ns bunch)
  - Cavity impedance, HOM power, fund. Power leakage

3. Performance and long term stability towards the HL-LHC

- Cavity performance
  - Maximum (and minimum) stable voltage with beam
  - Cryogenic heat load (with beam) & degradation with time
  - Cavity vacuum (aC-coating on either side of the cavity)
- RF gymnastics
  - Adiabatic ramping of voltage
  - Phase manipulation (anti-phasing, re-phasing…)
- Long term stability
  - Emittance growth, RF non-linearities (2ns bunch)
  - Cavity impedance, HOM power, fund. Power leakage

HiLumi HL-LHC PROJECT

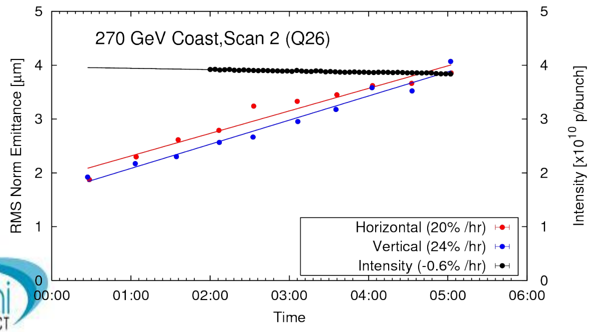
Past emittance growth in coasting beams

- **Different energy** coasts, primarily **single bunch** and **low intensity** were studied
  - Distinguish between collective effects and natural emittance growth
- Best spots for lower emittance growth identified to be 120/270 GeV with 1-4 x 10^{10} ppb

HiLumi HL-LHC PROJECT

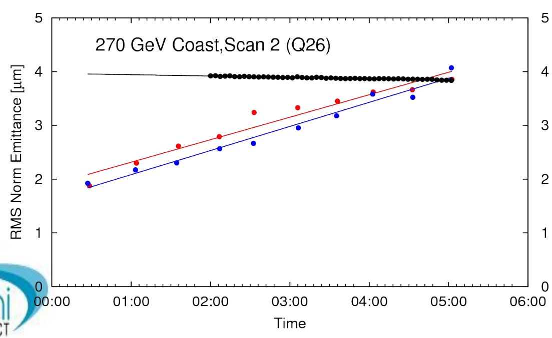
Past emittance growth in coasting beams

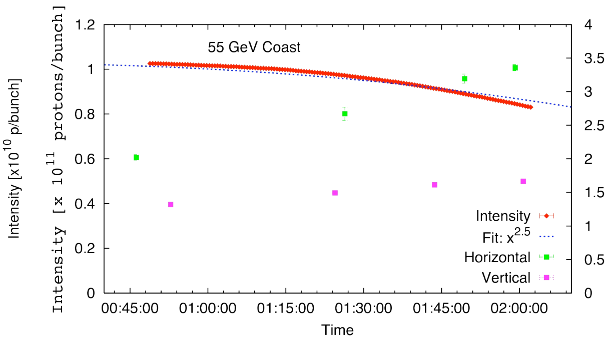
- **Different energy** coasts, primarily **single bunch** and **low intensity** were studied
  - Distinguish between collective effects and natural emittance growth
- Best spots for lower emittance growth identified to be 120/270 GeV with 1-4 x 10^{10} ppb
  - Similar growth in both planes



Past emittance growth in coasting beams

- **Different energy** coasts, primarily **single bunch** and **low intensity** were studied
  - Distinguish between collective effects and natural emittance growth
- Best spots for lower emittance growth identified to be 120/270 GeV with 1-4 x 10^{10} ppb
  - Similar growth in both planes
  - Lower energies and higher intensities always gave worse results

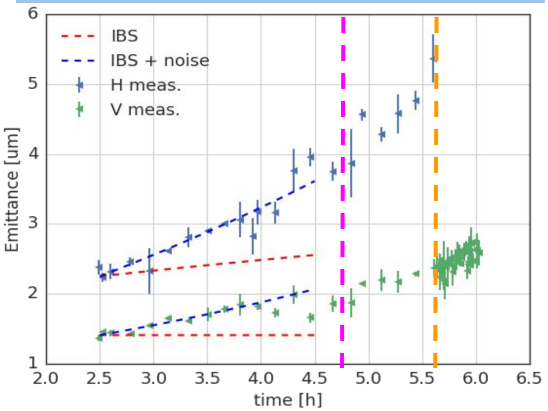




HiLumi HL-LHC PROJECT

Emittance growth in coasting beams @ 270GeV

Transverse

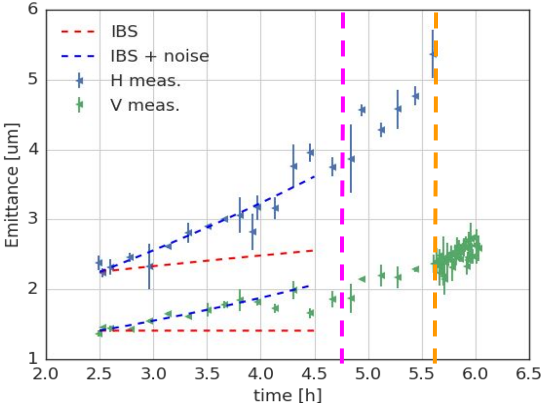


- Low bunch intensity
- Chroma increase → Clear slope increase of the emittance growth
- Impact of the WS → negligible
- IBS can explain part of the H growth
    - Clear residual growth on top of IBS similar for H and V

HiLumi HL-LHC PROJECT

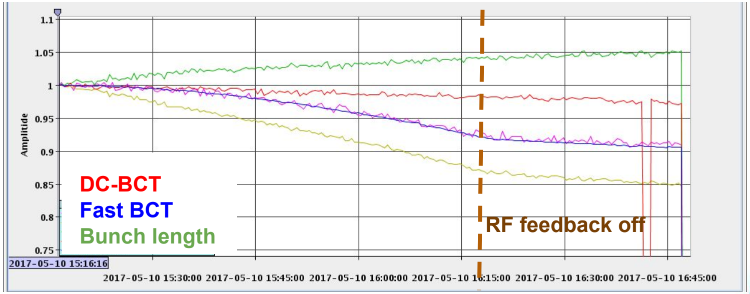
Emittance growth in coasting beams @ 270GeV

Transverse



- Low bunch intensity
- Chroma increase → Clear slope increase of the emittance growth
- Impact of the WS → negligible
- IBS can explain part of the H growth
  - Clear residual growth on top of IBS similar for H and V

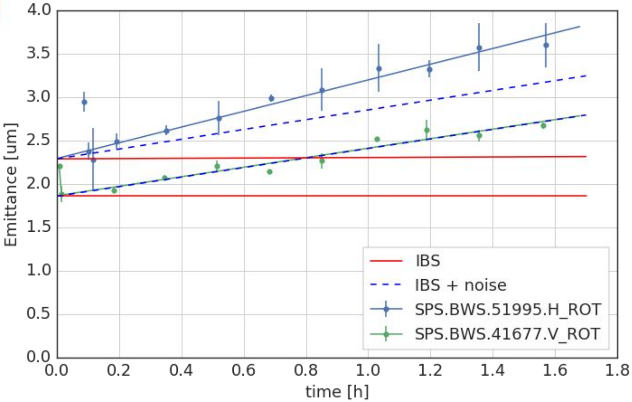
Longitudinal



- Slow **off bucket losses** were observed during all MDs
- Source of the losses was identified → **RF feedback!**
- **coast MDs with single bunch should be done with the RF fb off!**

Emittance growth in coasting beams @ 270GeV

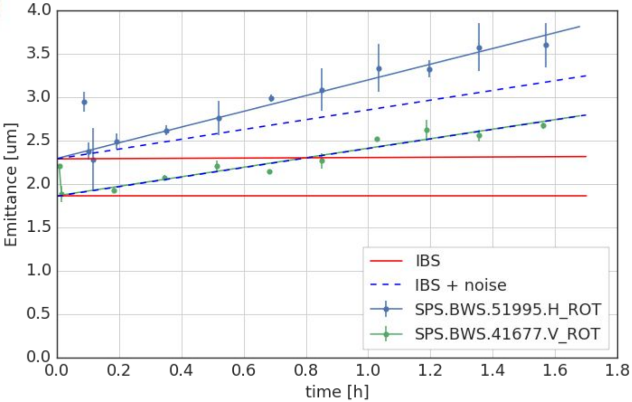
Q20 optics



- Very **similar** results with **Q26**
  - Similar V growth
  - Residual growth similar in both planes
- **No strong argument to move to Q20**

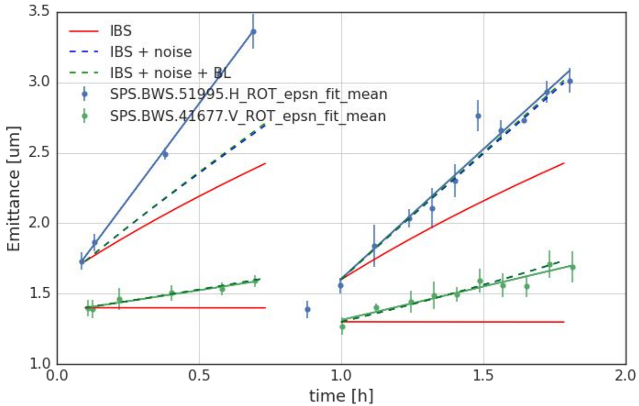
Emittance growth in coasting beams @ 270GeV

Q20 optics



- Very **similar** results with **Q26**
  - Similar V growth
  - Residual growth similar in both planes
- **No strong argument to move to Q20**

Nominal Intensity

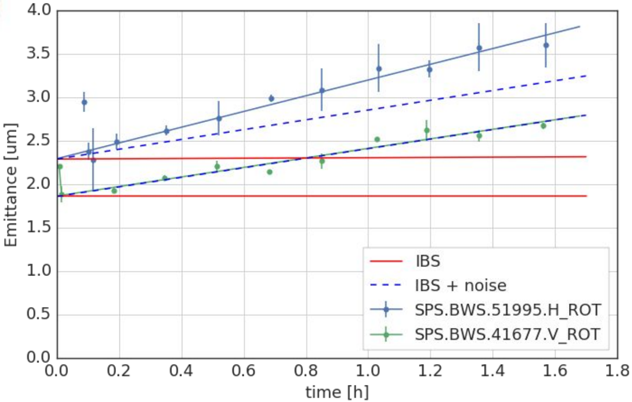


- Parasitic MD with **nominal intensity** (1.1×10^{11})
- **No dependence of the residual V growth on intensity**

HiLumi HL-LHC PROJECT

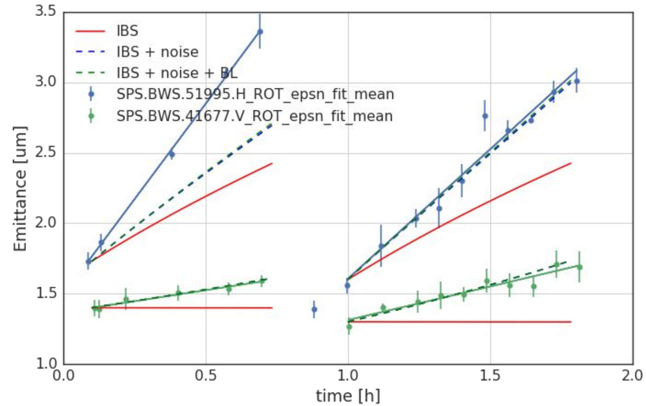
Emittance growth in coasting beams @ 270GeV

Q20 optics



- Very **similar** results with **Q26**
  - Similar V growth
  - Residual growth similar in both planes
- **No strong argument to move to Q20**

Nominal Intensity



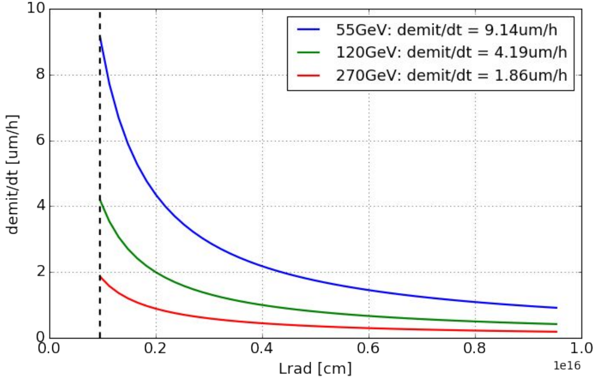
- Parasitic MD with **nominal intensity** (1.1×10^{11})
- **No dependence of the residual V growth on intensity**

Possible source of noise: vacuum, power supply ripple, unknown source of noise

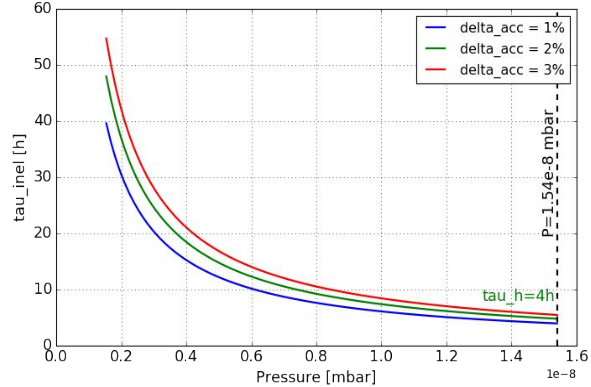
HiLumi HL-LHC PROJECT

Emittance growth in coasting beams: Impact of residual gas scattering

$d\varepsilon_y/dt$ = f(Radiation length)



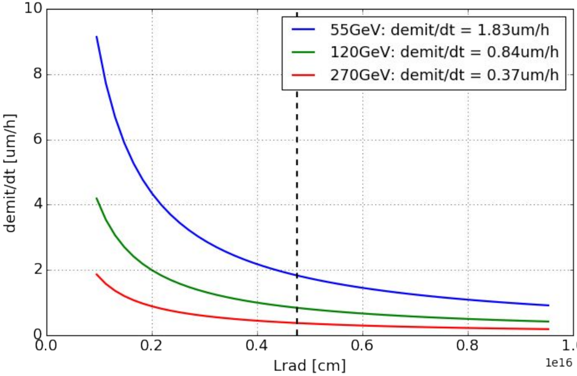
lifetime = f(pressure)



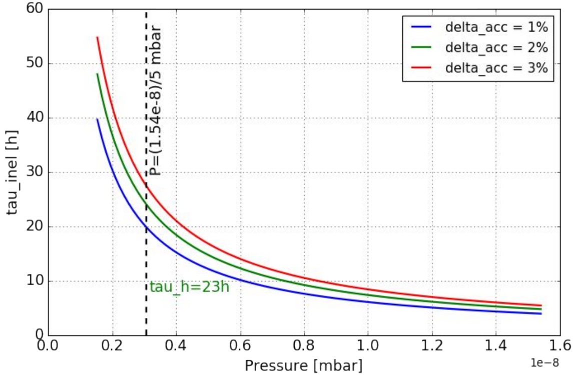
- Vacuum composition measurements in the SPS in 2011: ref
- Predictions based on measured values → larger emittance growth and smaller beam lifetime than the ones observed in the machine

Emittance growth in coasting beams: Impact of residual gas scattering

$d\varepsilon_y/dt$ = f(Radiation length)



lifetime = f(pressure)



- Vacuum composition measurements in the SPS in 2011: ref
- Predictions based on measured values → larger emittance growth and smaller beam lifetime than the ones observed in the machine
- For better vacuum conditions both emittance growth and lifetime can be reproduced
- MD foreseen at the end of the year to validate the observations
  - In collaboration with the vacuum group

Summary of MD results

	Emit. H/V [μm]	Nb [10^{10}]	Chroma H/V	V_{RF} [MV]	Bunch length [ns]	Long. emit. [eV. sec]	H growth [μm/h]	V growth [μm/h]	σ_l growth [%/h]
May 2015									~10
Coast 11	0.8/0.9	1.5	3.8/2.7	4.5	1.5		2.3	**0.3**	
Coast 12	4.2/1.5	1.5	red.	4.5	1.5		1.0	**-0.2**	
Coast 2	1.8/1.0	1.25	red.	4.5	1.5		1.3	**0.5**	
Coast 3	1.7/1.2	1.7	red.	3.5	1.5		0.9	**0.3**	
July 2016	2.85/2.16	2.25	2.5/2.5	5.1	1.96	0.41	0.59	**0.23**	~10
Dec. 2016									
Coast1	2.23/1.61	4.25	0.5/1	2	2.28	0.36	0.49	**0.30**	~10
Coast 2	2.25/1.41	1.65	0.5/1		2.3	0.36	0.55	**0.27**	~10
ξ increase	4.0/1.98		2.5/3		-		1.52	**0.51**	-
multi-scans	-/2.3		2.5/3		-		-	**0.82**	-

HiLumi HL-LHC PROJECT

Summary of MD results

	Emit. H/V [μm]	Nb [10^{10}]	Chroma H/V	V_{RF} [MV]	Bunch length [ns]	Long. emit. [eV. sec]	H growth [μm/h]	V growth [μm/h]	σ_l growth [%/h]
May 2017	Focus on the off bucket losses								
June 2017	2.1/1.7	2.5	1/1.6	5	1.9	0.41	0.67	**0.37**	~10
4 July 2017 Q20 Coast 1 Coast2	7.3 / 4.8 2.5/2.0	2.2 2.2	0.7/1.4	5	1.7 2.0	0.33 0.45	0.33 0.83	**0.4** **0.5**	~10 ~10
9 Aug. 2017 **Coast 1** **Coast 2**	1.73/1.4 1.6/1.3	12 11	-				2.71 1.84	**0.31** **0.48**	

4. High intensity RF operation

- Beam induced **failure scenarios** as a function of bunch high intensity and number of bunches
    - Beam aperture near crabs might need 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”
- Special attention to injection & ramp (**parasitic impedance** to beam)
- Note: HOM power interlock at 200 W from any of the 6 couplers (RF feedthrough limit)

HiLumi HL-LHC PROJECT

Other aspects

- Alternative methods for CC phase measurements
  - Independent beam-phase measurement from BPMs next to the CM
- CC RF multipoles measurements (Driving the cavity as an AC dipole)
- Impact of the bunch shape on the response of the BPMs
  - Under study with the BI group
- Induced emittance growth from the CC in the SPS

Beams

- Mostly single bunch, up to nominal intensity for CC validation
- 25ns lhc beams up to 4 batches (limited by the HOM power) for the high intensity operation
- Q26 optics

Summary

- We expect the SPS CC test to take place in four phases
- Simulations with the demonstrated voltage (2.5MV per cavity) show no impact on measurement program
  - Preparation studies and MDs using SPS instrumentation ongoing
- Several natural emittance growth MDs already performed
  - Strong chromaticity dependence in H
  - H and V difference due to ibs
  - Source of noise with vacuum and power supply ripple being studied as main candidates
- Instrumentation for crabbing validation
  - Head tail monitor calibration studies at nominal and low intensity show promising results
  - Wire scanners can be used as an alternative through the profile change
  - BSRT monitors have been commissioned
  - Effect of RF non-linearity on BPM readings under study
- No instabilities are expected in the SPS unless the fundamental mode feedback is removed (software change) of the HOM damping removed (hardware intervention)

Summary of MD Strategy for 2018

	What	When	MD slots
0	RF commissioning	Mar-Apr	~ 4 weeks
1	RF-beam synchronization	May-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

- RF synchronization and counter-phasing: dedicated long MDs.
  - 4 x 24h (appropriate shifts tbd) mandatory for system validation 1) & 2)
- Crab-bypass is designed for full remote control: **access not needed** for MDs
- For 3, if cavity is truly transparent during the SPS energy cycle, some parasitic MDs feasible
- For 4, dedicated MDs for high intensity validation. Parasitic MDs only possible with fixed target

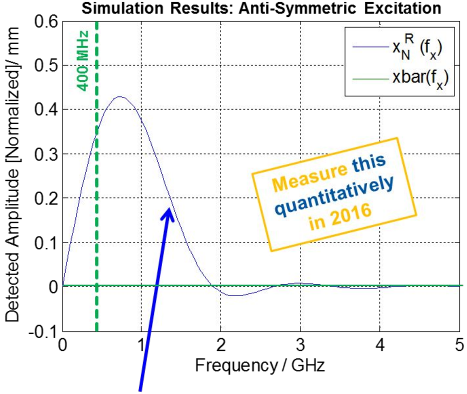
HiLumi
HL-LHC PROJECT

Thank you

Additional Topics

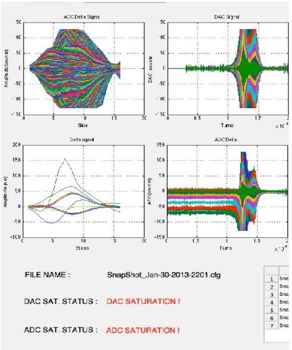
- Interplay with the SPS transverse damper & use of damper instrumentation (including WBFS)
- Use crab cavities as an AC dipole for measurement of RF multipoles

Present Damper

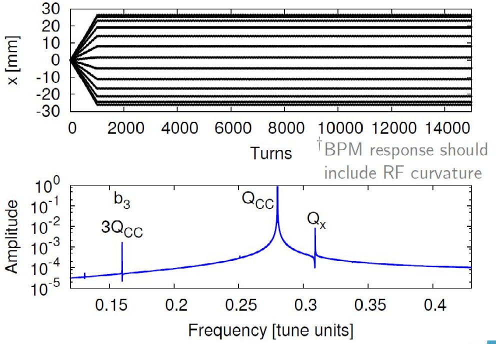


alternate processing scheme to detect and indicate anti-sym. oscillations:

Wideband FB



CC as AC-Dipole

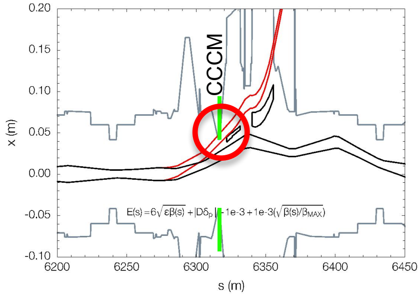


Courtesy: G. Kotzian, R. Tomas et al.

Compatibility of crab-cavity CM with SPS Operation

CCCM aperture

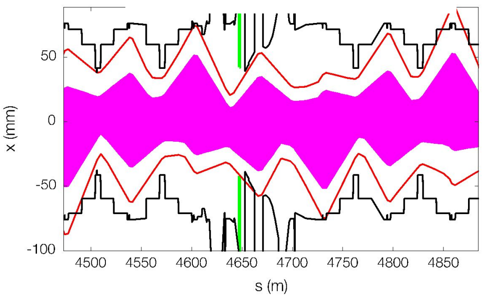
LHC beam extraction in LSS6



Fast extraction to LHC
Crab-cavity in beam does not yield enough aperture for extracted beam

H.Bartosik @
SPS Test Day, I
https://indico.cern.ch/event/463435/

NA slow extraction in LSS6



Slow extraction of fixed target beam at 400GeV, incl. extraction bump
purple : raw beam envelope
red: beam envelope + tolerance

Crab cavity in beam is compatible with slow extraction to North Area
No need for bumper dipole interlocking (opp. to Coldex)

Compatibility with SPS fixed target 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).

H. Bartosik

Natural emittance growth studies until 2012

	Unit	Sep 2010	Oct 2010	May 2011	July 2011
Energy	GeV	55	120	120	270
Qx,y	-	0.13/0.18	0.13/0.18	Several tunes	0.13/0.18
ξx,y		2-3	2	0.5	0.5
Intensity	$\times 10^{11}$	1.1	0.5	0.2	0.2
# Bunches	-	1	12	1	1
$\varepsilon_{x,y}$	μm	3.1/2.8	1.5-2.0	2.5	2.5
V_{RF}	MV	3.0	4.0 (1)	4.6 - 6.5	4.6 - 6.5

Energy [GeV]	Intensity [$\times 10^{11}$]	Qx/Qy	Voltage [MV]	$d\varepsilon_x/dt$ [/hr]	$d\varepsilon_y/dt$ [%/hr]	dεy/dt [μm/h]
55	1.0	0.13/0.18	3.0	140-370%	57%	1.6
120	0.5 (12b)	0.13/0.18	2.0-4.0	100-300%	40-90%	0.6-1.8
120	0.1	0.13-0.33	2.0-4.0	18%	17%	0.43
270	0.4	0.13/0.18	3.0	20-23%	14-24%	0.35-0.6

- **Different energy** coasts, primarily **single bunch** and **low intensity**
  - Distinguish betwee collective effects a natural emittance growth
- Best spots identified to be 120/270 GeV with 1-4 e10 ppb
  - The lowest emittar growth
  - Similar results in b planes
- Lower energies and higher intensities always gave worse results

The multiple elastic Coulomb scattering will cause the transverse emittance of the beam to grow. The rate of the normalized emittance growth is expressed as

$$\frac{d\epsilon_{(x,y),N}}{dt} \simeq \frac{1}{2}\gamma \left\langle \beta_{(x,y)} \right\rangle \dot{\Theta}^2_{(x,y),rms} \propto \frac{1}{\gamma}\frac{1}{L_{rad}},$$

The average rate of change of the transverse scattering angle $\dot{\Theta}^2_{rms}$ is

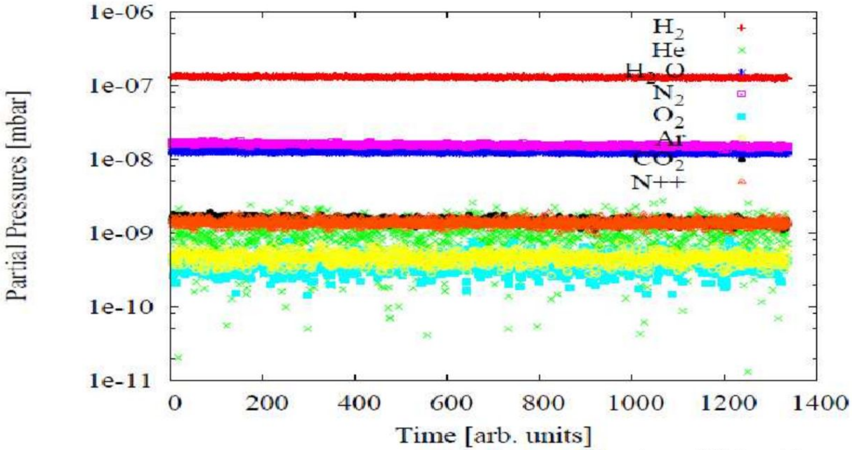
$$\dot{\Theta}^2_{(x,y),rms} = \left(\frac{13.6MeV}{m_p c^2 \gamma}\right)^2 \frac{Z_P^2}{A_P^2}\frac{c}{L_{rad}},$$

The radiation length L_{rad} can be written as

$$\begin{aligned}\frac{1}{L_{rad}} &= \sum_i^{N_{species}} \frac{\rho_i \left(g/cm^3\right)}{X_{0,i}\left(g/cm^2\right)} \\ &= \sum_i^{N_{species}} \frac{10^3 \cdot p_i\left(mbar\right) \cdot M_i\left(g/mol\right)}{R\left(erg/K\,mol\right) \cdot T\left(K\right) \cdot X_{0,i}\left(g/cm^2\right)}.\end{aligned}$$

Courtesy H. J. Kim, T. Sen

Pressure without beam



(Courtesy of Holger Neupert)

- SPS MD May 10, 2011.
- Figure shows the (corrected) pressure profile without beam, in between beam cycles.
- SPS MDs for beam emittance used “low intensity” beams.
- These pressures are used for estimates.

Courtesy H. J. Kim, T. Sen

Radiation lengths: Lrad

Gas	Average static pressure [mbar]	Density* [g/cm^3]	Radiation length* L_{rad} [cm]
N_2	1.54×10^{-8}	1.77×10^{-14}	2.1×10^{15}
Water vapor	1.24×10^{-8}	9.15×10^{-15}	3.9×10^{15}
H_2	1.28×10^{-7}	1.04×10^{-14}	5.8×10^{15}
CO_2	1.45×10^{-9}	2.62×10^{-15}	1.4×10^{16}
Ar	4.58×10^{-10}	7.52×10^{-16}	2.1×10^{16}
N^{++}	1.35×10^{-9}	7.81×10^{-16}	4.9×10^{16}
O_2	3.97×10^{-10}	5.21×10^{-16}	6.6×10^{16}
He	9.46×10^{-10}	1.55×10^{-16}	6.1×10^{17}

* Gas temperature is assumed to be 300 K.

Courtesy H. J. Kim, T. Sen

SPS Instrumentation

- **BPMs**
  - MOPOS system (possibility of DOROs acq chanel)
    - Orbit mode - 100μm, Trajectory - 400μm
  - Two new BPMs around the crab
  - Special PUs (transverse damper, WBFS, exponential PU)
- **Head-Tail Monitor**
  - HT monitor - 100μm resolution for 1.6 sec
  - New EO-Pick-up and MIM under-development
    - Possibly available by 2018
- **Wire scanners** for emittance measurements
- **BGI** under re-commissioning and cross calibration in 2017
- Extra **BLMs** around the crab-cavity to be finalized

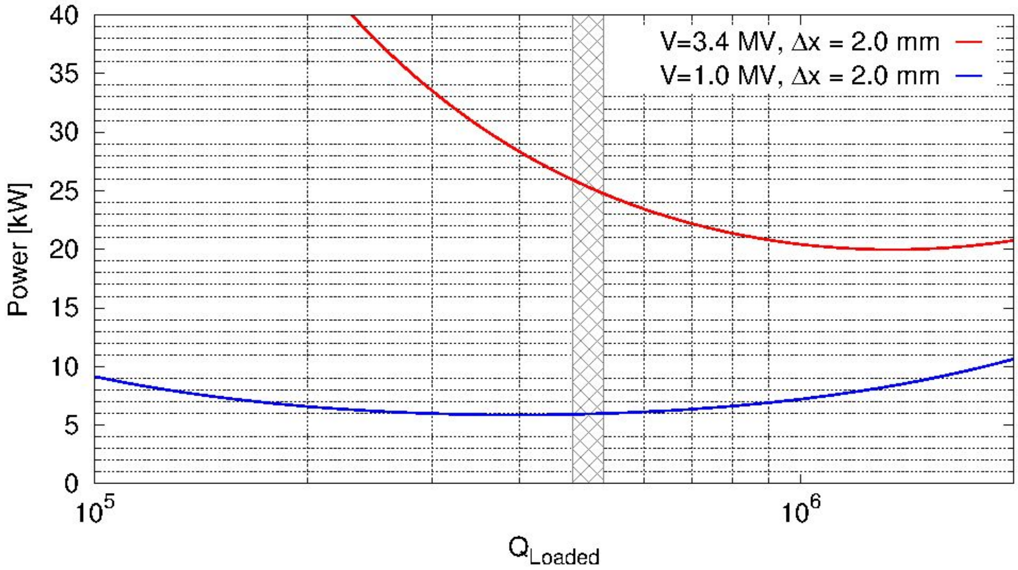
Natural emittance growth in coasting beams

- **Chromaticity** plays an important role, especially in the vertical plane
  - A systematic chromaticity scan MD has been planed
- Intrabeam scattering can explain only part of the growth. Residual growth similar in both planes (for low chroma)
- Source of the off bucket losses has been identified to be the RF feedback!
- Q20 and Q26 optics give similar results
  - Q26 optics remains our main optics for the tests, unless a strong argument reveals in favor of Q20
- **The vertical emittance growth always at the same levels!**
  - Not sensitive to intensity, optics, initial conditions
  - Sensitive to beam energy
- A good candidate for the vertical emittance growth is the residual gas scattering
  - An MD is foreseen at the end of the year in collaboration with the vacuum group

HiLumi HL-LHC PROJECT

RF Power Calibration with Beam

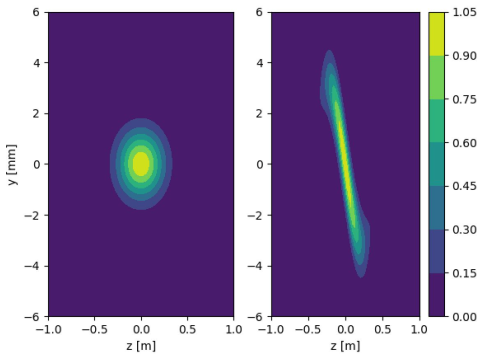
- Maximum required power with I_b = 350 mA (200 bunches, N_b = 1.7x10^{11} p/b)
- Available maximum is 40 kW

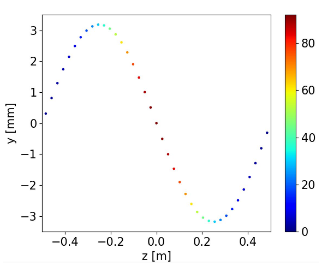


5MV

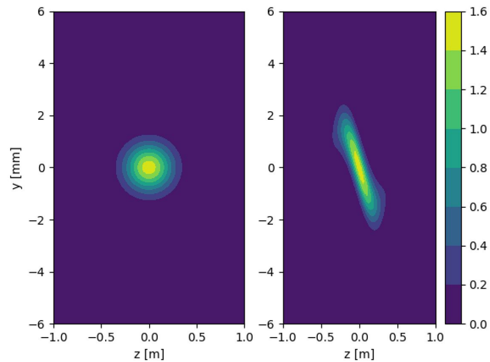
HT

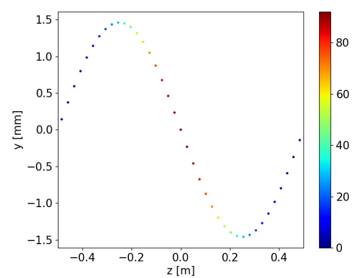
55GeV



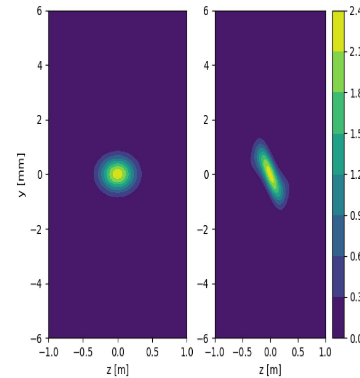


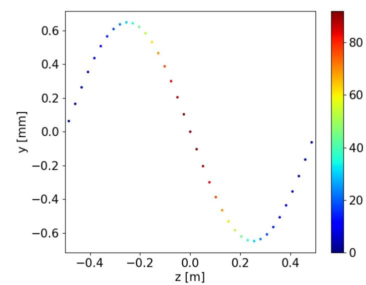
120GeV





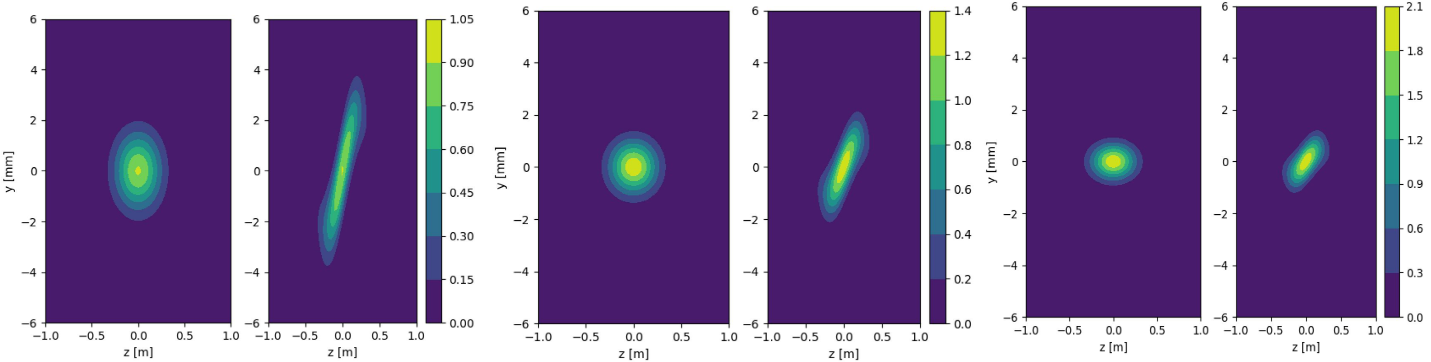
270GeV





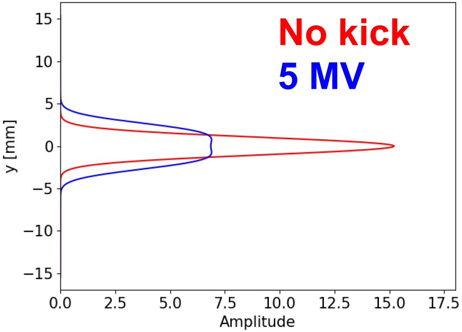
WS

55GeV 120GeV 270GeV

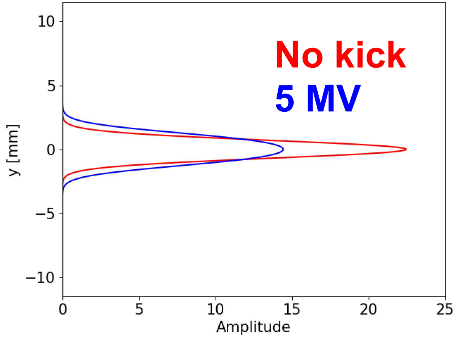


WS

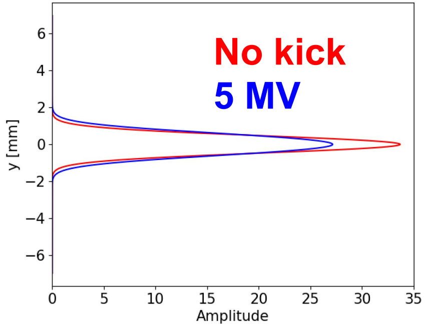
55GeV



120GeV



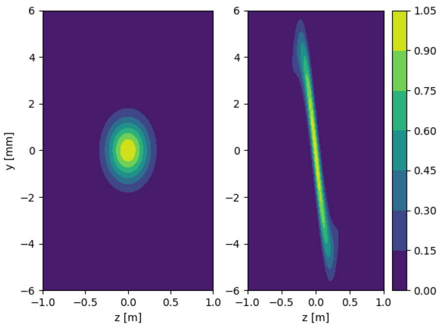
270GeV

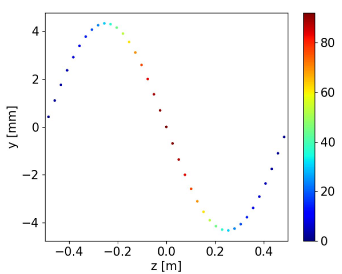


6.8MV

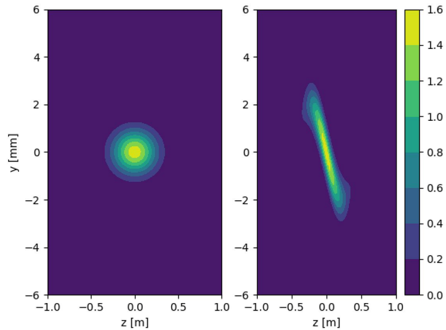
HT

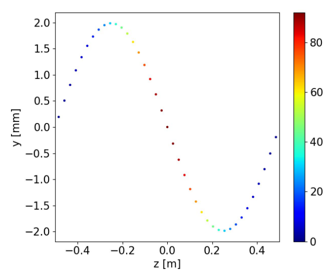
55GeV



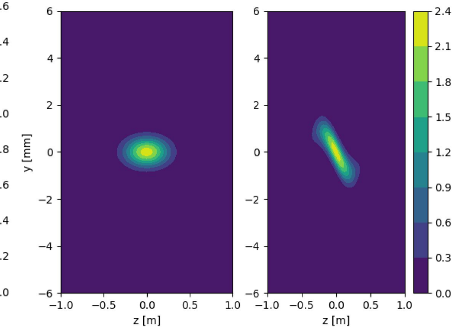


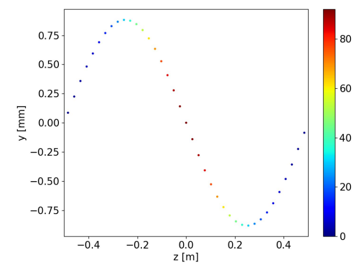
120GeV



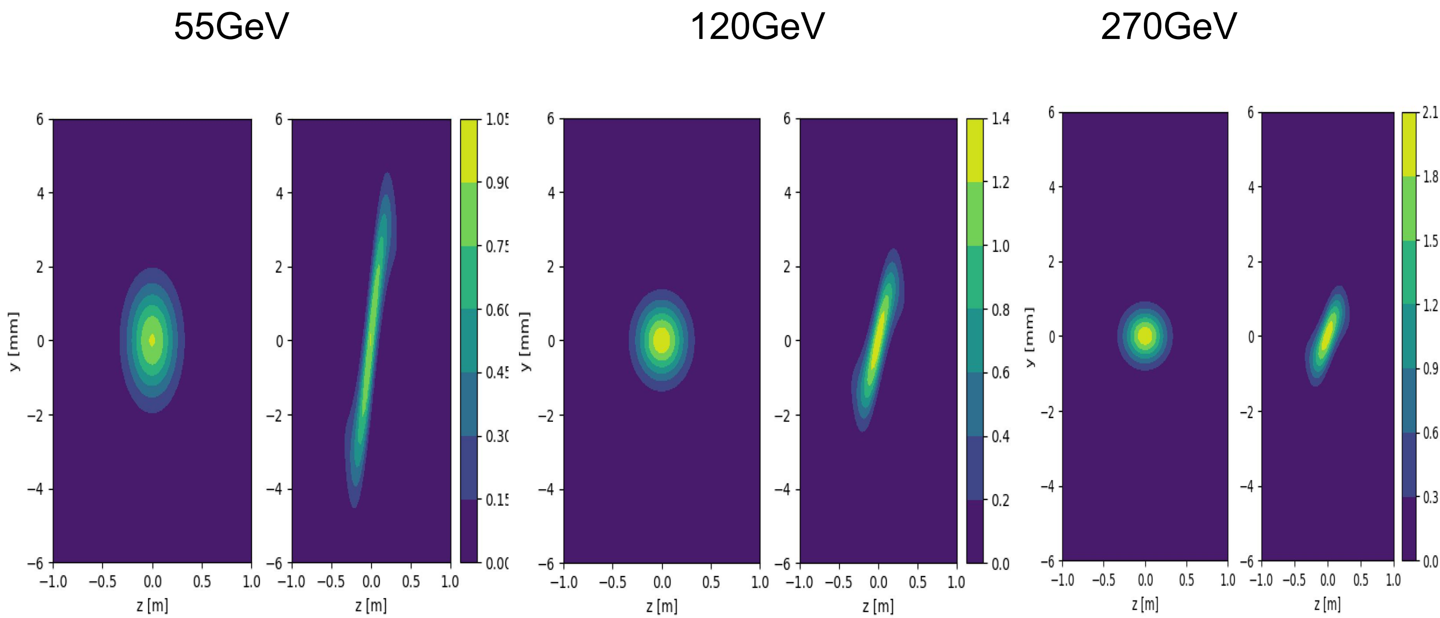


270GeV



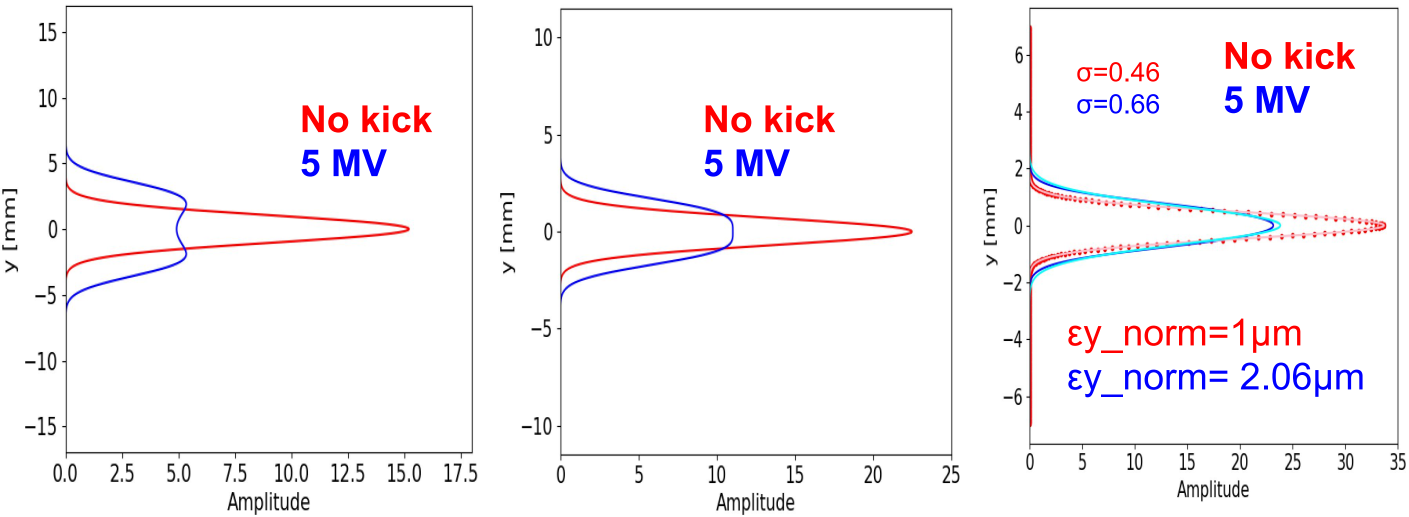


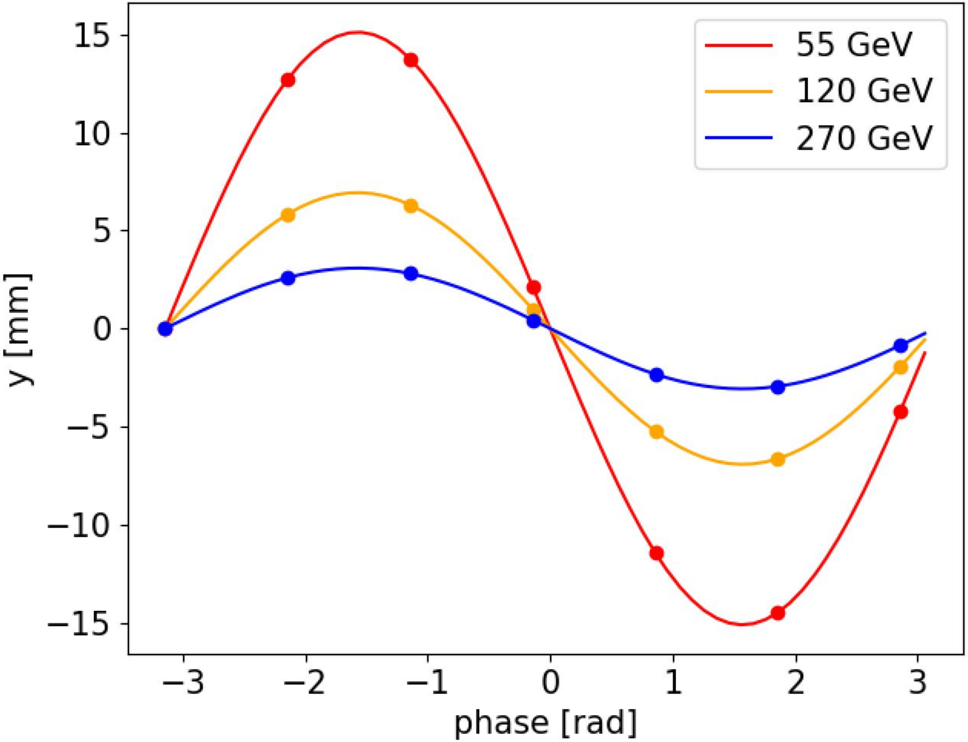
WS



WS

55GeV 120GeV 270GeV





WS
location

Making the upper estimate of the instability growth rate

- Looking at the most unstable CB mode
  - Assuming it falls on the peak of the HOM spectrum
- Rigid bunch approximation (m = 0)
- No damper
- Q' = 0

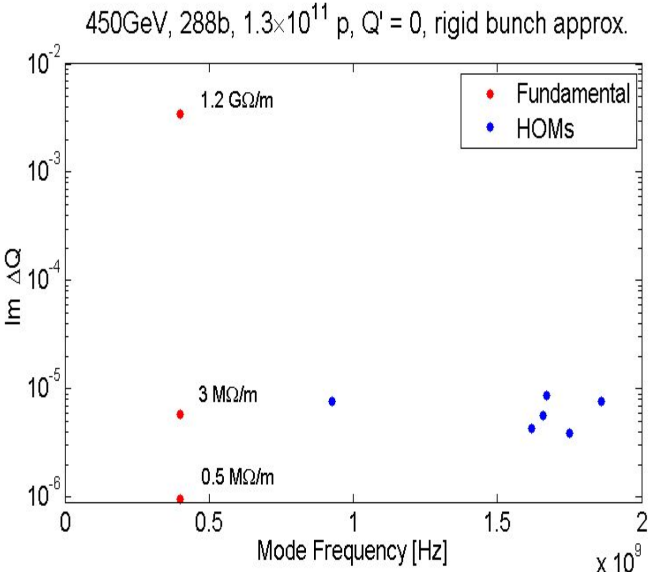
- Chao Eq. (5.114):

$$\Omega - \omega_\beta = -i \frac{M N_b r_0 c}{\gamma T_0 Q_x} \frac{R_s}{Z_0}$$

S. Antipov, M. Stefan Beck, F. Giordano, B. Salvant

No visible effect of the HOMs on beam dynamics expected, except for undamped 400 MHz mode

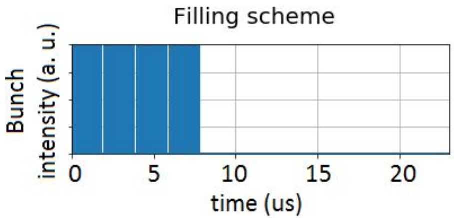
Contribution of one crab cavity



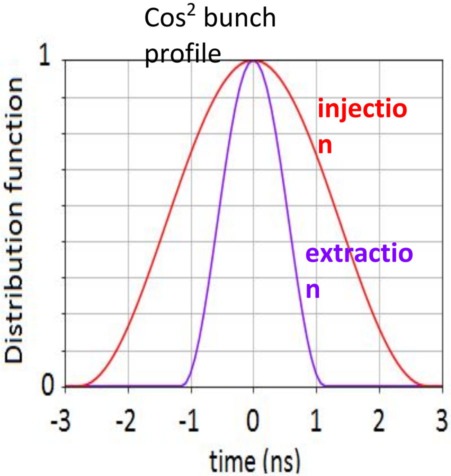
S. Antipov, M. Stefan Beck, F. Giordano, B. Salvant

Update on HOM power loss at SPS

Initial Estimates:
S. Antipov, *et al.*, “Review of Expected Crab Cavity Heat Loads Due to Impedance”, WP-2 Meeting, 13.06.17



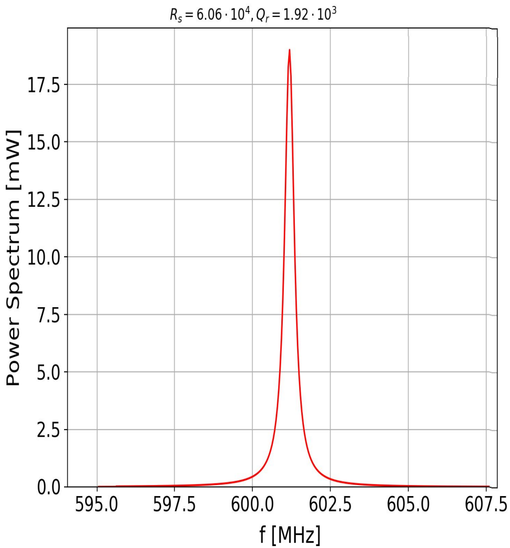
Intensity	1.3×10^{11} ppb
No. bunches	288
Bunch length, extraction	1.65 ns
Bunch length, injection	4.0 ns



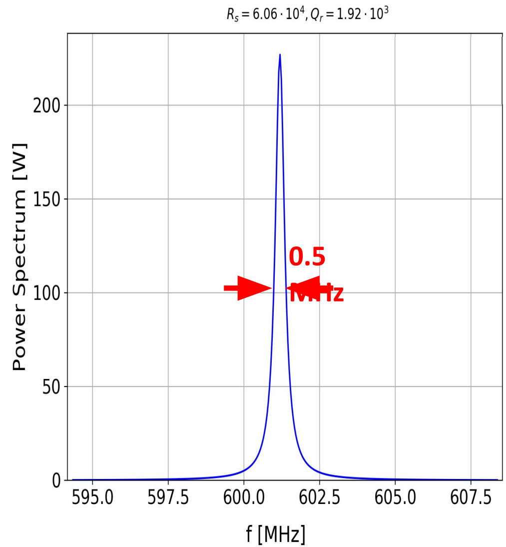
S. Antipov, M. Stefan Beck, F. Giordano, B. Salvant

Up to 200 W at extraction for the worst HOM:
f = 590 MHz, R_s = 60.6 kΩ, Q = 1.9x10^3

Injection, 4.0 ns bunch length



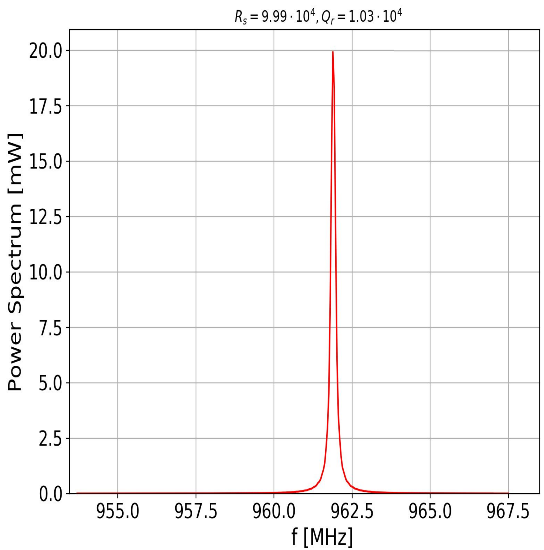
Extraction, 1.6 ns bunch length



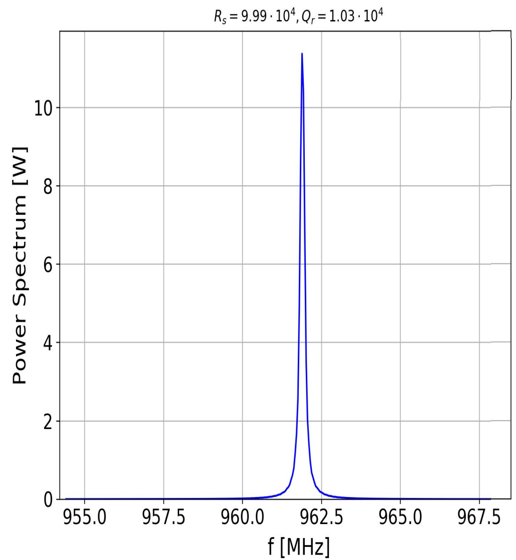
F. Giordano

Up to 10 W at extraction for the second worst:
f = 959 MHz, R_s = 100 kΩ, Q = 10^4

Injection, 4.0 ns bunch length



Extraction, 1.6 ns bunch length



F. Giordano