Beam stability challenges for High Luminosity Large Hadron Collider

S. ANTIPOV, CERN

JOINT DESY AND UNIVERSITY HAMBURG ACCELERATOR PHYSICS SEMINAR
DESY 13/08/19

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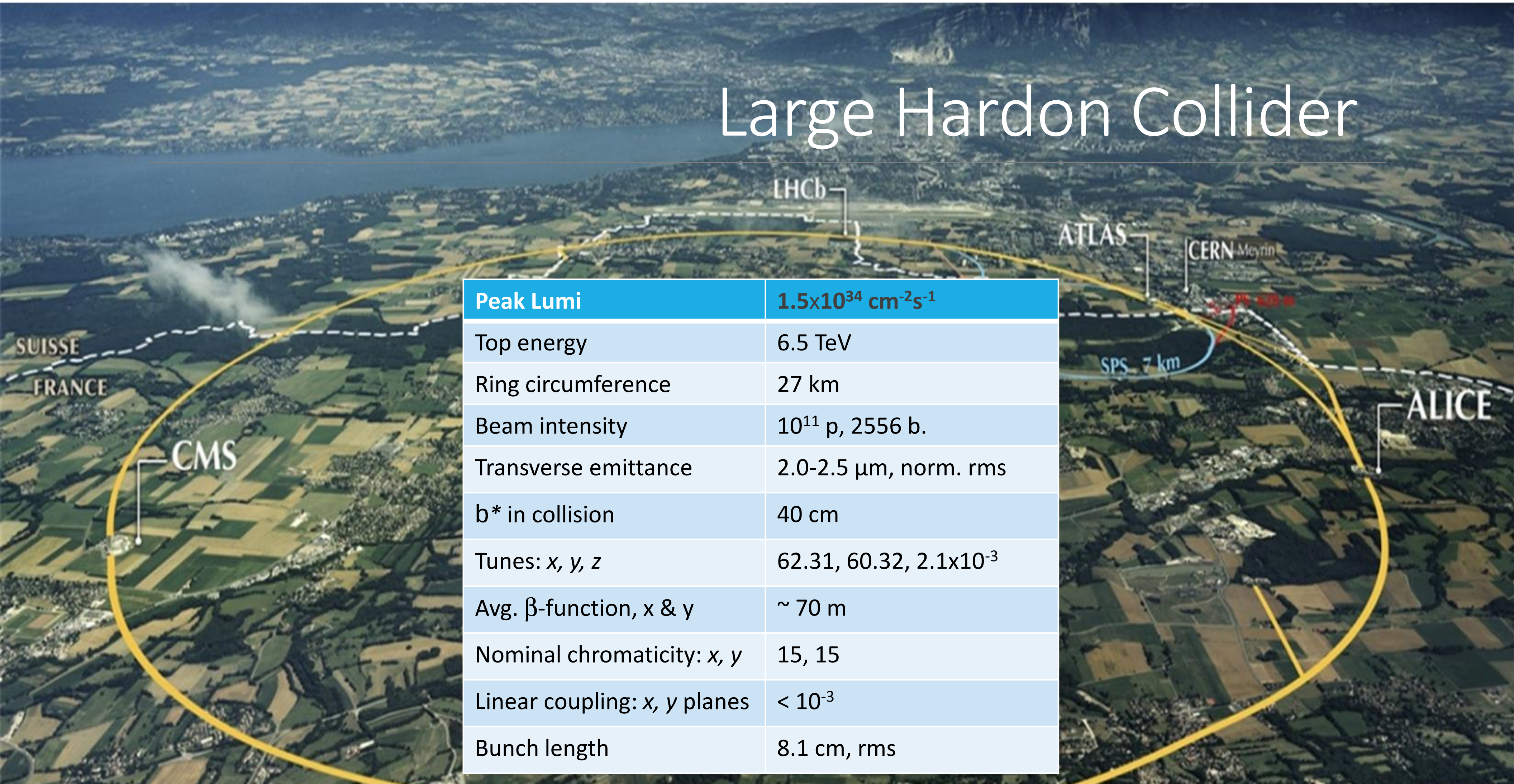
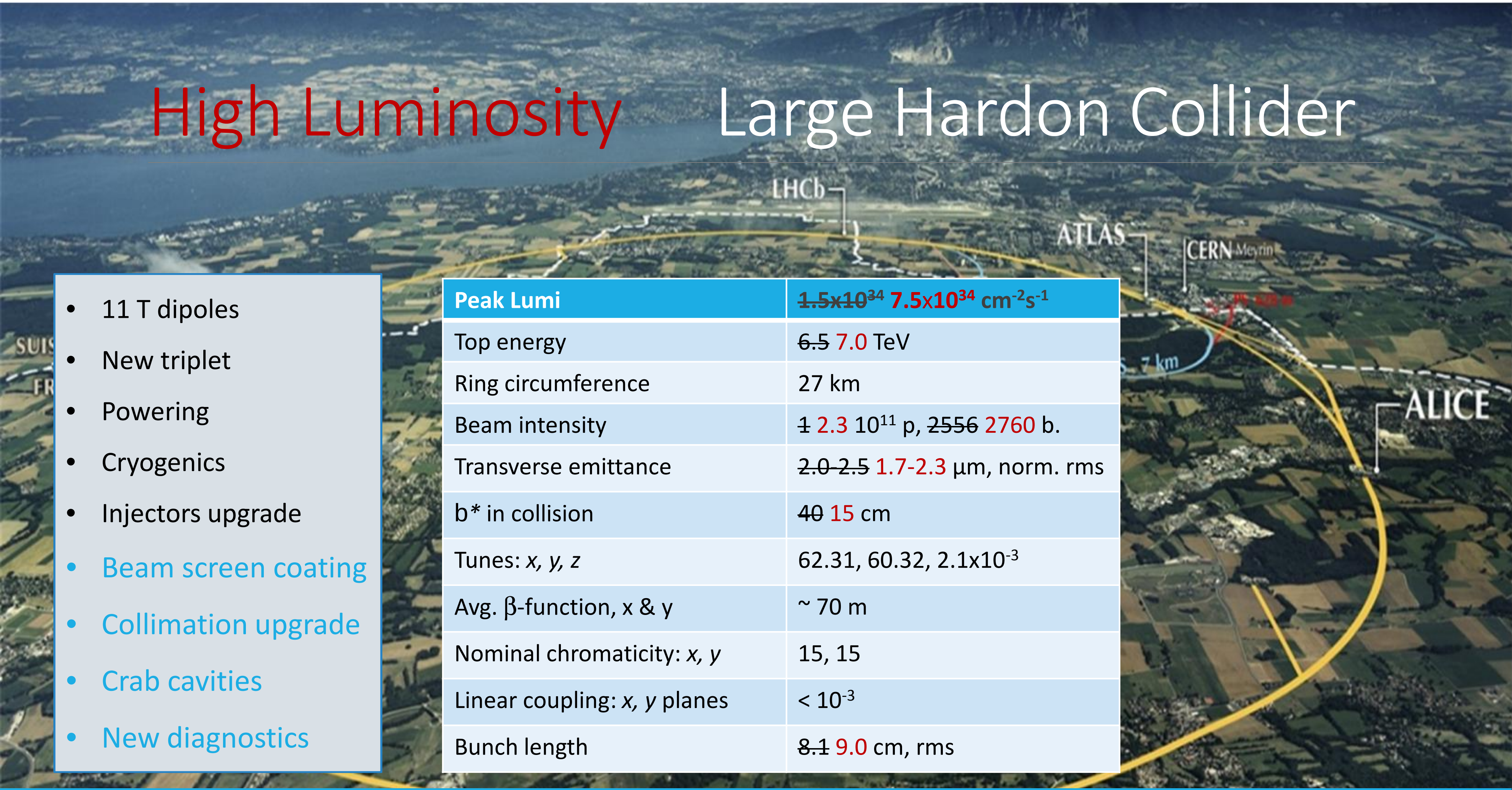
A. Burov, V. Lebedev (FNAL)

Large Hardon Collider



Peak Lumi	**1.5x10^{34} cm^{-2}s^{-1}**
Top energy	6.5 TeV
Ring circumference	27 km
Beam intensity	10^{11} p, 2556 b.
Transverse emittance	2.0-2.5 μm, norm. rms
b* in collision	40 cm
Tunes: *x, y, z*	62.31, 60.32, 2.1x10^{-3}
Avg. β-function, x & y	~ 70 m
Nominal chromaticity: *x, y*	15, 15
Linear coupling: *x, y* planes	< 10^{-3}
Bunch length	8.1 cm, rms

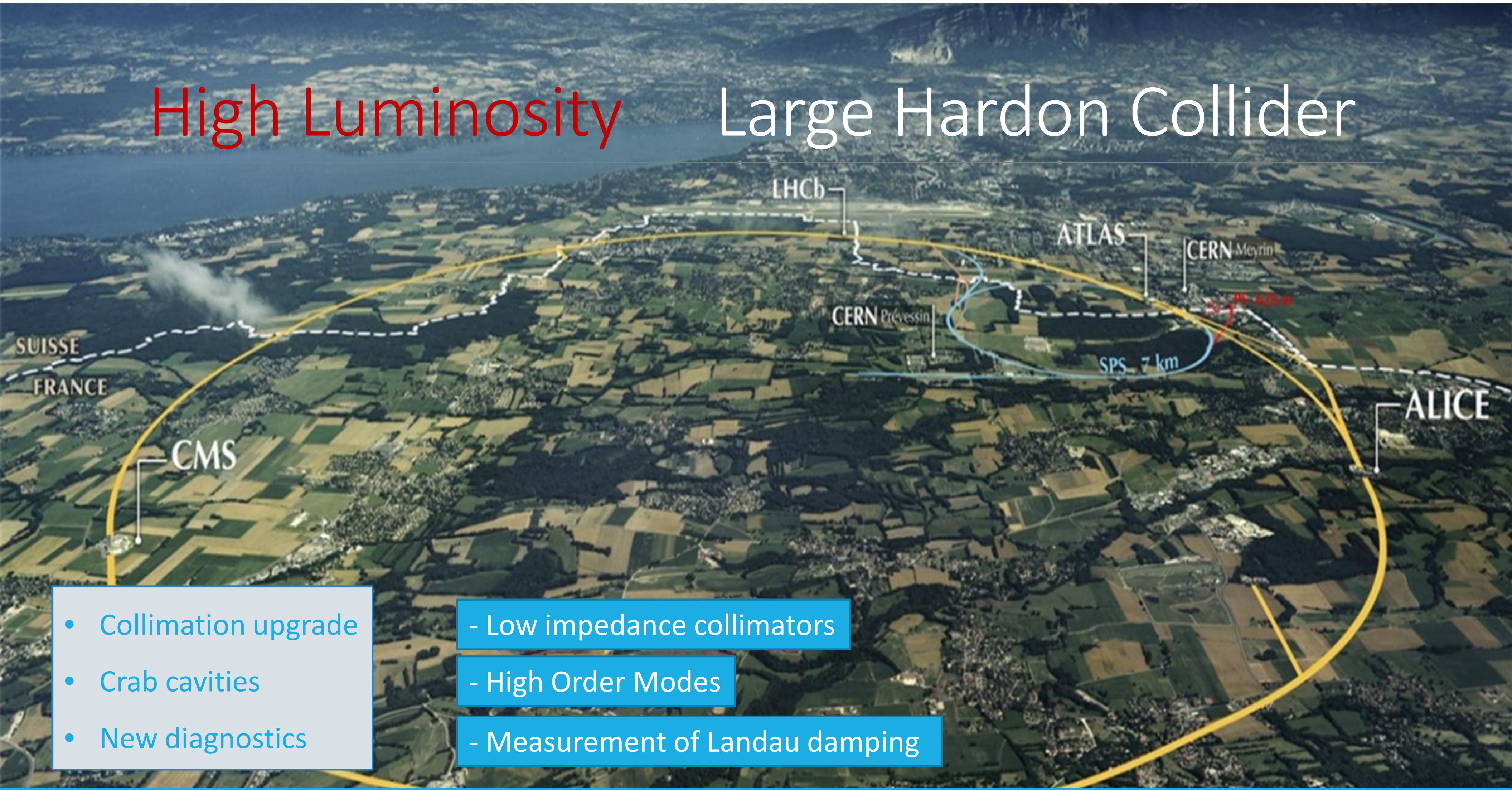
High Luminosity Large Hardon Collider



- 11 T dipoles
- New triplet
- Powering
- Cryogenics
- Injectors upgrade
- Beam screen coating
- Collimation upgrade
- Crab cavities
- New diagnostics

Peak Lumi	~~1.5×10^{34}~~ **7.5×10^{34} $cm^{-2}s^{-1}$**
Top energy	~~6.5~~ 7.0 TeV
Ring circumference	27 km
Beam intensity	~~1~~ 2.3 10^{11} p, ~~2556~~ 2760 b.
Transverse emittance	~~2.0-2.5~~ 1.7-2.3 µm, norm. rms
b* in collision	~~40~~ 15 cm
Tunes: *x, y, z*	62.31, 60.32, 2.1×10^{-3}
Avg. β-function, x & y	~ 70 m
Nominal chromaticity: *x, y*	15, 15
Linear coupling: *x, y* planes	$< 10^{-3}$
Bunch length	~~8.1~~ 9.0 cm, rms

High Luminosity Large Hardon Collider



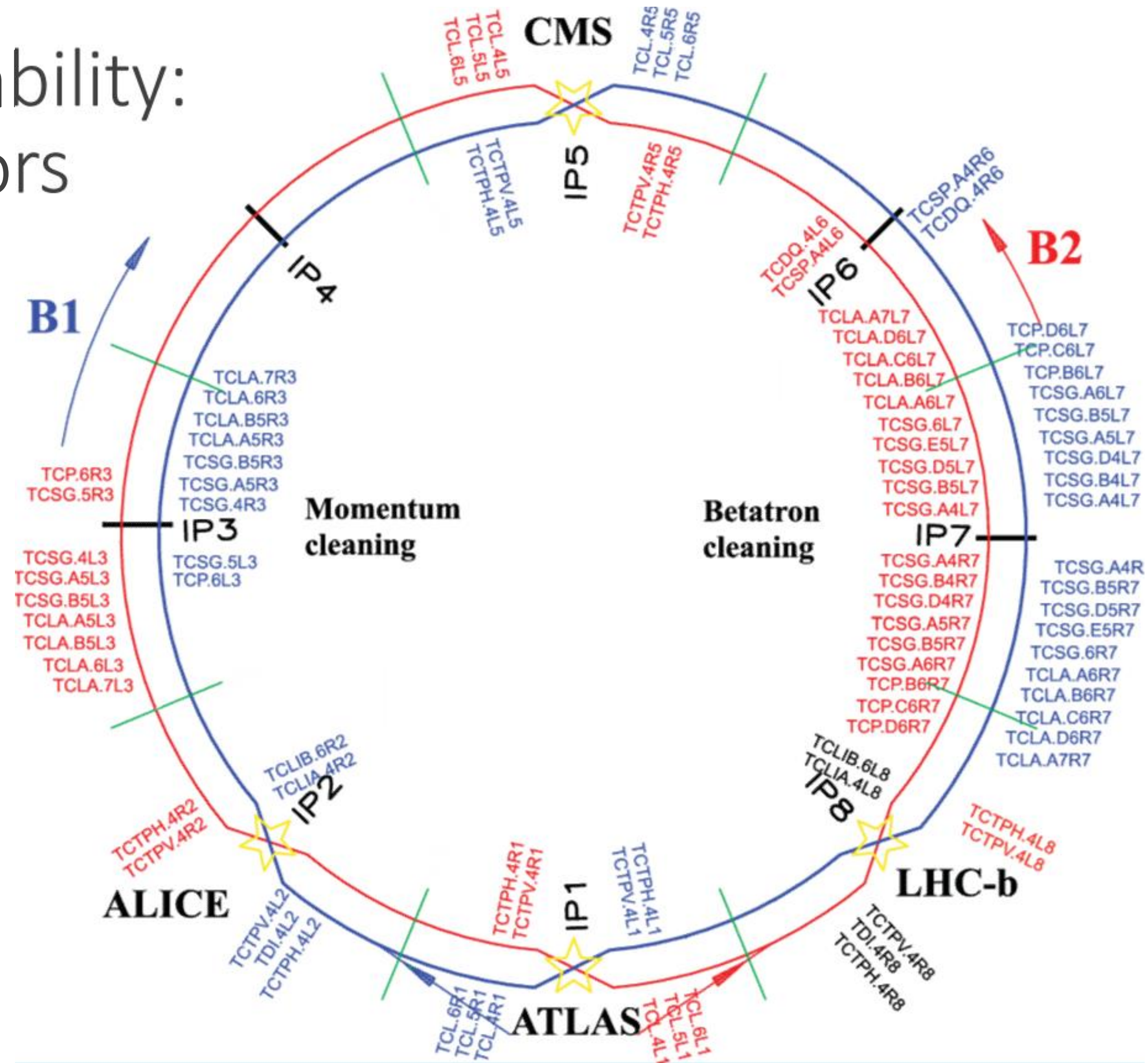
- Collimation upgrade
- Crab cavities
- New diagnostics

- Low impedance collimators

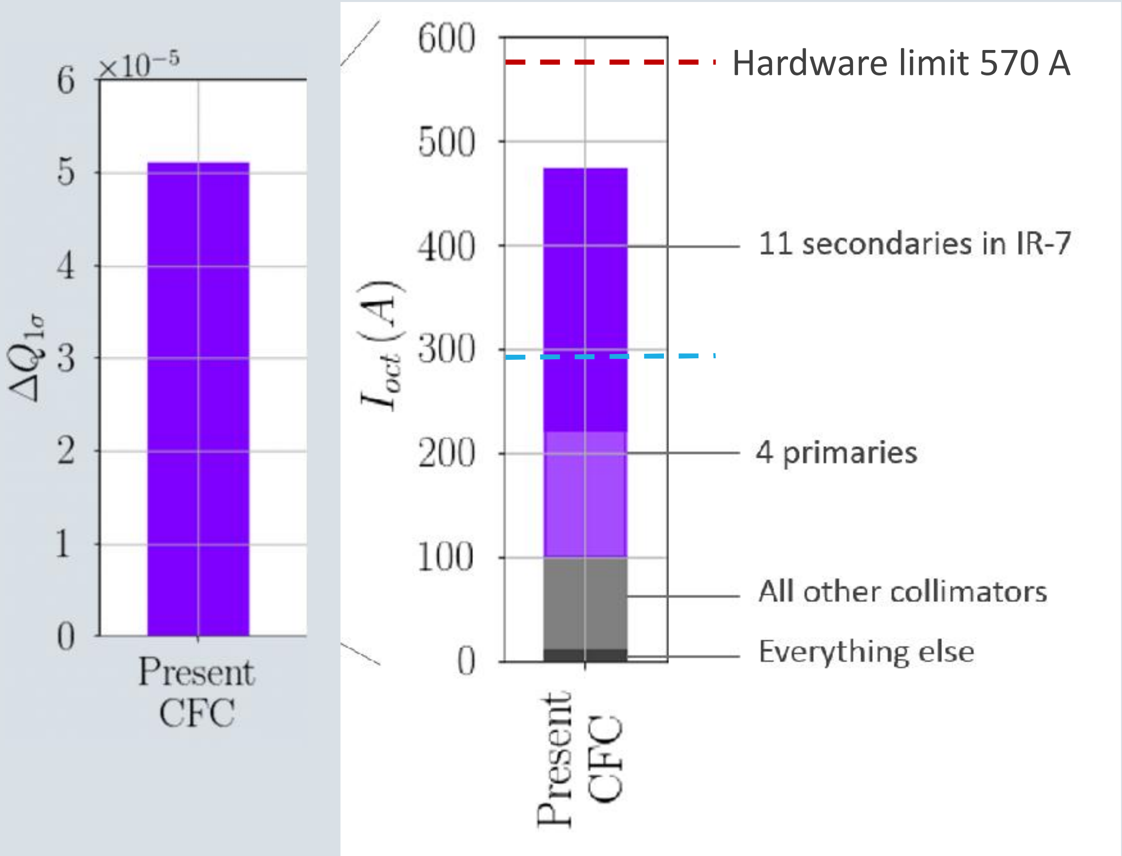
- High Order Modes

- Measurement of Landau damping

Beam Stability: Collimators



Impedance of LHC collimators has to be reduced for the Hi-Lumi upgrade

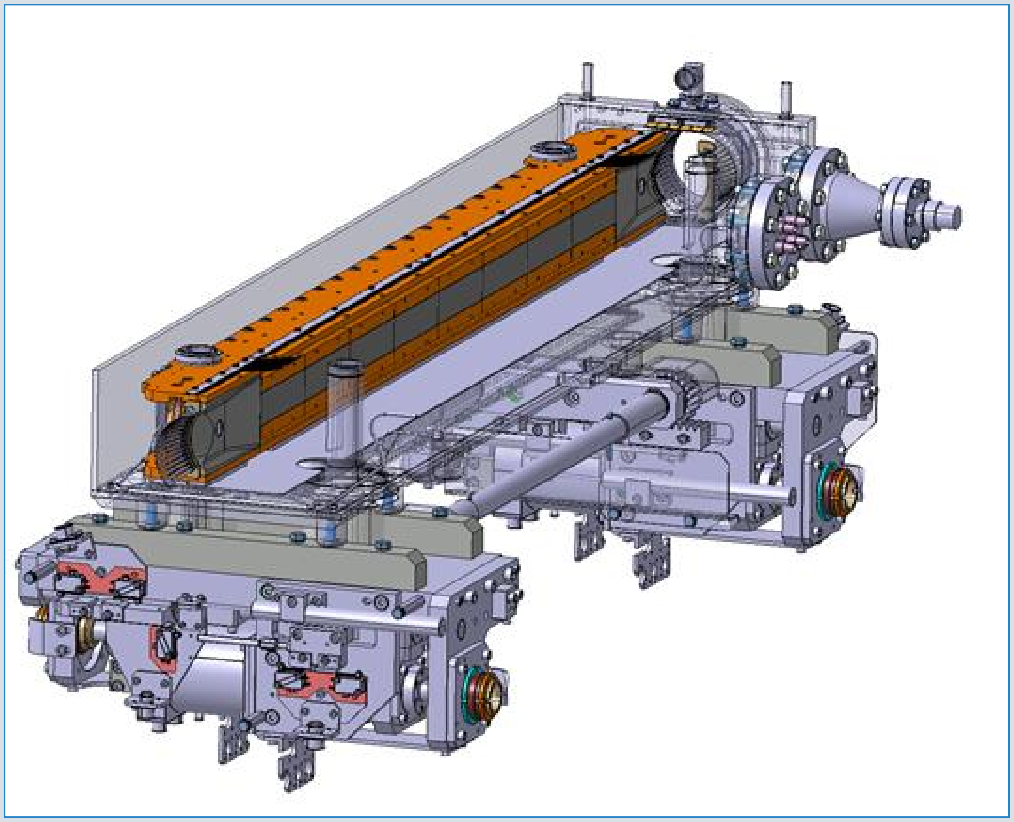


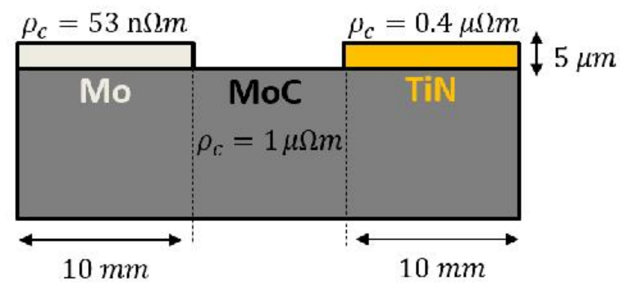
Need x2 margin at least
from the operational experience:

- Linear coupling
- Magnet imperfections
- Feedback noise
- Optics errors
- Uncertainty of beam distribution

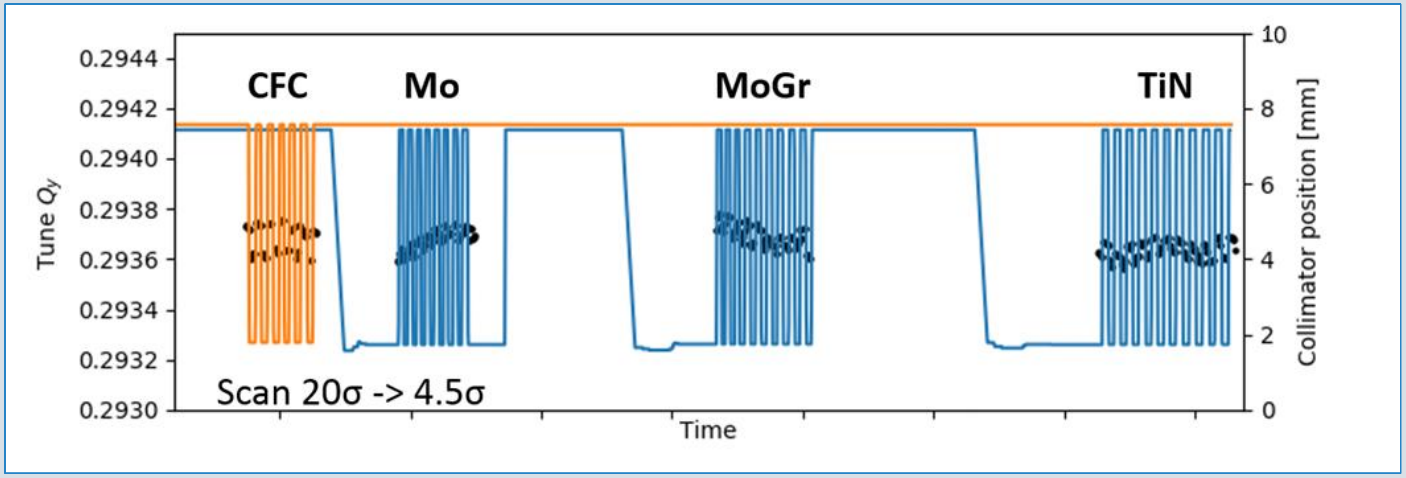
X. Buffat *et al.,* Hi-Lumi'17, Madrid, Spain, 2017
L. Carver *et al.*, *PRAB* **21**, 044401, 2018
E. H. Maclean *et al.,* LMC meeting, CERN, Apr. 2018

TCSPM prototype collimator



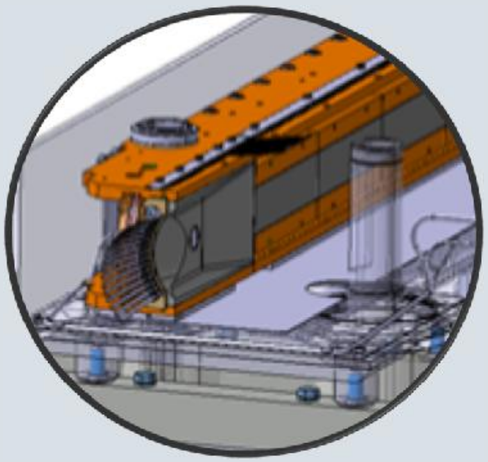


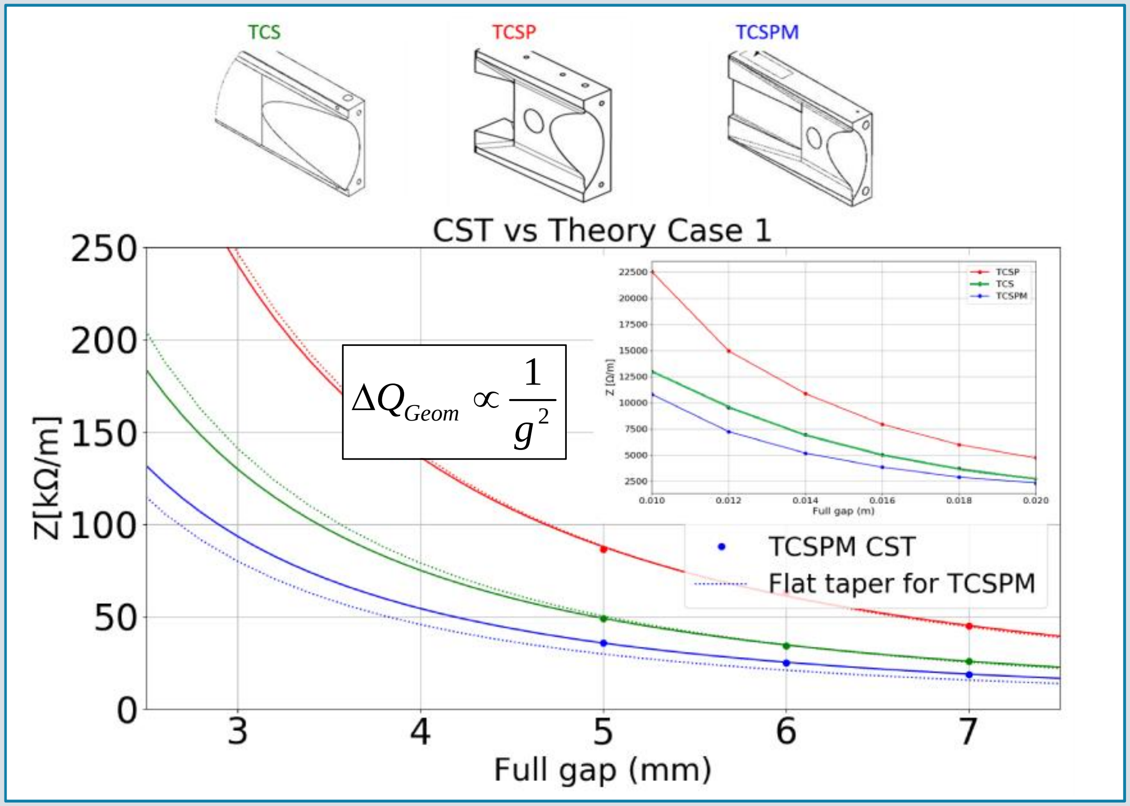
Fast cycling the collimator opening to determine its tune shift



Int	Q'	t_b	Lower gap	Higher gap	Cycle time	Data points	Acq length
1.2 $\times10^{11}$ p	7	1.1 ns	3.5 – 6 σ	20 σ	1 sec	~100 / gap	1000 turns
1.9 $\times10^{11}$ p	7	1.1 ns	5 – 6 σ	14 σ	1 sec	~100 / gap	1000 turns

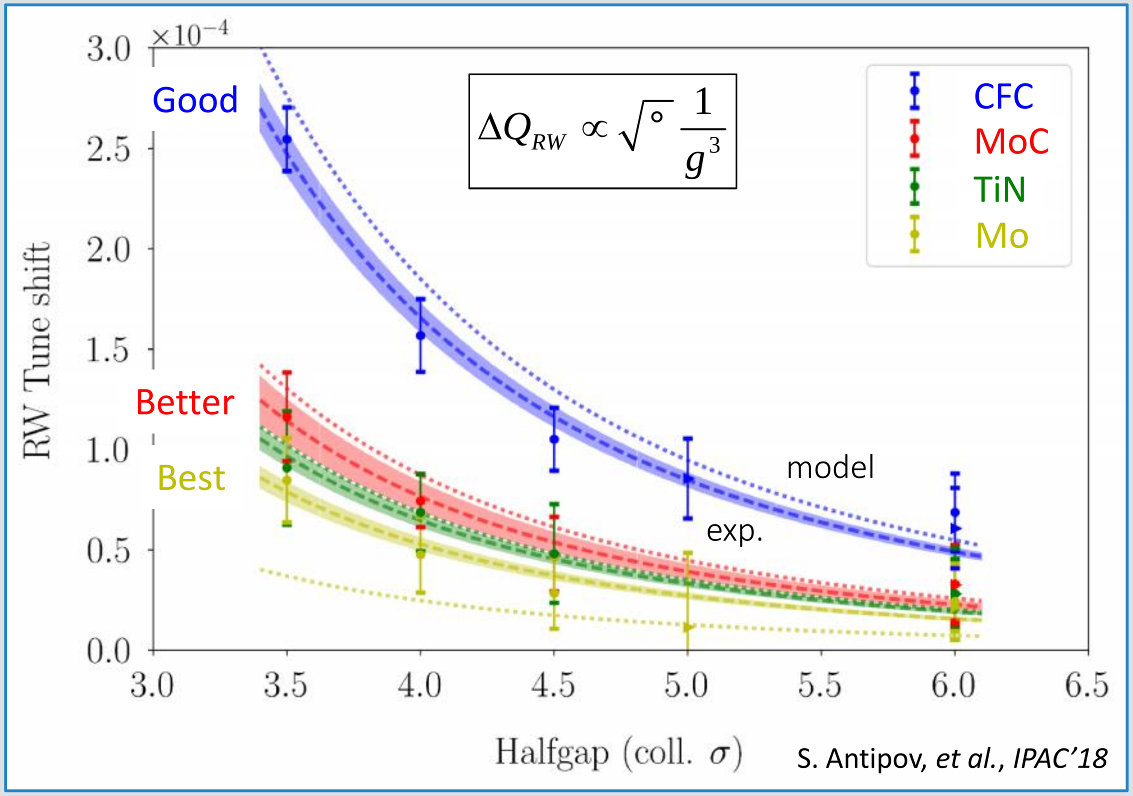
Can use flat taper approximation for transitions





E. Carideo, M.Sc. Thesis, Universita del Sannio, Benevento, Italy (2019)

The largest reduction of the resistive wall tune shift measured for Mo coating

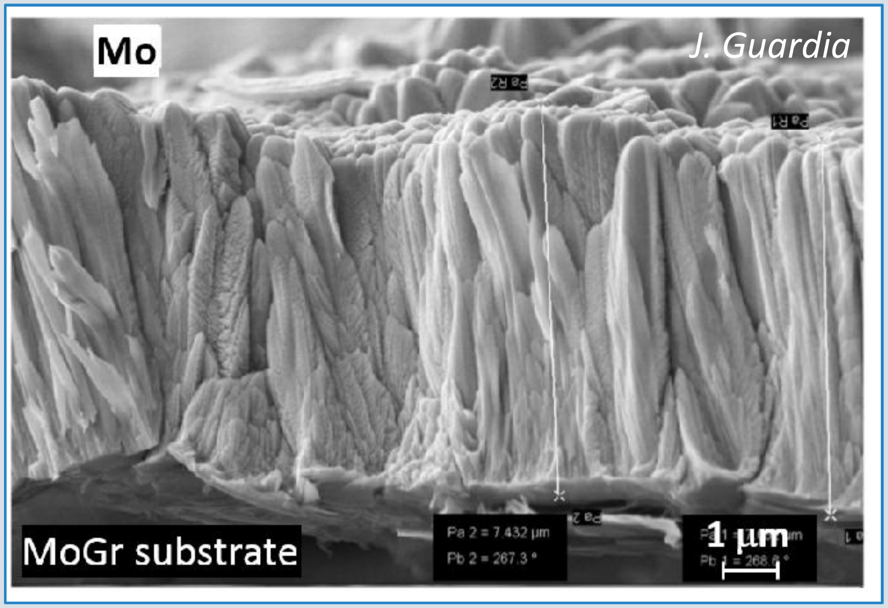


Measured vs expected resistivities (nΩ-m)

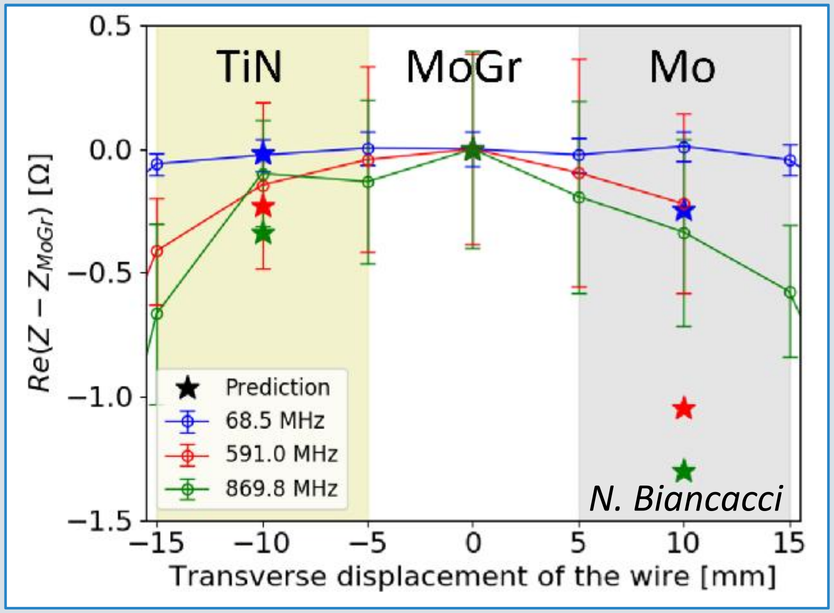
Material	Model	Beam
CFC	5000	4030 ± 370
MoGr	1000	770 ± 70
TiN	400	350 ± 40
Mo	52	250 ± 40

Lower Mo conductivity due to microstructure of the coating

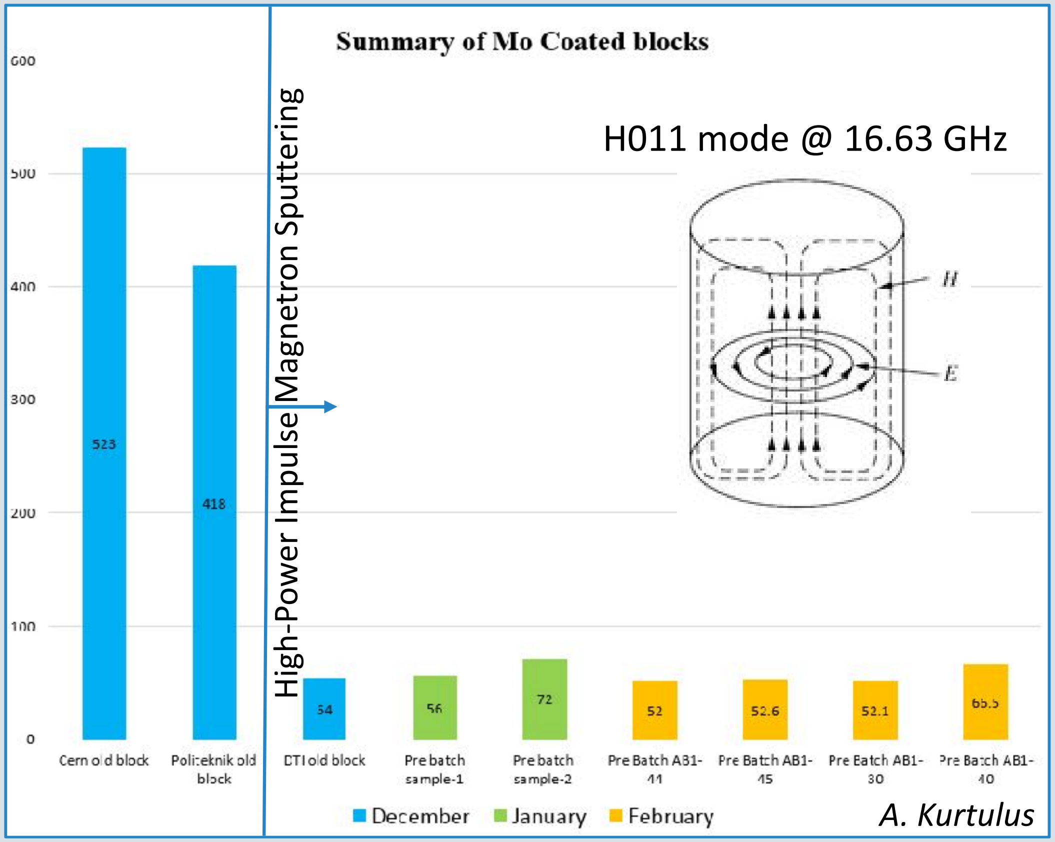
Confirmed by SEM imaging



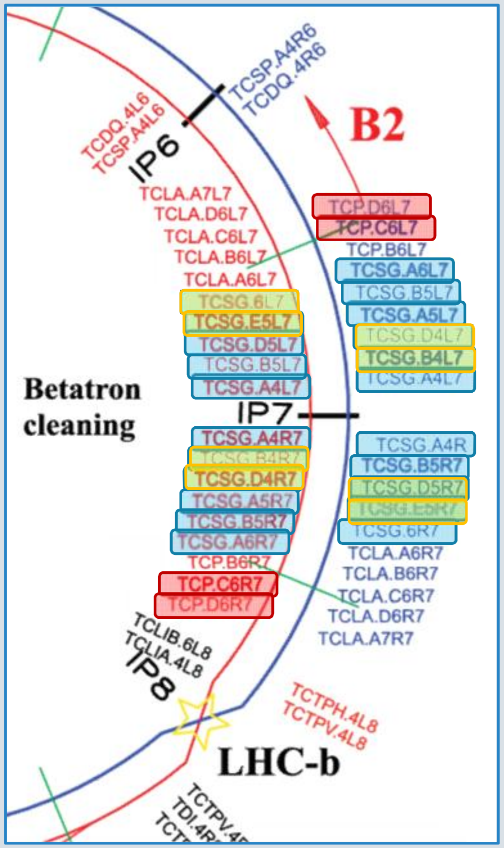
and RF measurements

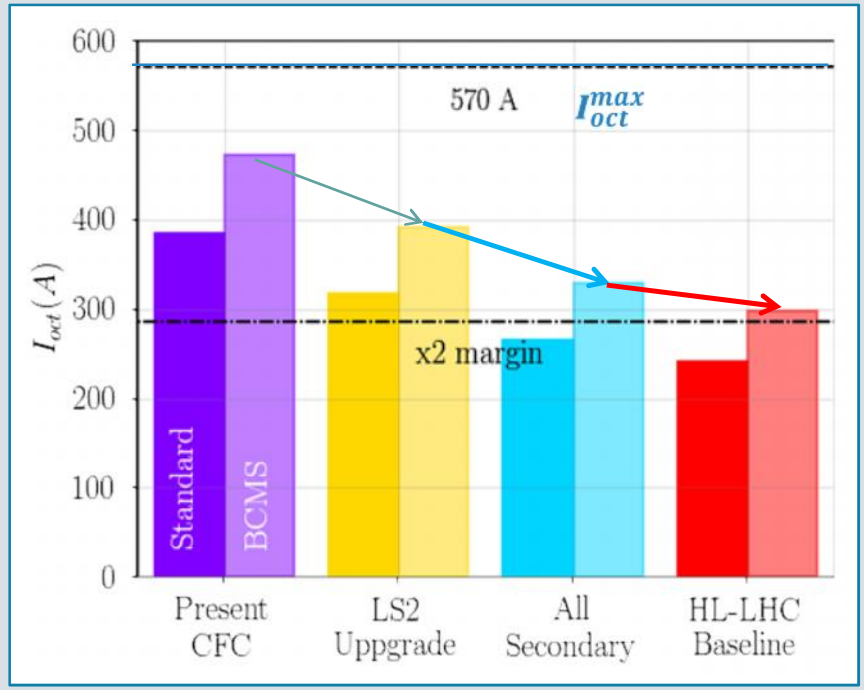


Change of coating procedure dramatically improved conductivity of the coating



Staged upgrade



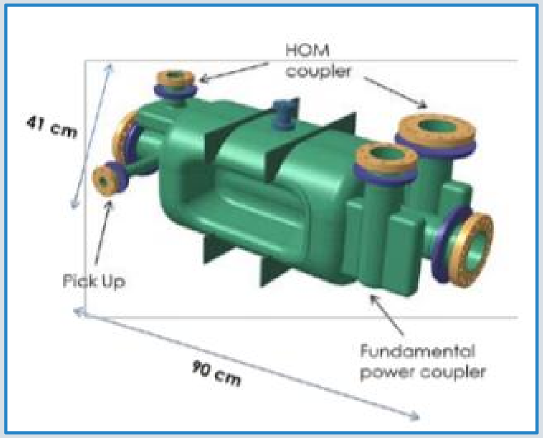


- Focus on the most critical, Horizontal plane
- Less exposed to regular collimation losses

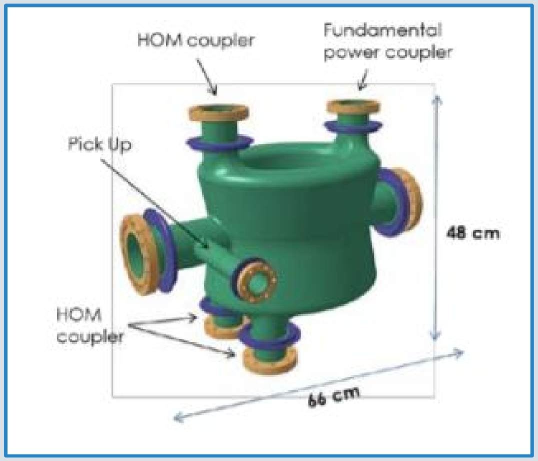
Beam stability: Crab Cavities

Crab cavities boost integrated luminosity by 10%

DQW-TYPE CAVITY



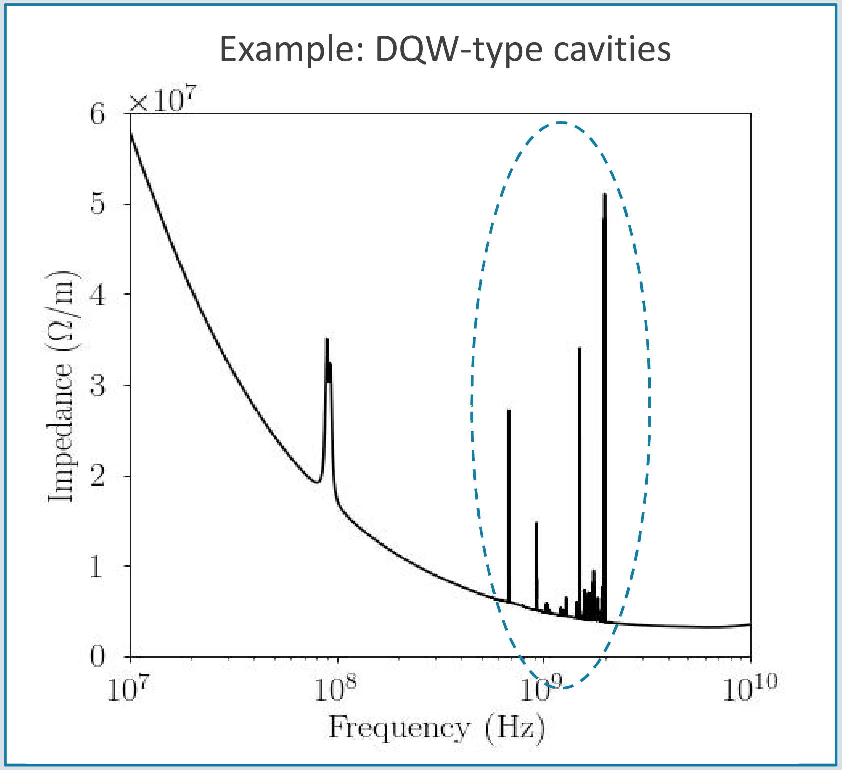
RFD-TYPE CAVITY



- Reduce effective event pile-up density by around 20%
- Extend the luminosity levelling at up to 7.5×10^{34} $cm^{-2}s^{-1}$

R. Tómas *et al.*, CERN Report No. CERN-ACC-2017-0088, 2017

Crab HOMs dominate transverse dynamics at the frequencies around 1 GHz

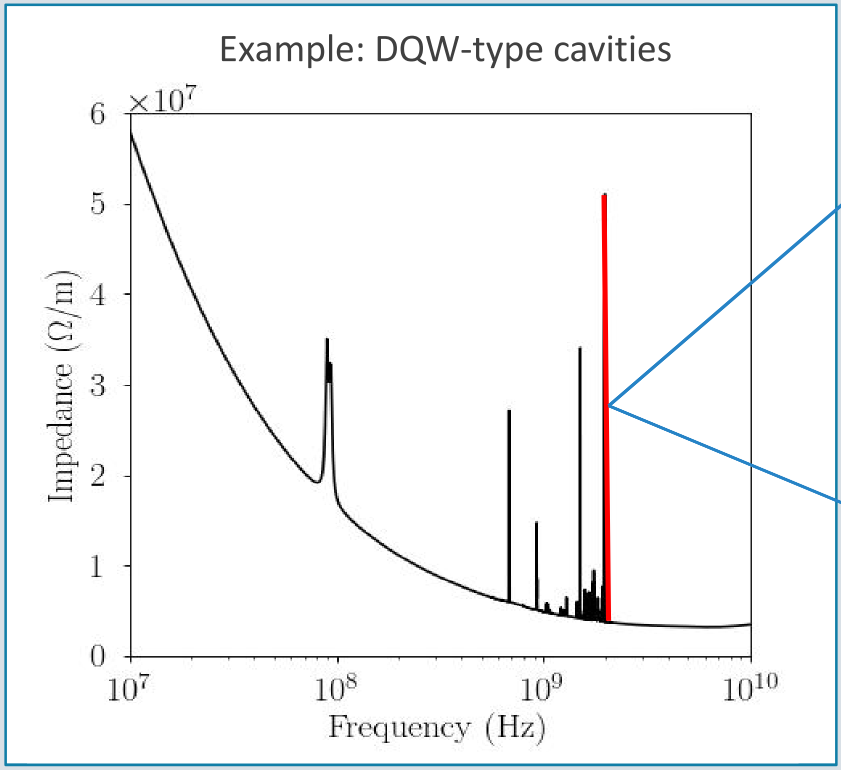


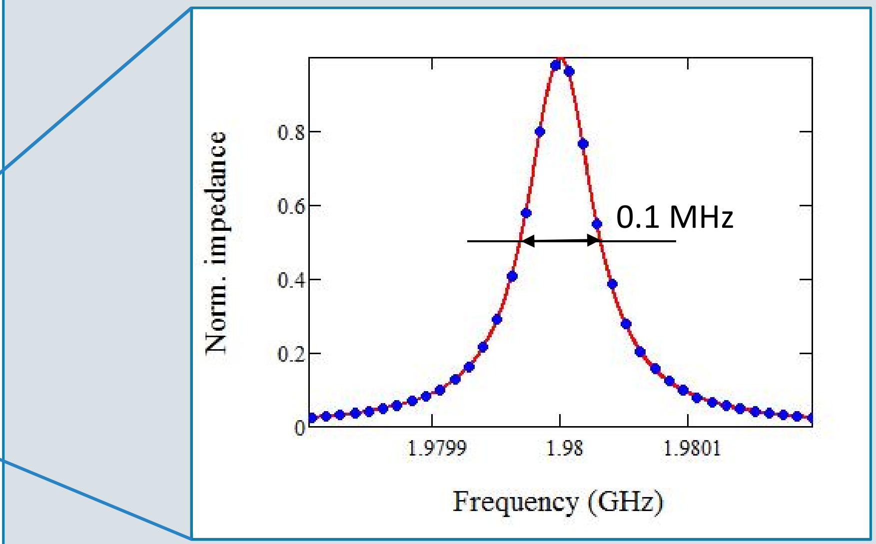
To ensure beam stability
HOMs should be kept under control

E. Metral, *et al.*, Beam intensity limitations,
4th Joint HiLumi LHC-LARP Annual Meeting, KEK, 2014

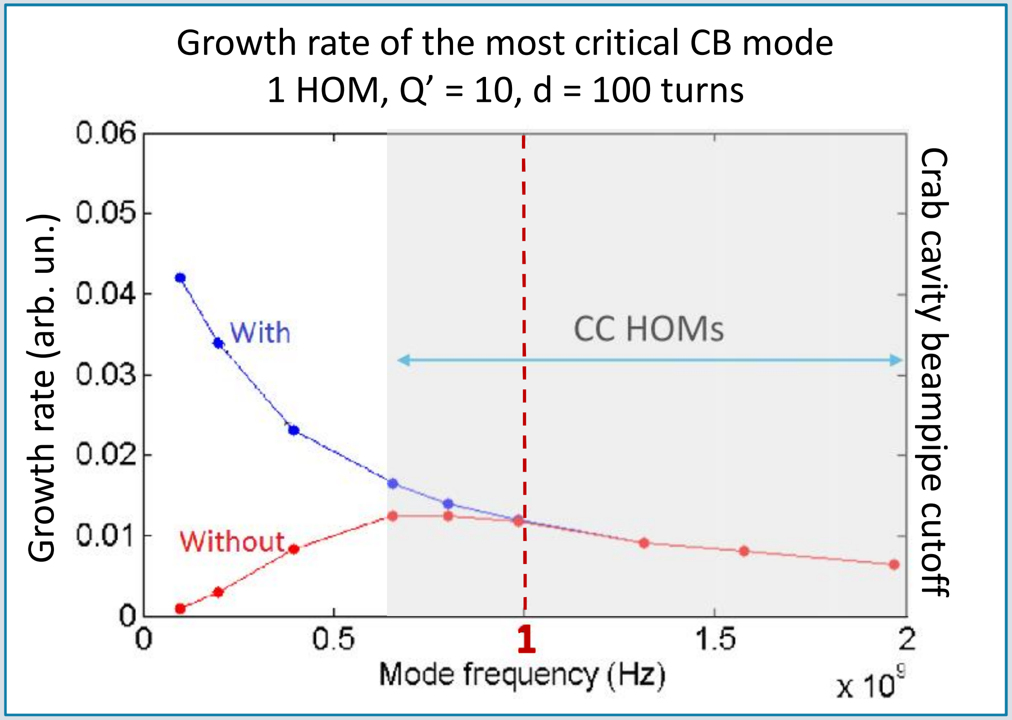
N. Biancacci, *et al.*, HL-LHC impedance and stability studies,
HiLumi Workshop, FNAL, 2015

The HOMs can excite collective instabilities in the beam

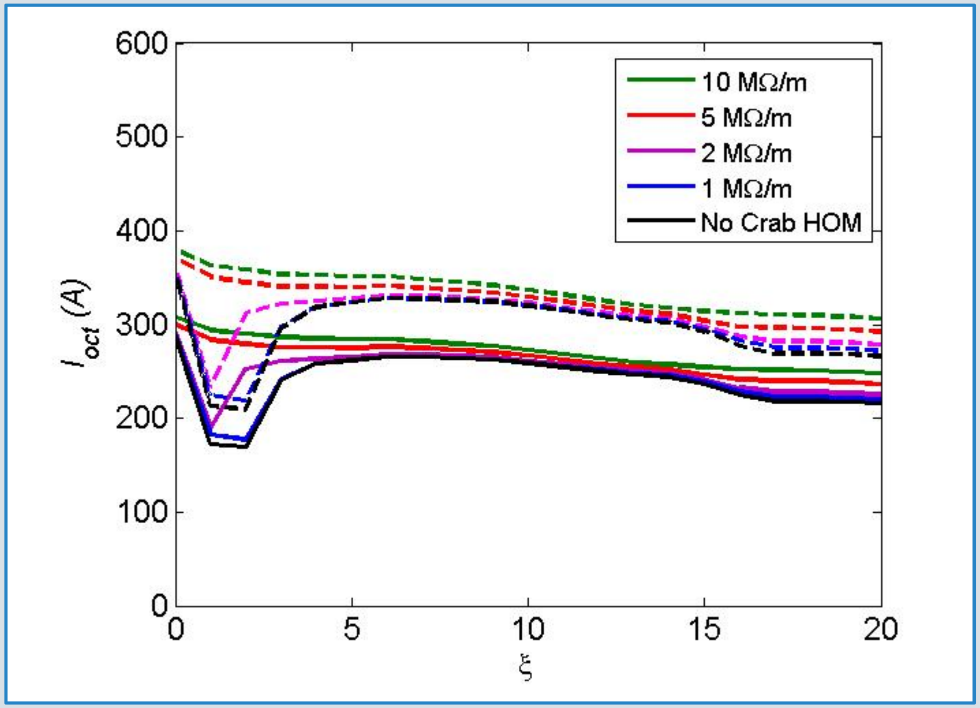




Transverse feedback is inefficient above 1 GHz



Need shunt impedance lower 1 MΩ/m



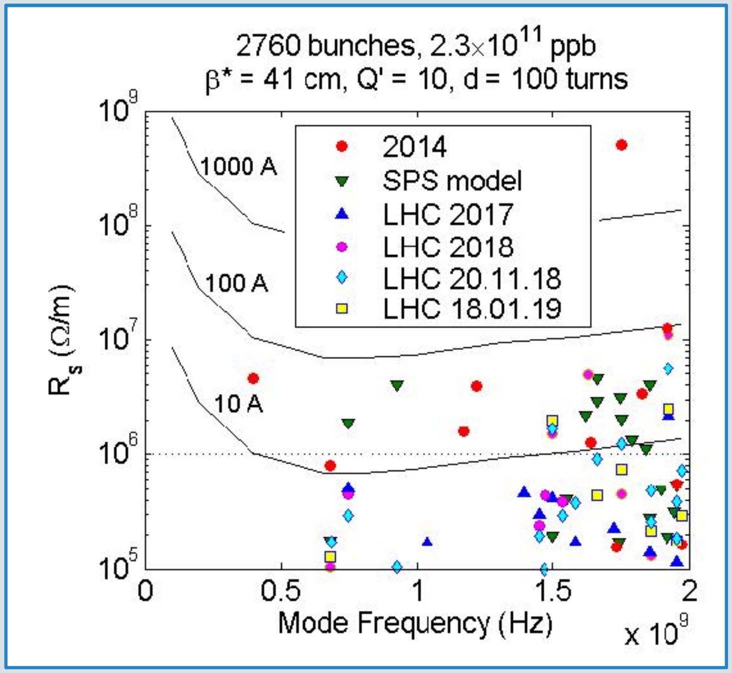
BCMS Beam ε = 1.7 μm

Standard Beam ε = 2.1 μm

S. Antipov *et al.*, *Phys. Rev. Accel. Beams* vol. 22, 054401, 2019

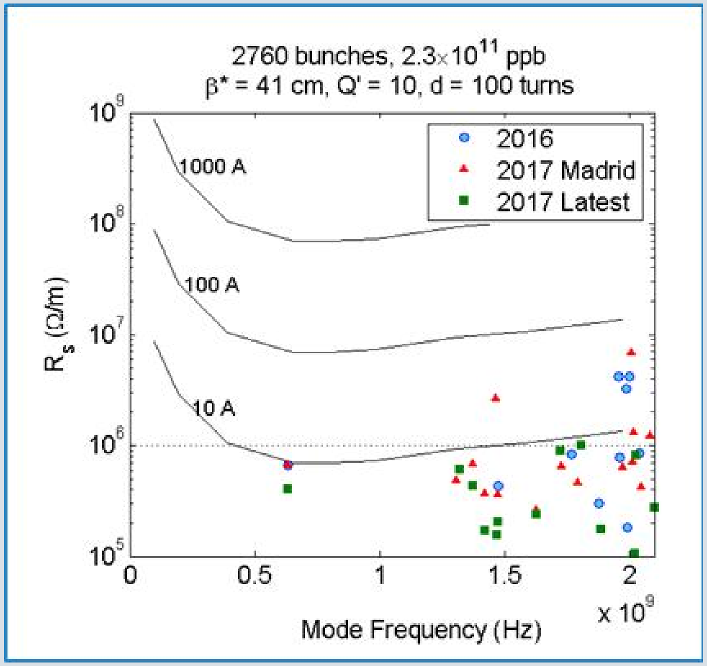
Cavity designs adjusted to lower HOM impact

DQW DESIGN



S. Antipov *et al.*, CERN, Jan 2019

RFD DESIGN

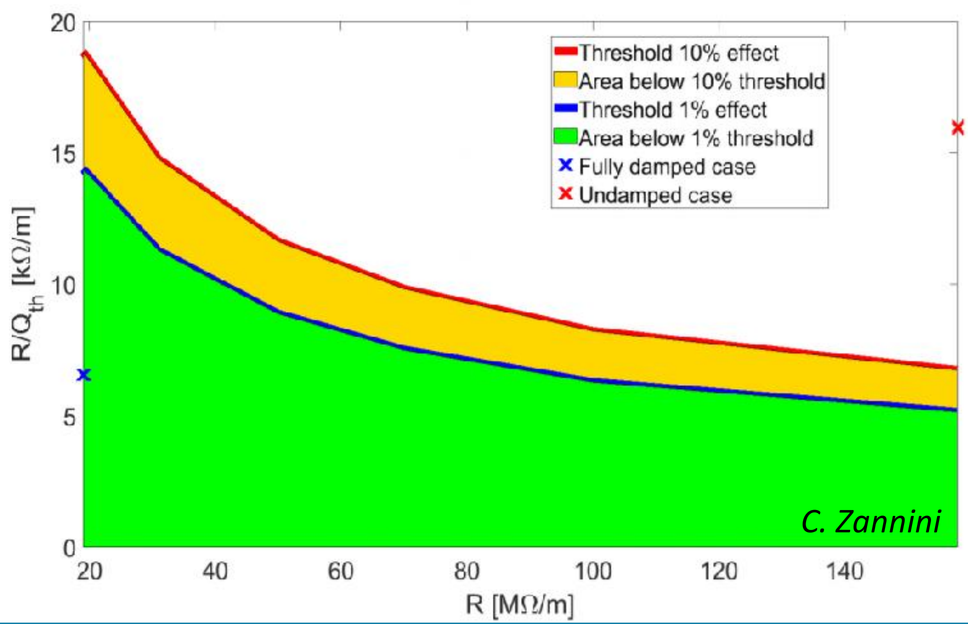


S. Antipov *et al.*, CERN, Dec 2017

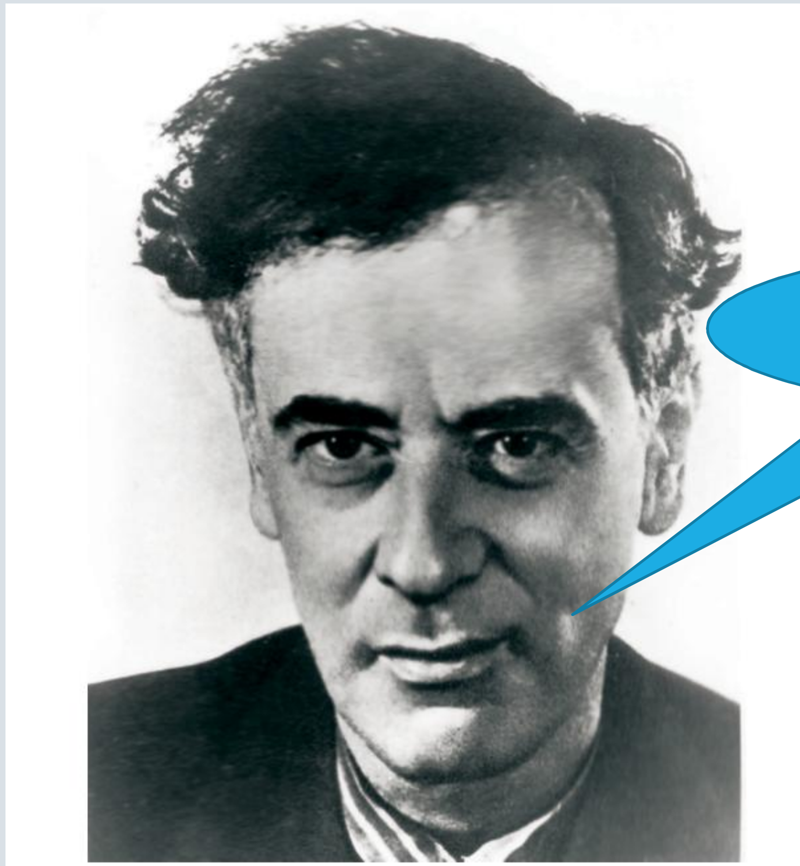
Similar effect identified in other machines

Recent example – 939 MHz HOM in SPS (C. Zannini)

939.45 MHz HOM in SPS has to be damped



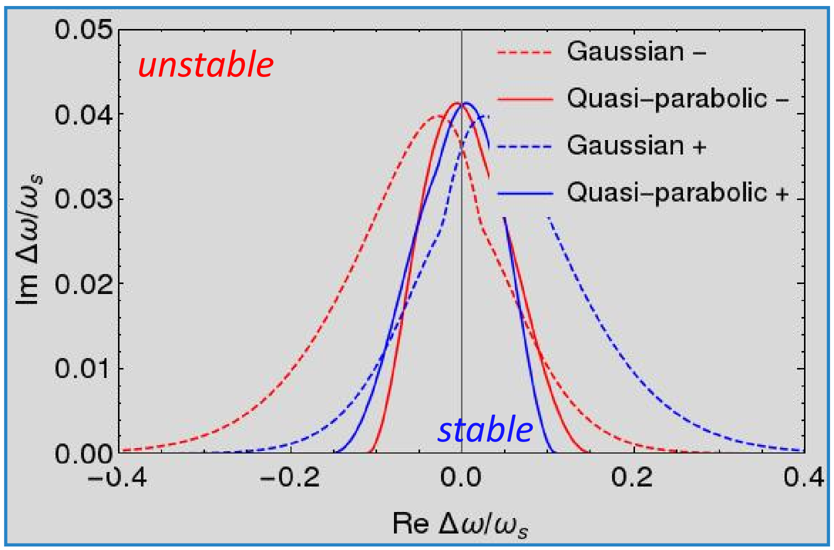
Measuring Landau damping



How well do we know Landau Damping?

Stability Diagram approximations:

Stability diagrams from Landau Octupoles in LHC



Top energy, nominal tunes and chromaticities

unperturbed with LD

$$\Delta\mu_{coh} / D(\Omega) = 1$$

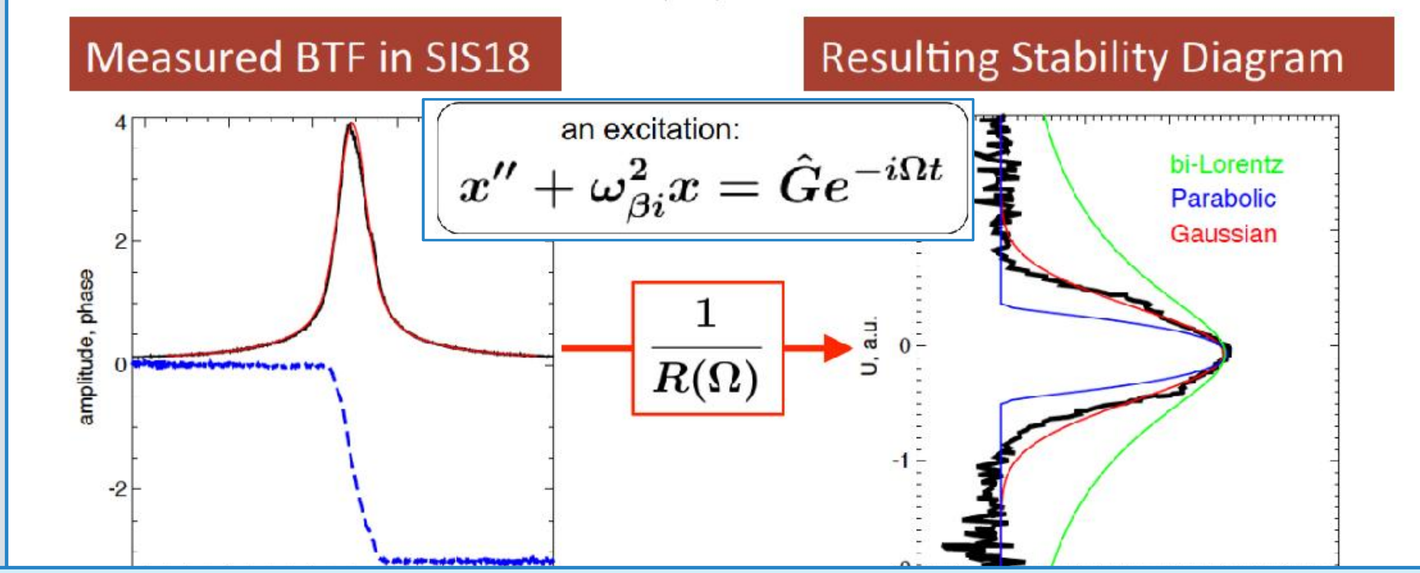
$$D(\Omega) = -\left(\int \frac{J \partial F / \partial J}{\Omega - \text{¢}\mu(J) + io} d\Gamma \right)^{-1}$$

The source – frequency spread

D. Möhl, H. Schönauer, Proc. IX Int. Conf. High Energy Acc., 1974
A. Chao, Phys. Coll. Beam Instab. in High Energy Acc., 1993

Can measure stability diagram by BTF

$$\Delta Q_{\mathrm{coh}} R(\Omega) = 1$$



In LHC, BTF measurements turn out to be rather challenging (T. Pieloni, LSWG Meeting, CERN 12.04.18)

- Beam losses during excitation
- Difficult to reconstruct Stability Diagram in the presence of impedance response

Can we make a more direct measurement?

Measurement of Landau Damping with antidamper

Beam as the driver of excitation

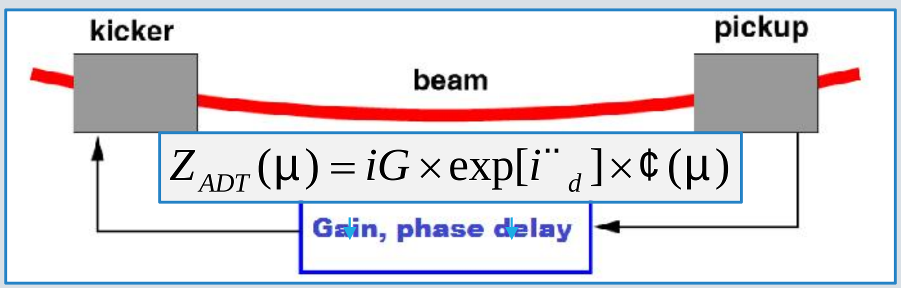
an excitation:

$$x'' + \omega_{\beta i}^2 x = \hat{G}e^{-i\Omega t}$$

x

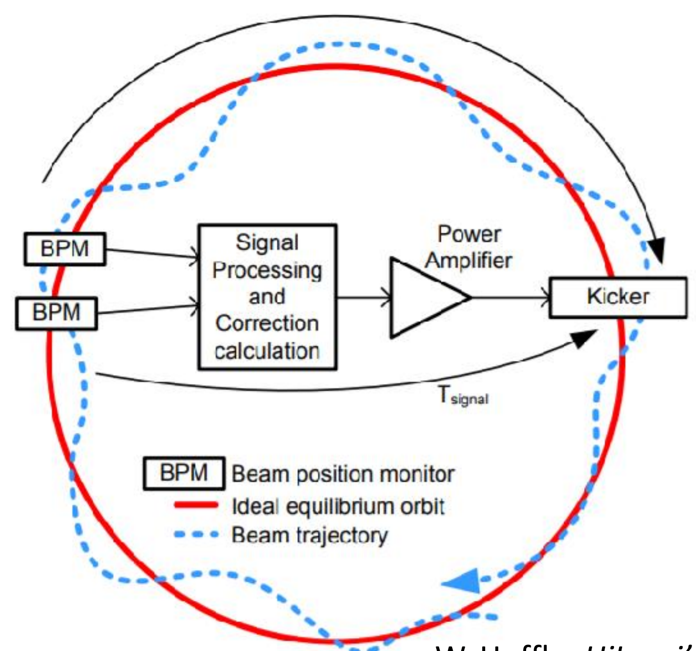
Feedback

Feedback acts as an effective impedance



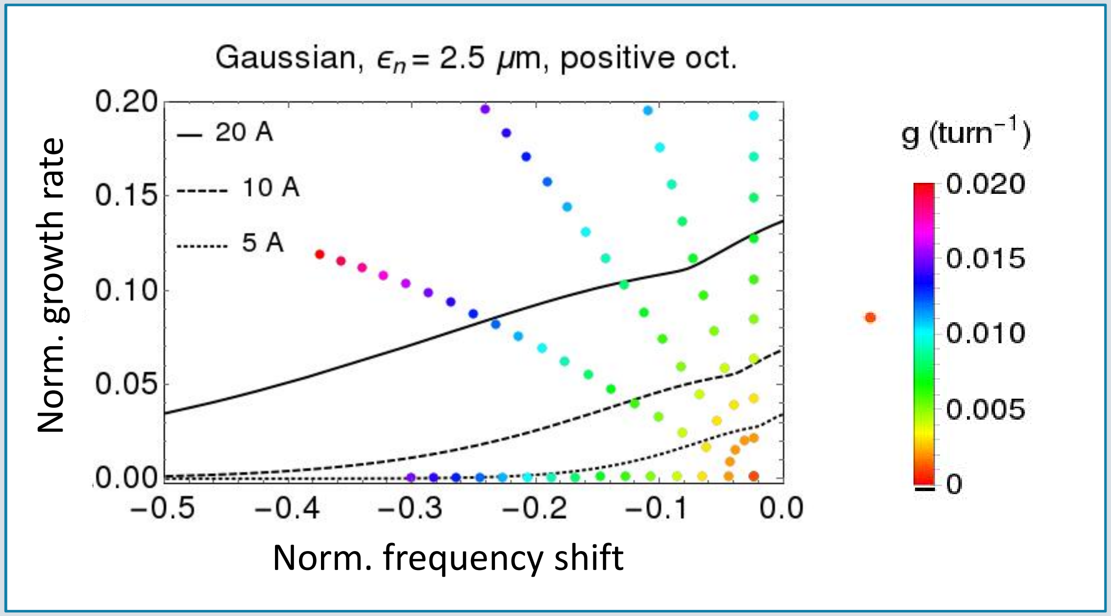
[A. Burov, *PRST AB* **17**, (2014)]
[E. Stern *et al.*, *Proc. IPAC'18*, Vancouver, May 2018]

LHC feedback system uses two pickups per plane



W. Hoffle, *HiLumi'15*

Adjusting gain and phase one can explore the full complex plane

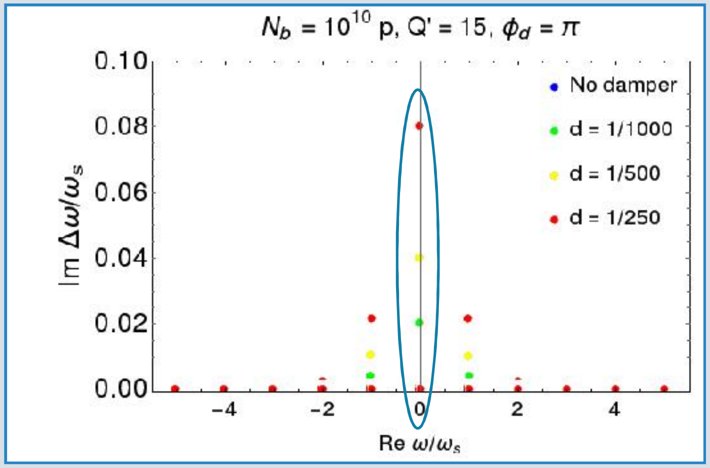


S. Antipov *et al.*, ABP-HSC Meeting, CERN, 19.03.18

Precise set-up needed to compare with theoretical predictions

Make sure the same mode the most unstable one in all regimes

- At non-zero chromaticity many modes are exited
- At LHC injection energy dipolar, 0 mode (normally) dominates



Control coupling, chromaticity, lattice nonlinearities

- Work at or close to nominal settings

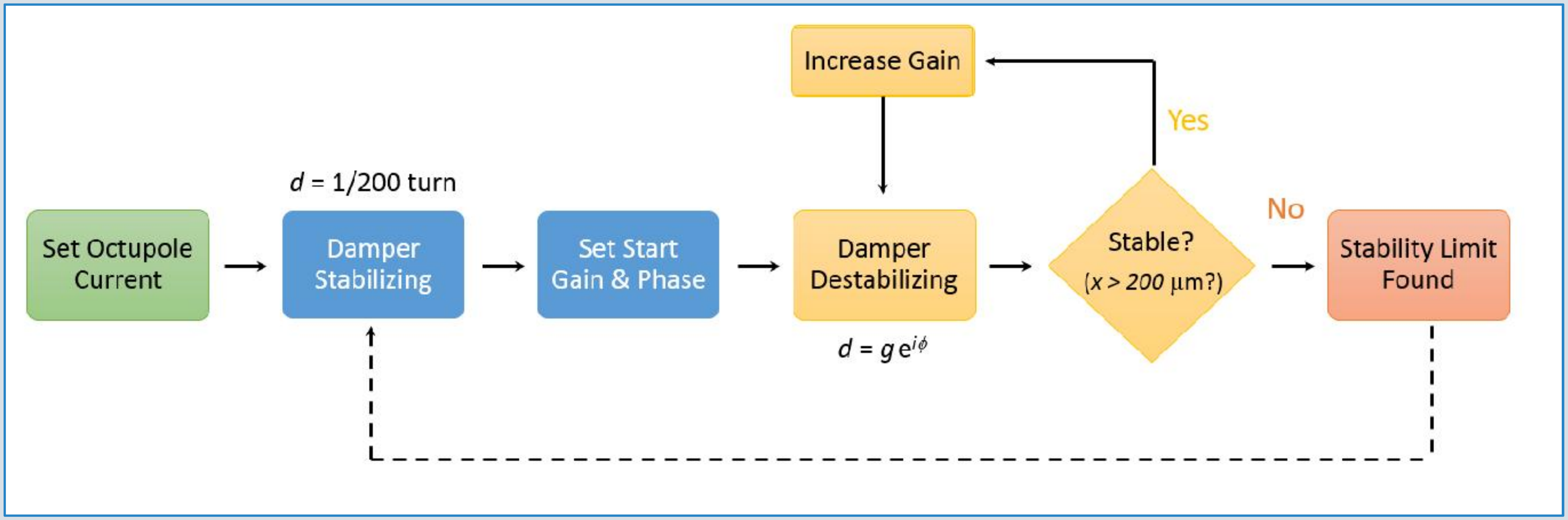
Minimize mode shift from impedance

- Top energy and (or)
- Low intensity probe beam

Minimize effect of space charge

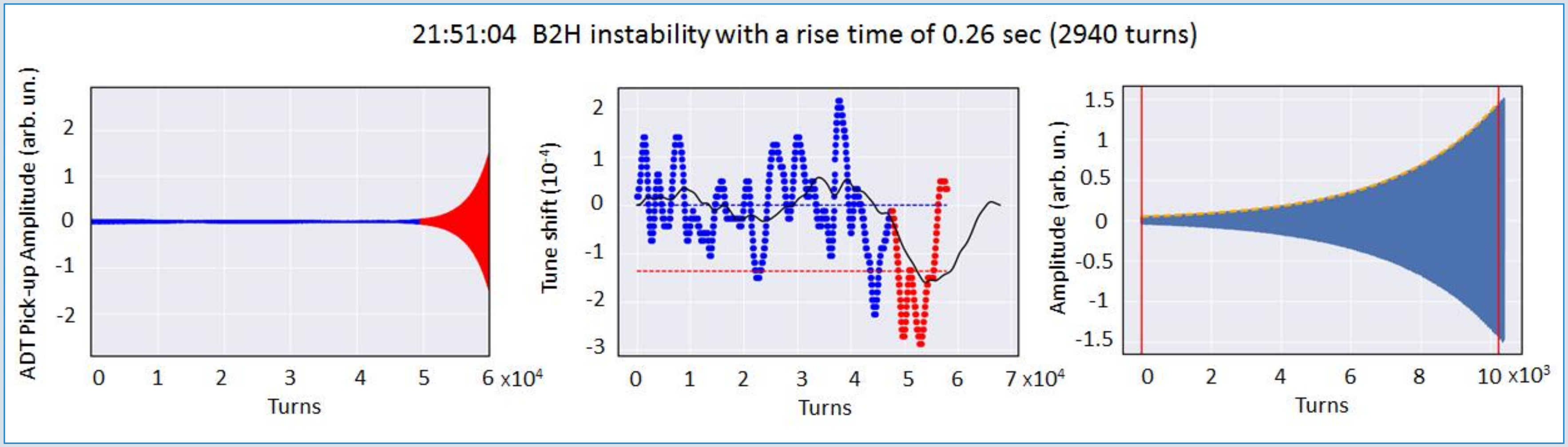
- Top energy and (or)
- Low intensity probe beam $\Delta Q_{SC} \sim 10^{-4} \sim 0.1 Q_s$

Procedure to measure stability diagrams

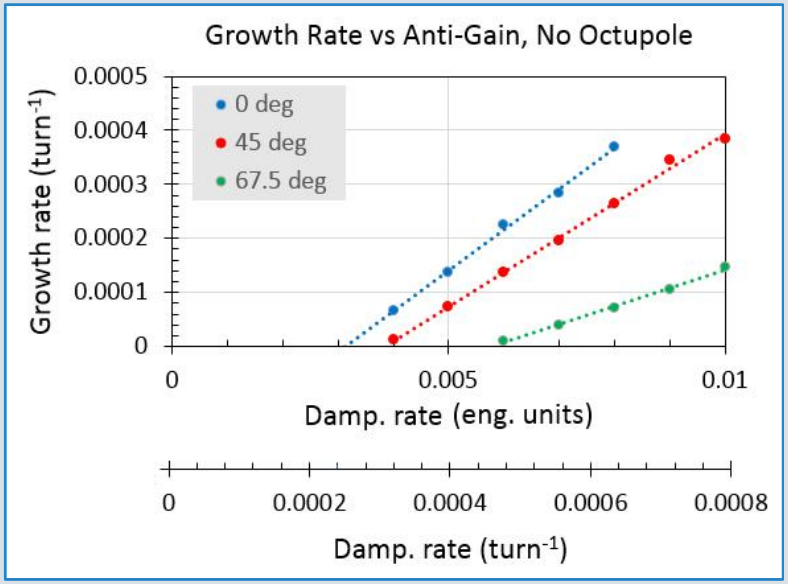


- Less than 5 min per data point
- Little to none emittance blow-up

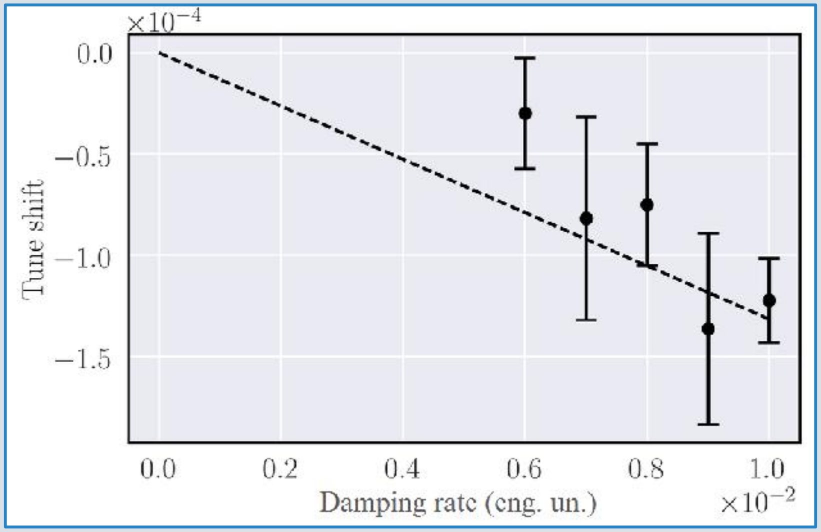
Obtaining rise time and tune shift



Transverse feedback fully qualified to act as a controlled source of impedance



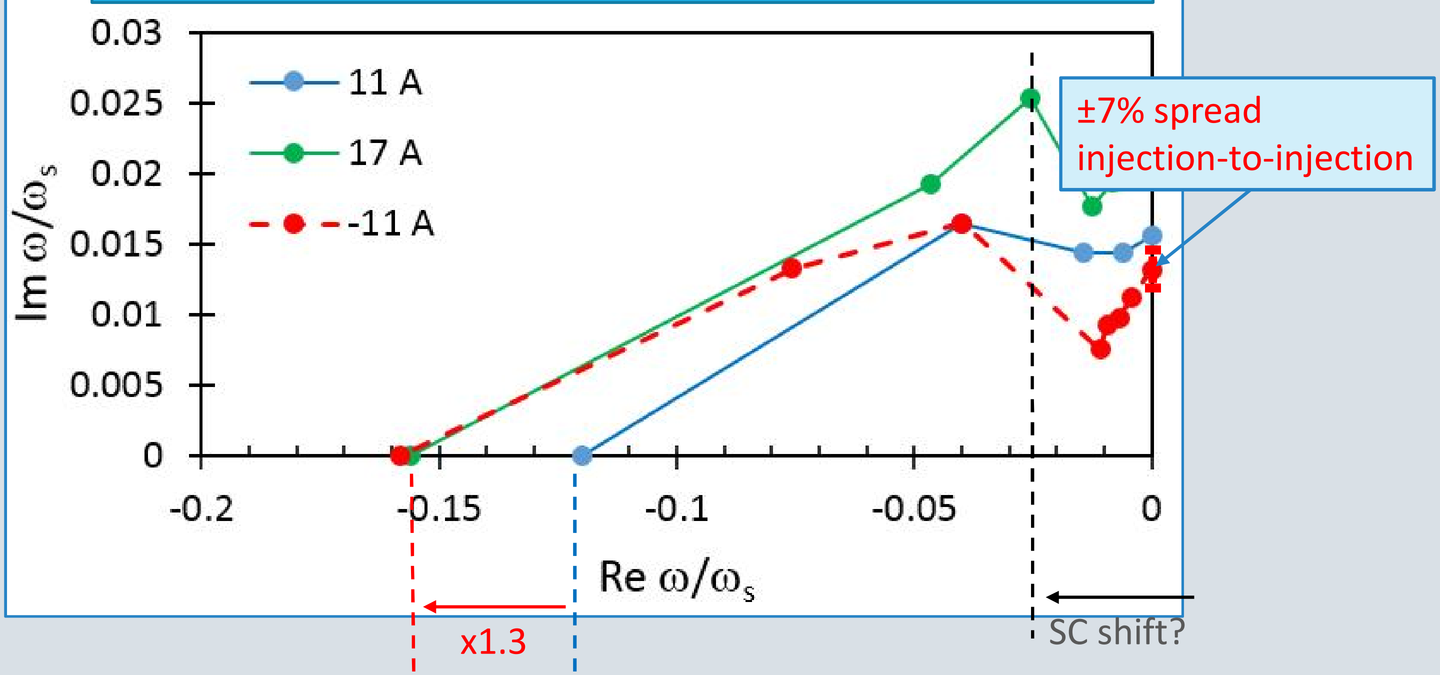
Tune shift agrees with growth rate within 30% for a 45 deg damper phase



Can measure Landau damping from nonlinearities at injection

Can measure stability diagrams

Technique can be applied to measure damping at 7 TeV flat-top after the end of the Long Shutdown in 2021



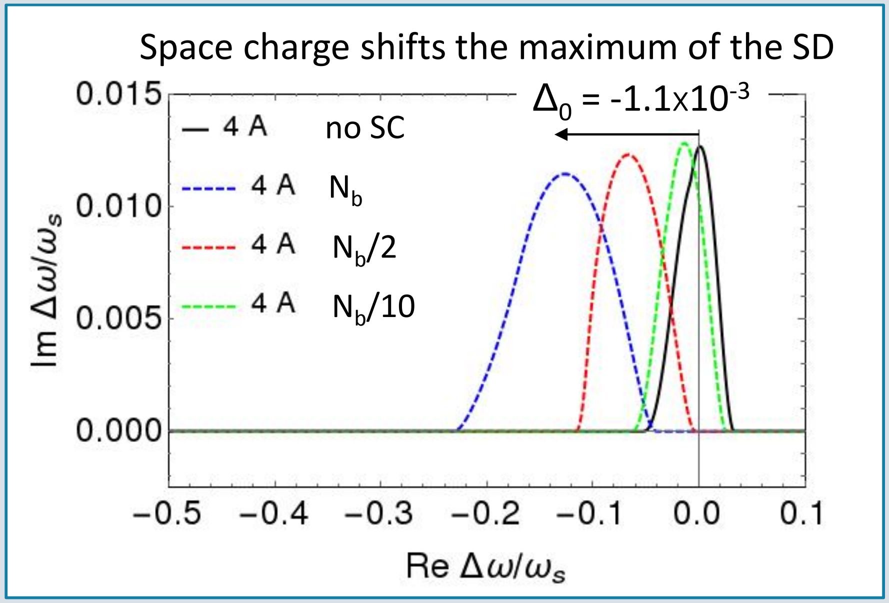
$\Delta Q_{sc} \sim 10^{-4} \sim 0.02\omega_s$

Accounting for space charge

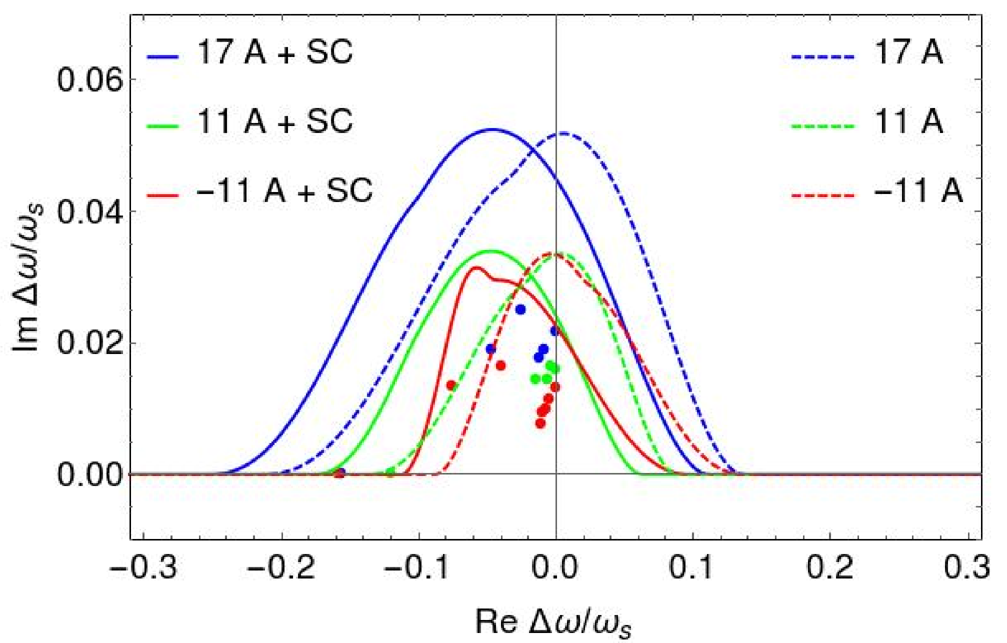
Simplified model:
- Métral, Ruggiero, CERN-AB-2004-025-ABP, 2004
- Coasting beam
- Quasi-parabolic transverse distribution
- Linear space charge

Extended to bunched beams
- Bill Ng, *Proc. HB'08*, Nashville, TN, 2008

Interplay of octupole detuning and nonlinear space charge may be important
- Observed in tracking simulations
- V. Kornilov *et al.*, *PRST-AB* **11**, 014201 (2008)



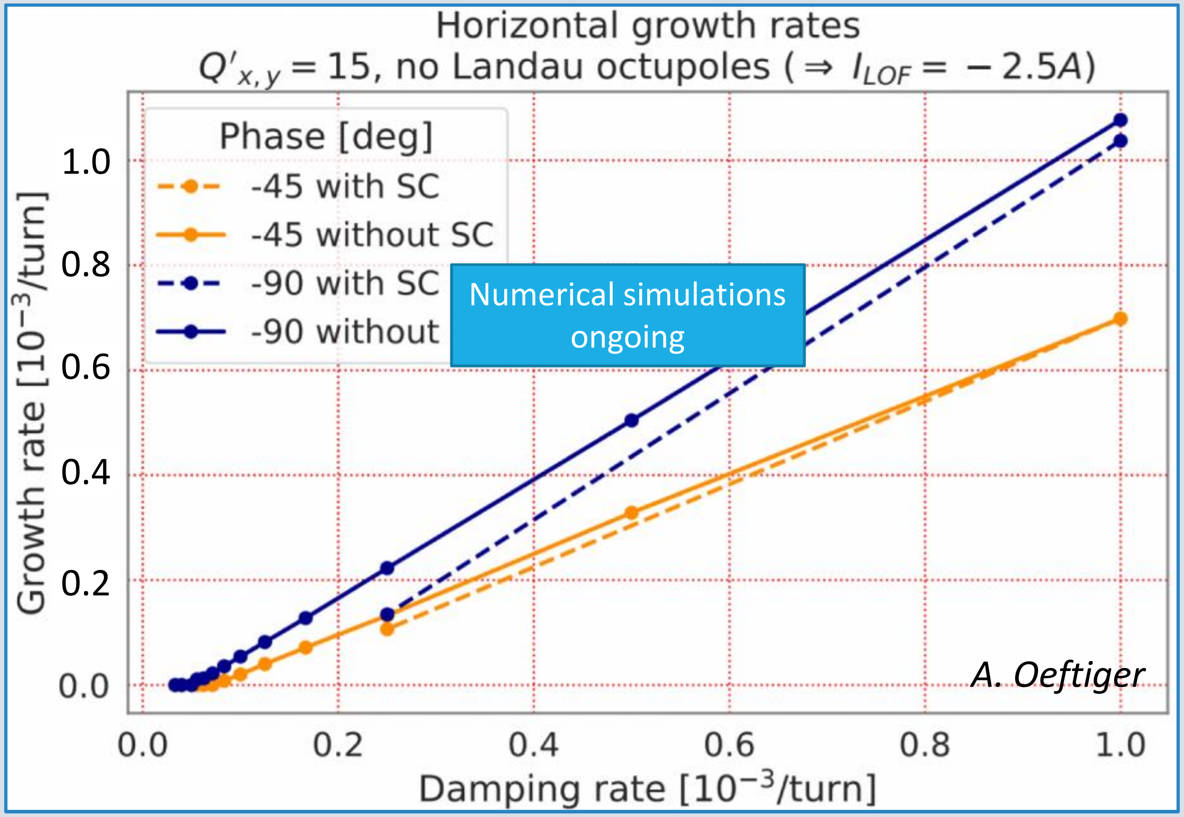
Results are in qualitative agreement with expectations



Things to account for:

- Nonlinearities?
  - Feed-down from decapole corr
  - Hysteresis inoctupole corr
  - A few Amps (E. McLean *et al.*)
- Transverse distribution?
  - Affects the width of SD

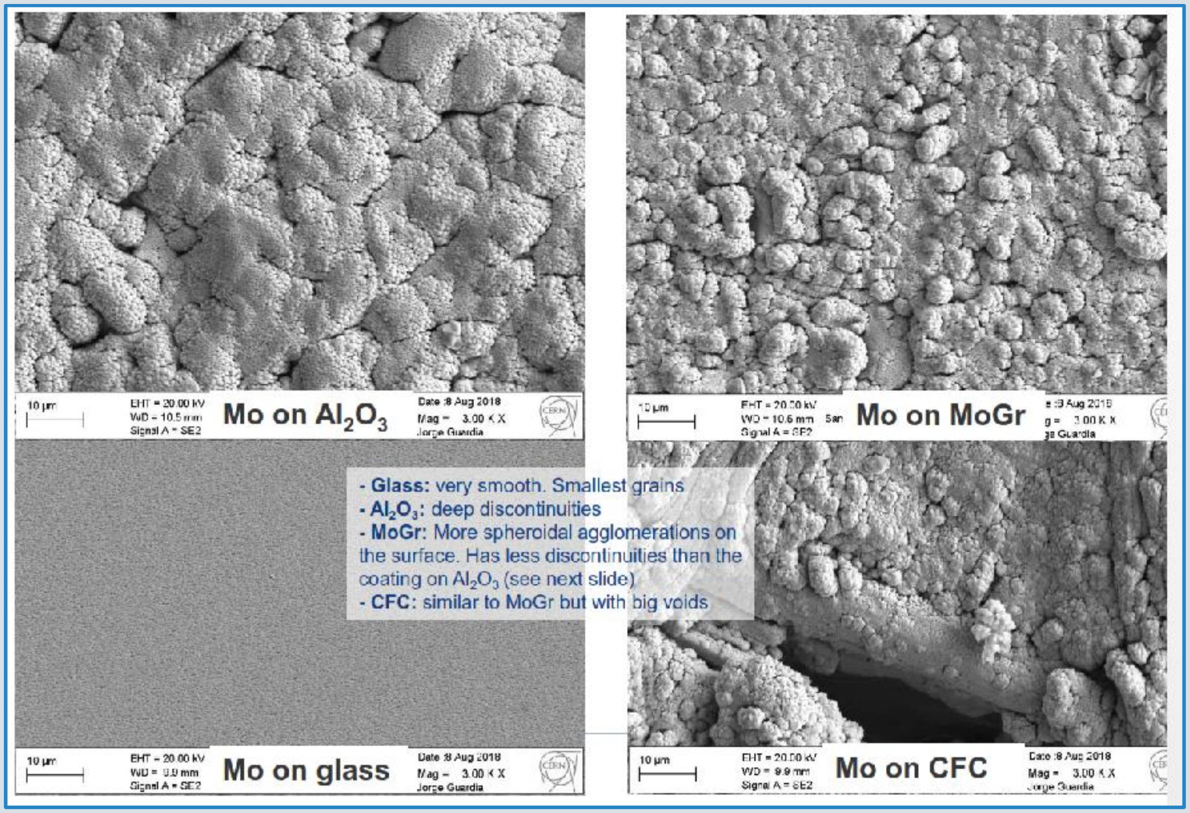
Space charge adds Landau damping affecting the calibration



Thank you for your attention

QUESTIONS?

Mo coating on different substrates



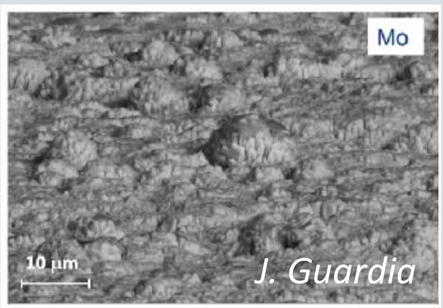
J. Guardia, Impedance Meeting, CERN, 08/24/18

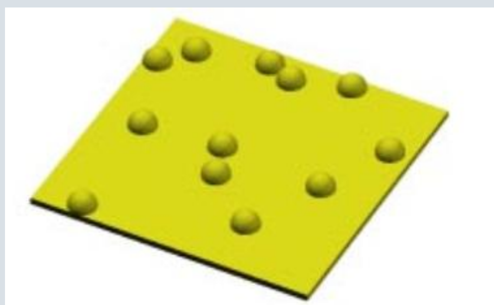
Roughness: Macroscopic details
Stupakov model

MODELLING ROUGHNESS AS A COLLECTION OF RANDOMLY DISTRIBUTED BUMPS

ADDITIONAL IMAGINARY IMPEDANCE SCALES AS $1/\mathrm{GAP}^3$

K. Bane and G. Stupakov, SLAC-PUB-8023, 1993





Chao (2.129), 1 bump: $$Z_1^{\perp}(\mu) = -iZ_0 \frac{r^2}{\circledR\, b^3}$$

Stupakov, per unit length: $$\frac{Z_0^{\parallel}(\mu)}{L} = -i\sim \frac{Z_0 \mu r}{2\circledR\, cb}$$

$$Z_1^{\perp}(\mu) = -i\sim L Z_0 \frac{r}{2\circledR\, b^3}$$

Size, < 10 µm

As resistive wall

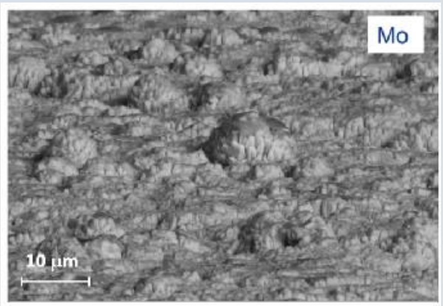
Packing factor, assume 1

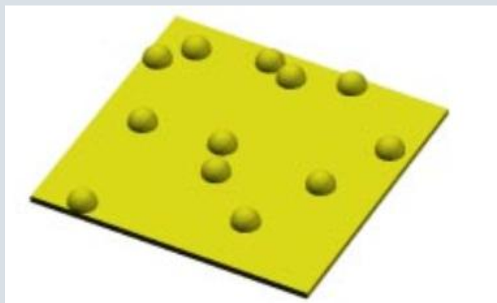
Stupakov model of roughness

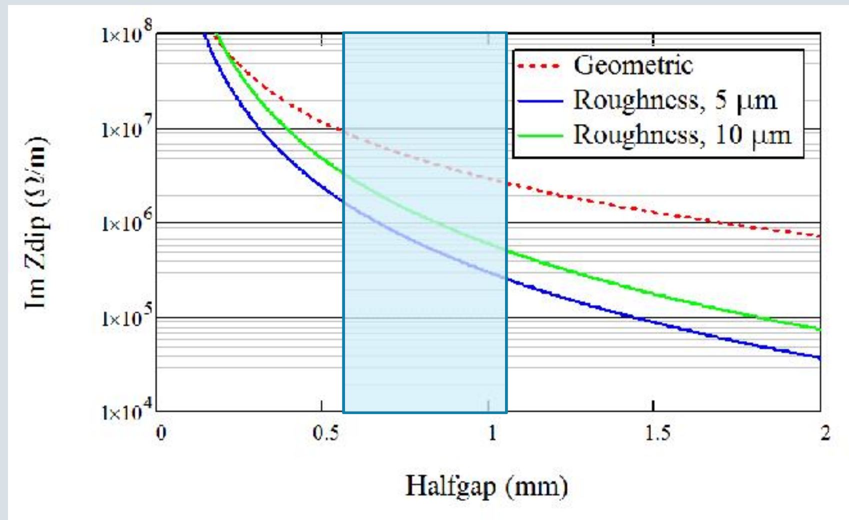
MODELLING ROUGHNESS AS A COLLECTION OF RANDOMLY DISTRIBUTED BUMPS

EXTRA TUNE SHIFT DUE TO ROUGHNESS IS TOO SMALL TO EXPLAIN THE EXPERIMENTAL FINDINGS

K. Bane and G. Stupakov, SLAC-PUB-8023, 1993

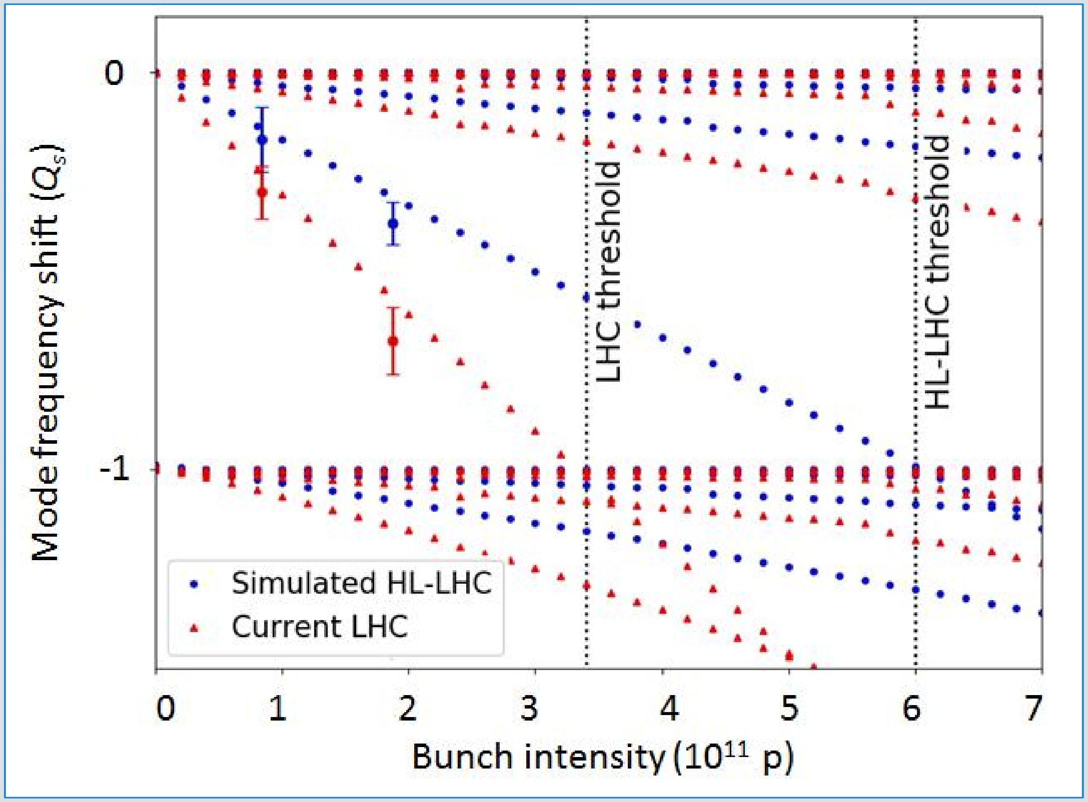




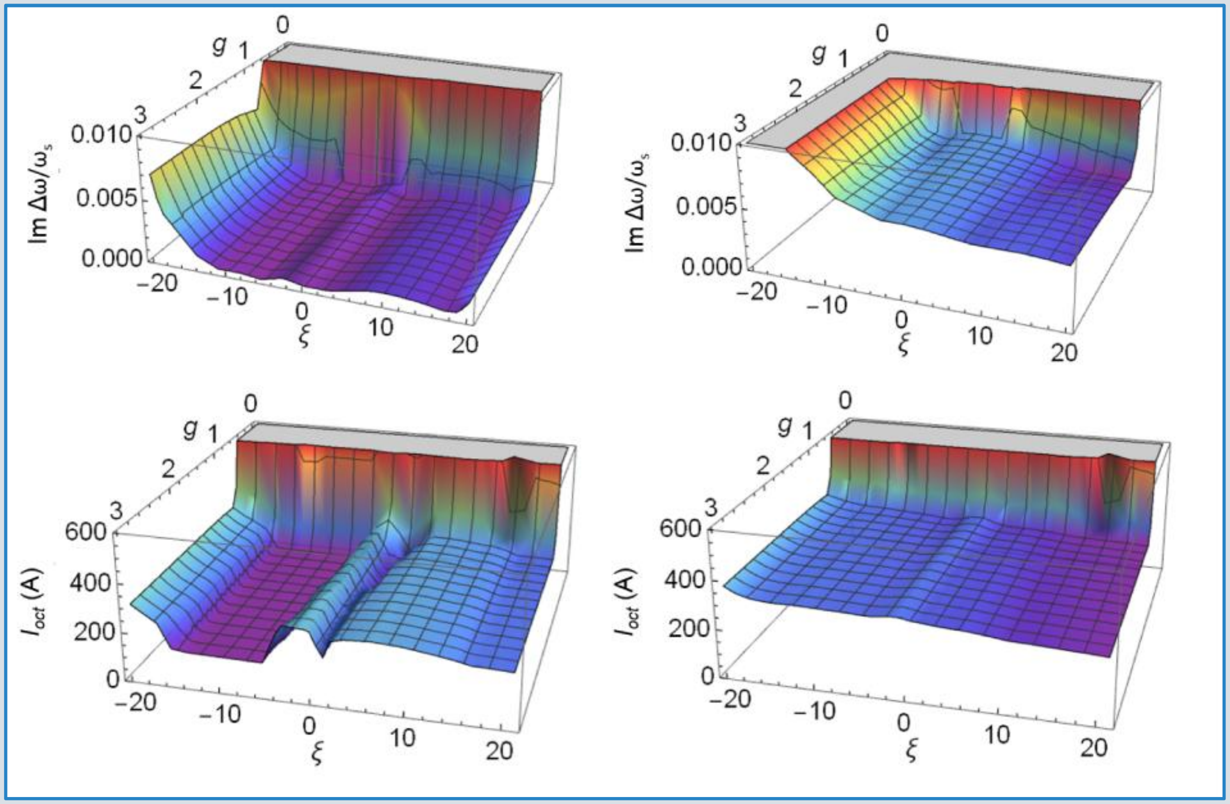


$$Z_1^{\perp}(\mu) = -i \sim L Z_0 \frac{r}{2® b^3}$$

Betatron cleaning secondary collimators are the target for impedance reduction



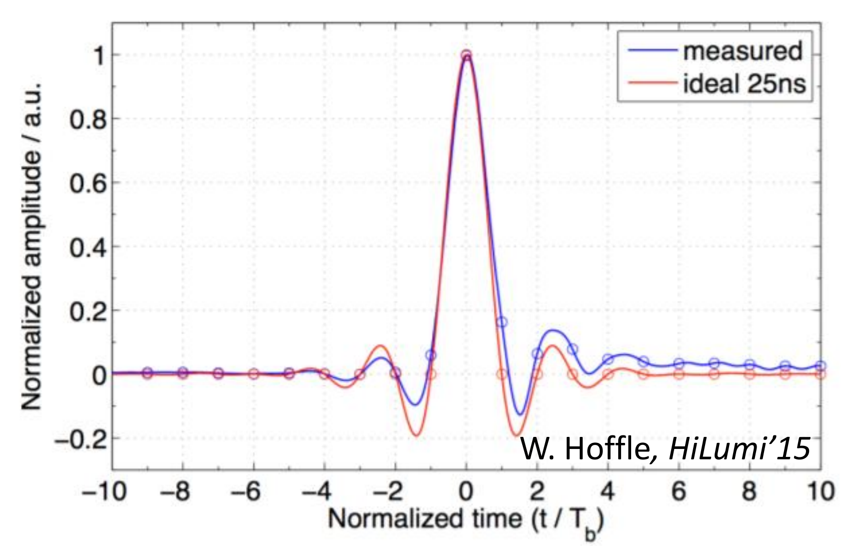
Must rely on octupole tune spread to stabilize



S. Antipov *et al.*, *Phys. Rev. Accel. Beams* vol. 22, 054401, 2019

Nearly ideal damper response

'FLAT' KICK CLOSE TO IDEAL DAMPER



W. Hoffle, *HiLumi'15*

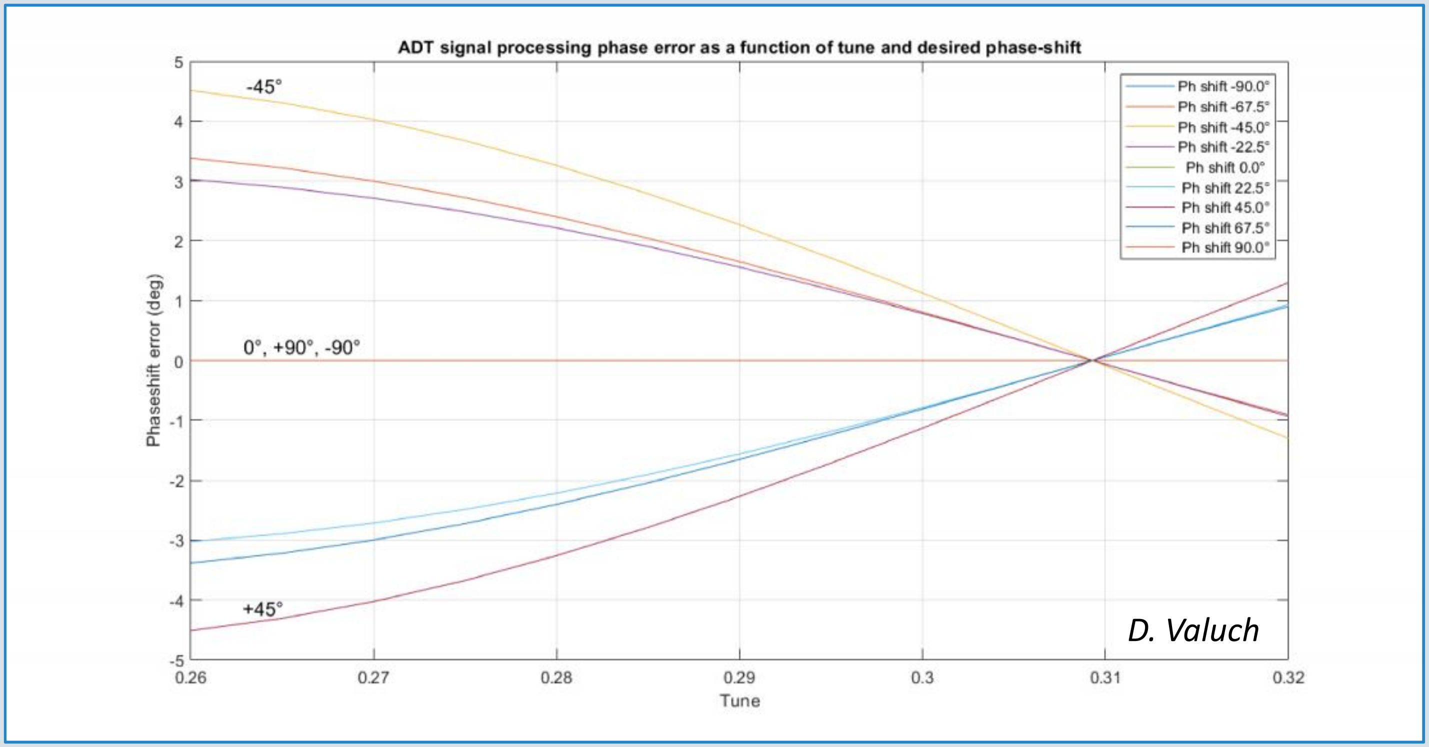
PHASE CAN BE CONTROLLED BETTER 1 DEG

Using two pick-ups with cancelling errors

Tune setting	$\Delta Q7$ (deg)	$\Delta Q9$ (deg)	ADT Phase error (deg)
0.260	3.4	-3.2	0.2
0.265	3.2	-3.1	0.1
0.270	3.0	-2.8	0.2
0.275	2.8	-2.6	0.2
0.280	2.5	-2.3	0.2
0.285	2.1	-1.9	0.2
0.290	1.7	-1.6	0.1
0.295	1.3	1.2	0.1

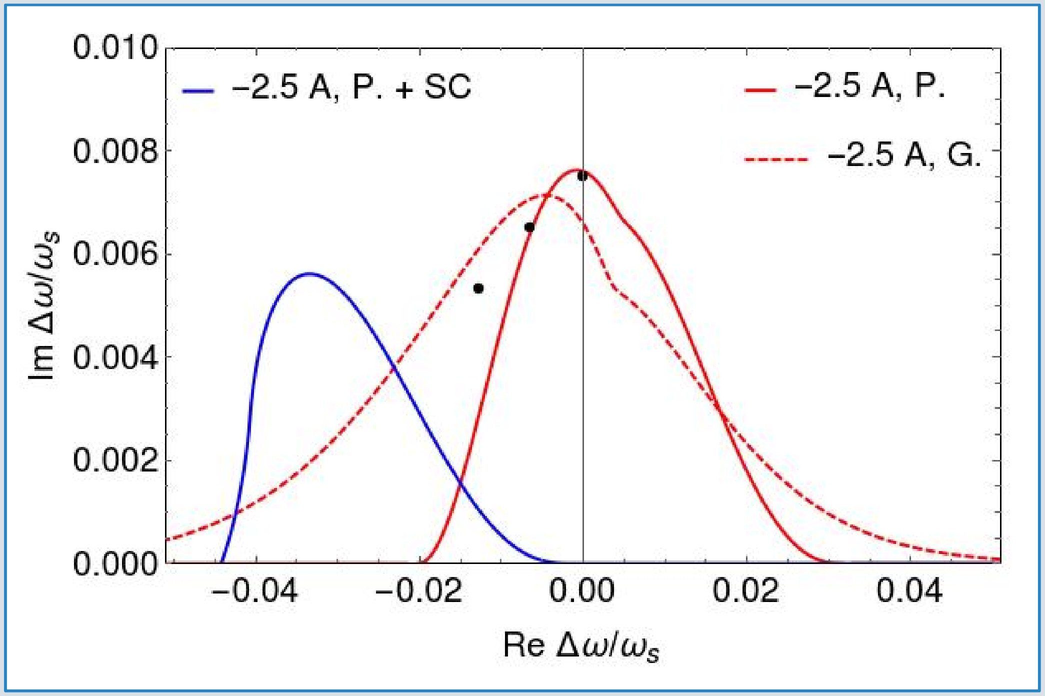
D. Valuch

A signle pick-up gives a phase setting error around a couple deg

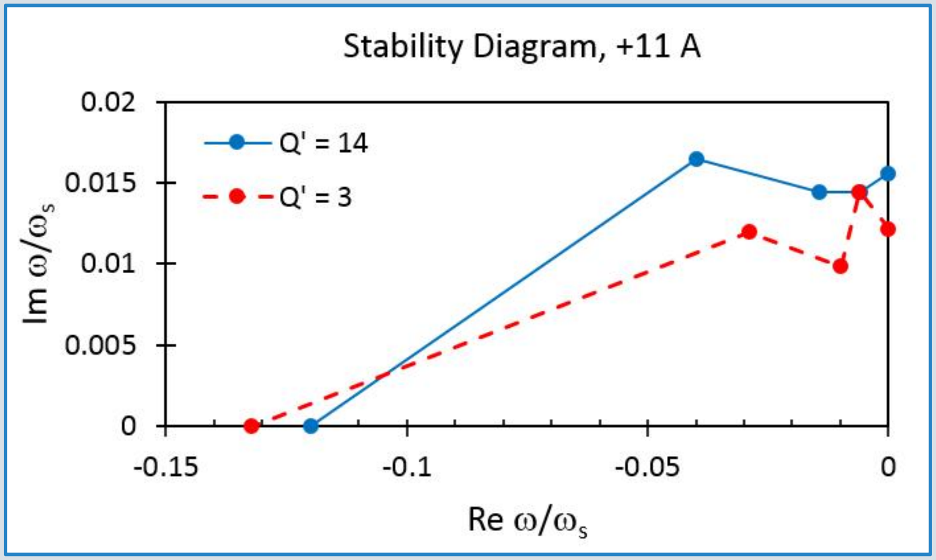


Landau damping from natural nonlinearities

Uncorrected lattice nonlinearities are expected to produce a 2.5 A equivalent octupole tune spread

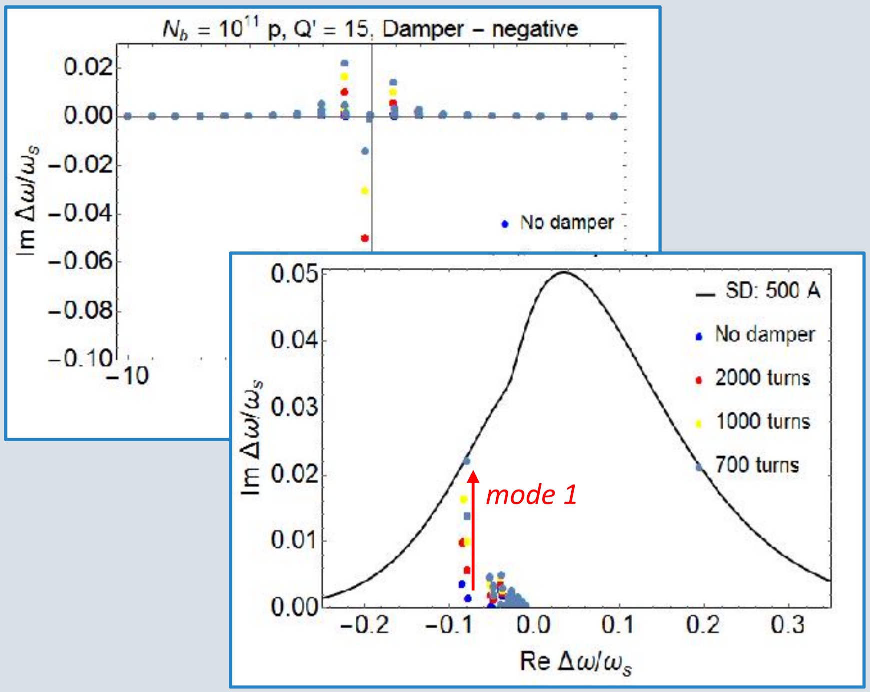


Results at different chromticities agree

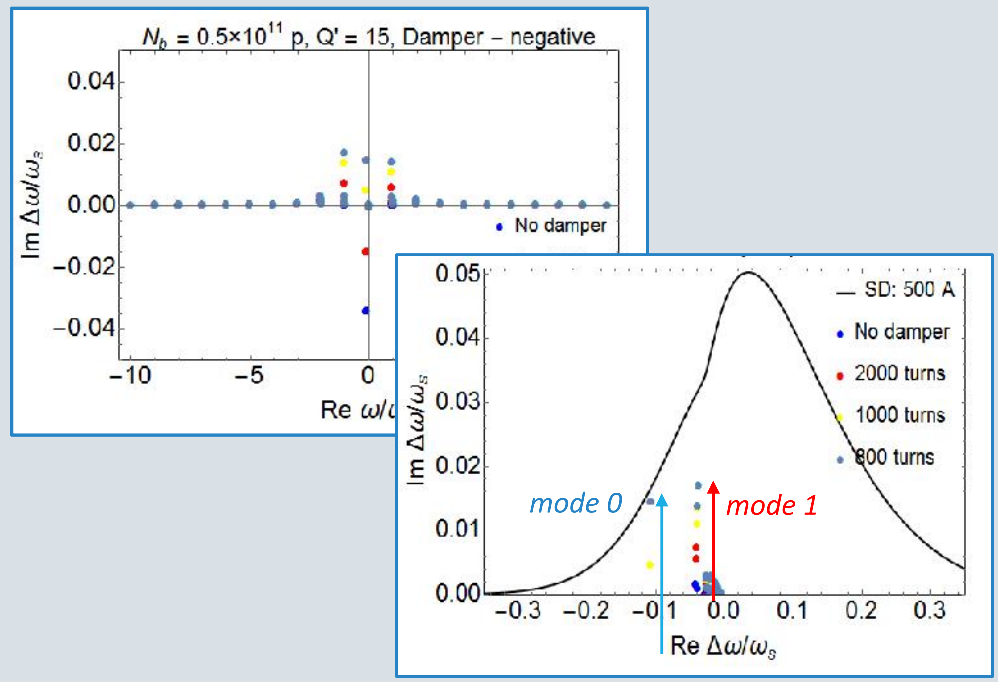


Interference from other modes

GOOD – ONE DOMINANT MODE



BAD – MULTIPLE MODE WITH SIMILAR GROWTH RATES



Simulation for LHC at 6.5 TeV and Q' = 15, S. Antipov, APB-HSC Meeting, CERN, 19.03.18