HL-LHC impedance and stability studies

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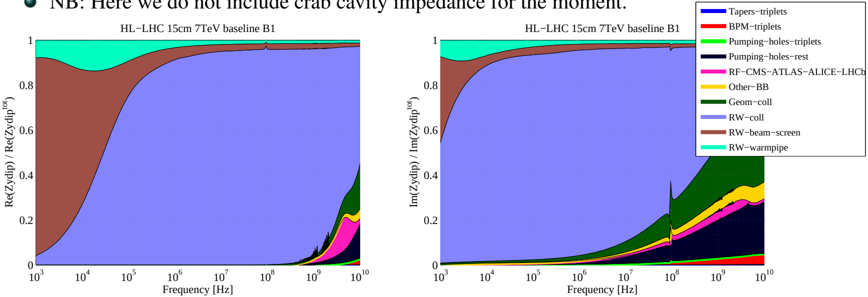
and the WP 2.4, Collimation colleagues and the crab cavity designers!

Outline

1. The HL-LHC collimator upgrade scenarios
    - IP3+IP7 upgrade with Mo - MoC jaws
        - Impedance of the machine
        - Impedance margins
        - Stability margins
    - Only IP7 upgrade with Mo - MoC jaws
    - IP3 retraction and IP7 upgrade with Mo - MoC jaws
2. New coating materials
    - Stability curves with Q'=+3
3. Crab Cavities studies
    - HOM studies
    - Single bunch growth rates Vs Q'
4. Conclusions

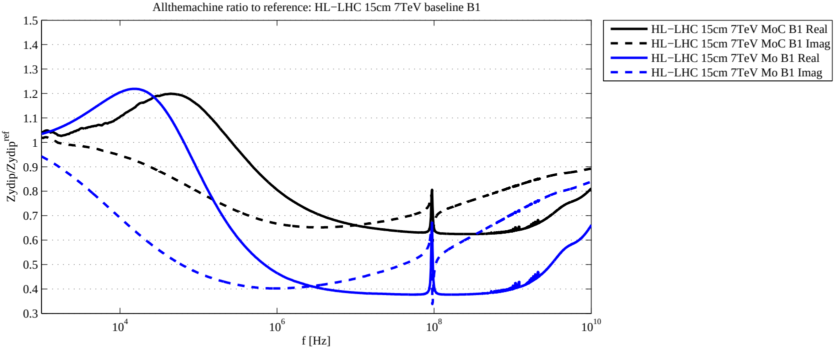
HL-LHC collimator upgrade scenarios.

- Old baseline of the HL-LHC impedance model with different CFC collimators.
- NB: Here we do not include crab cavity impedance for the moment.



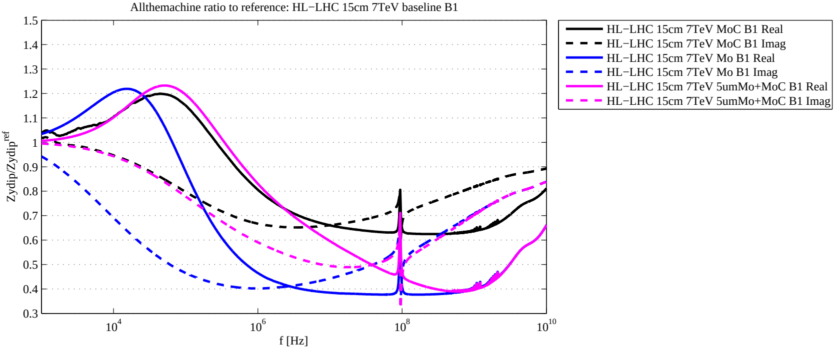
→ CFC collimators represent the highest contributors to the HL-LHC impedance over a wide range of frequencies.
→ New jaws materials for the secondaries (TCSGs) were therefore explored.

- Impedance gain with MoC and Mo collimators in both the TCSGs in IP3 and IP7.



→ With MoC collimators the impedance is reduced to 60% (range 10 MHz - 1 GHz).
→ With Mo collimators the impedance is reduced to 40% (range 10 MHz - 1 GHz).

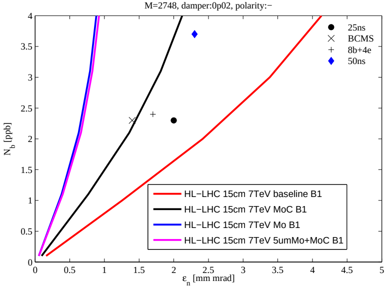
- Impedance gain with MoC and Mo collimators in both the TCSGs in IP3 and IP7.



→ With MoC collimators the impedance is reduced to 60% (range 10 MHz - 1 GHz).
→ With Mo collimators the impedance is reduced to 40% (range 10 MHz - 1 GHz).

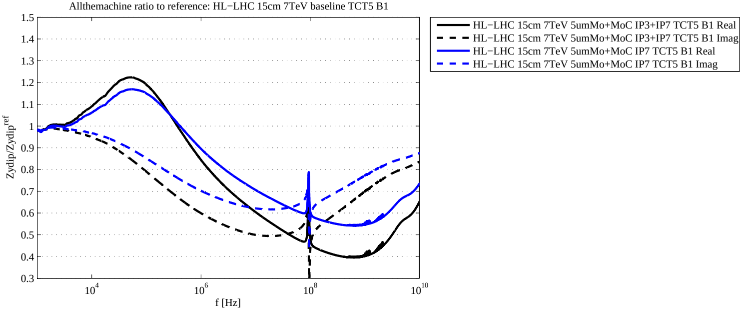
NB: A similar reduction can be achieved coating the MoC with 5 μm of Mo!

- The effect of coating was studied → we can increase the stability region.
- The same stability threshold studies presented in HiLumi 2014 were performed for $Q' = 15$ units (based on 2012 scaling).



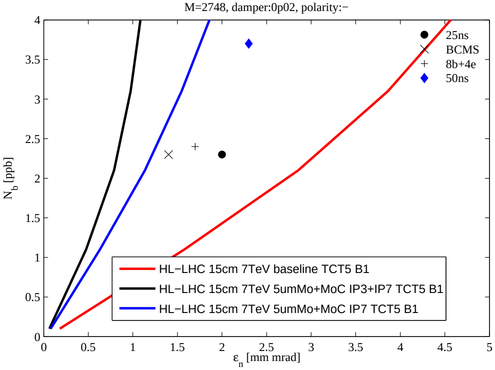
→ Beneficial effect of Mo already visible confirmed also for a coating of $5\mu m$.
→ All beams stable for Mo or Mo coating with negative octupole polarity.

- Impedance gain with 5 μm Mo coated collimators in the TCSGs in IP7 only.



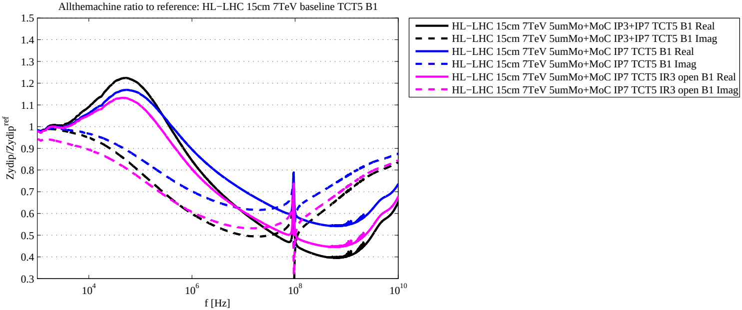
→ Coating only the TCSGs in IP7 we reduce the gain to a maximum of ≃ 15%.
→ We go from 40% of the baseline CFC impedance, to 55% maximum.

- Stability area when coating only the TCSGs in IP7 and leaving those in IP3 in CFC.



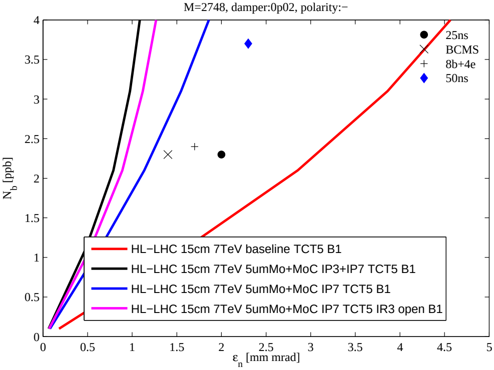
→ For negative octupole polarity, all beams are stable but less margin than before.

- The TCSG in IP3 can be retracted to reach more stability



→ Opening the TCSG in IP3 we recover up to a 5% reduction of the precedent margin.

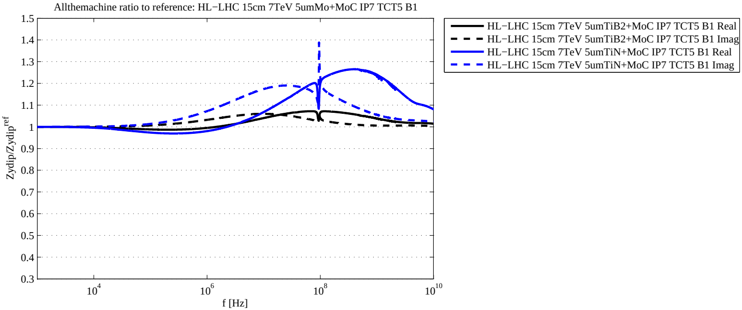
- Stability area when coating only the TCSGs in IP7 and leaving those in IP3 in CFC.



→ All beams are now stable.

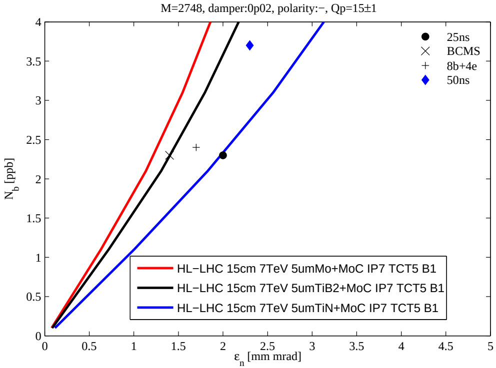
New materials other than the Mo (σ_c = 18.7 MS/m) for coating on MoC have been recently proposed:

- TiN: (σ_c = 2.5 MS/m)
- TiB2 (σ_c = 11.1 MS/m)



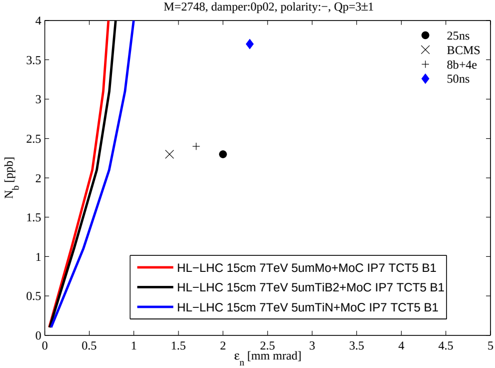
→ 5 μm of TiN coating 30% less effective than Mo coating
→ 5 μm of TiB2 coating 10% less effective than Mo coating

- Stability area when coating only the TCSGs in IP7 and leaving those in IP3 in CFC.
- Setting $Q' = 15 \pm 1$.



→ At the edge of instability only with 5 μm of TiB2 coating with negative octupole polarity.
→ All beams unstable with TiN.

- Stability area when coating only the TCSGs in IP7 and leaving those in IP3 in CFC.
- Setting $Q' = 3 \pm 1$.

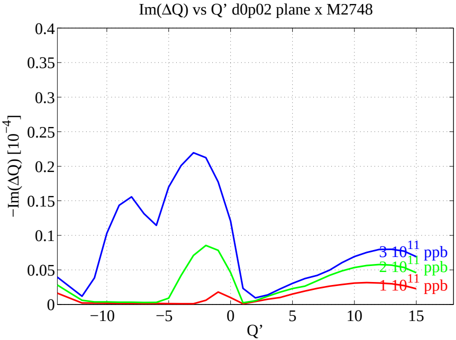


→ If we can grant the precision on Q', in principle we can achieve higher stability areas.

Why is this not the default option?

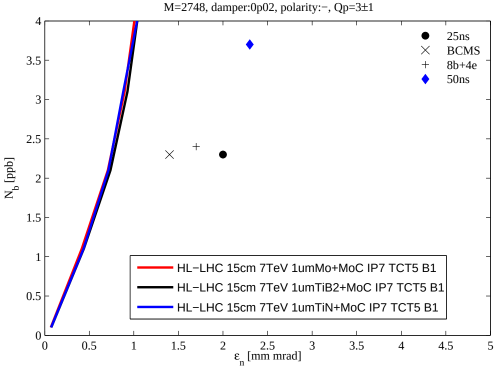
Example from the studies of **LHC** stability at β^* 80 cm:

- Study of the most unstable modes rise-times with damper of 50 turns, varying Q'.
- Minimum instability growth rate at Q'=3 but need good Q' control (±1 unit).



PS: -Im(ΔQ) = 10^{-4} → Instability growth rate = $7s^{-1}$ → 1500 turns (140 ms);
PPS: No scaling is assumed here: rise times from the impedance model as-it-is.

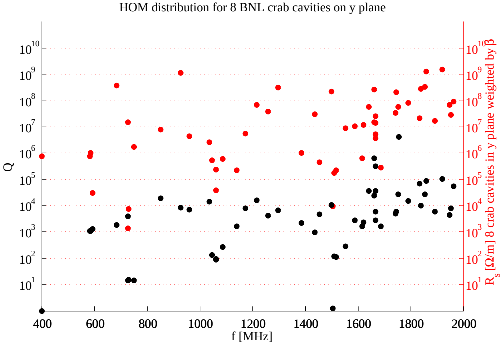
- Stability area when coating only the TCSGs in IP7 and leaving those in IP3 in CFC.
- Setting $Q' = 3 \pm 1$ and coating at 1μm.



→ We could achieve stability also with 1 μm coating!
→ LHC run II will give us the possibility of confirming this observations.
→ New (many) other coating and bulk materials are being tested.

HL-LHC crab cavities studies:

- Crab cavities can help in improving the HL-LHC luminosity recovering the head on beams overlap at the IPs.
- The high transverse voltage needed reflects on the strength of the HOMs
- The number of crab cavities and the location at high $\beta = 3600$ m exceptionally amplify both single and coupled bunch effects.



- The HOMs can vary in frequency uniformly between ±3 MHz.
- The HOMs will be sampled differently depending on single bunch or coupled bunch regime.

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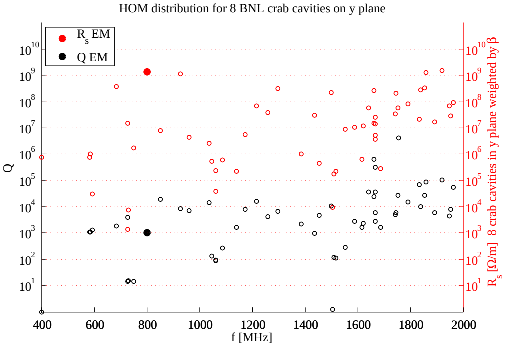
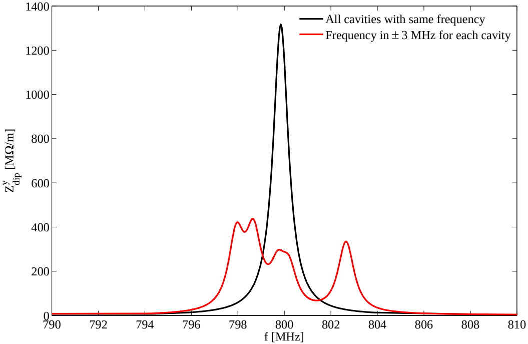
In order to introduce the general approach we choose an example mode (EM) with:

f_r = **800** MHz, R_s = **1.3** GΩ/m, Q=**1000**.



Single bunch growth rate of the EM: HOM simulation procedure.

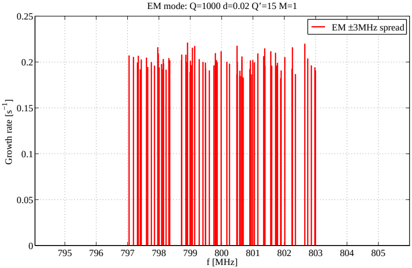
1) Sum the HOM of each of the cavity within a uniform distribution: $f_r' \in (f_r - 3\text{ MHz}, f_r + 3\text{MHz})$.

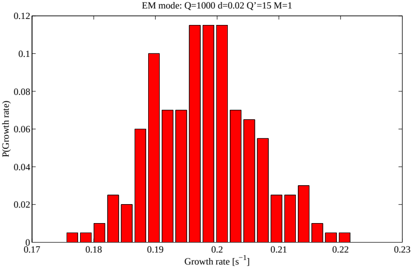


→ The R_s can be reduced up to a factor $\simeq 8$ or less depending on the Q.
→ In this case R_s is reduced by a factor $\simeq 4$.

Single bunch growth rate of the EM: HOM simulation procedure.

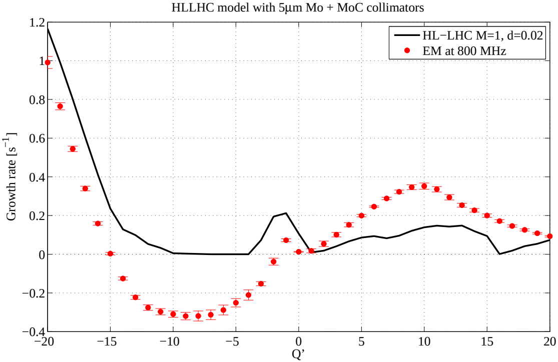
1) Sum the HOM of each of the cavity within a uniform distribution: $f_r' \in (f_r - 3\text{ MHz}, f_r +\ 3\text{MHz})$.
2) Calculate the growth rate of the instability as a function of Q' and 50 turns damper.
3) Derive the probability function related to the growth rate distribution.



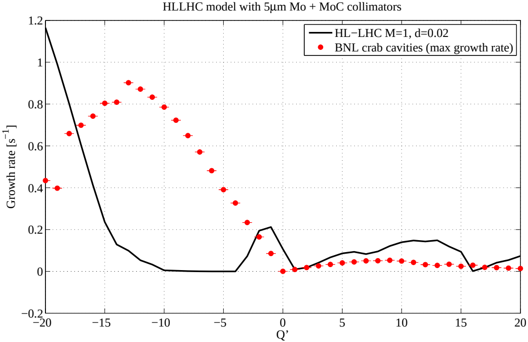


Single bunch growth rate of the EM: HOM simulation procedure.

1) Sum the HOM of each of the cavity within a uniform distribution: $f_r' \in (f_r - 3\text{ MHz}, f_r + 3\text{MHz})$.
2) Calculate the growth rate of the instability as a function of Q' and 50 turns damper.
3) Derive the probability function related to the growth rate distribution.
4) Compare it with the HL-LHC baseline scenario (5μm Mo + MoC).



- **Single bunch** growth rates from all the crab cavities HOMs.
- Only one statistical process realization is shown (full statistics studies on going...)



→ Additional 50% growth rate contribution to the HL-LHC machine for $Q' > 0$.

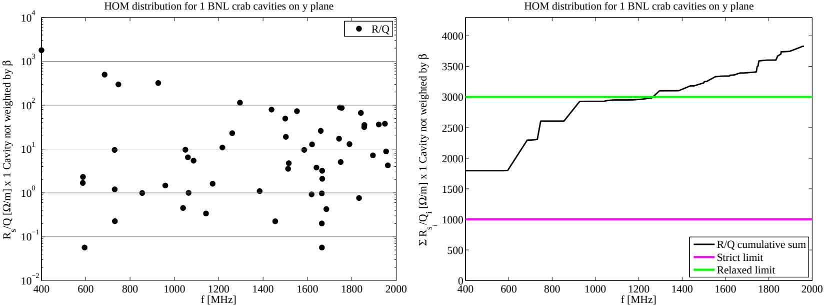
Single bunch observations:

- The crab cavities bring an additional 50% growth rate contribution to the HL-LHC machine for $Q' > 0$.
- 8 crab cavities introduce $(R_s/Q)_{tot}^{max}$ $\simeq$30 kΩ/m in one plane not accounting for the β function.
- To be in the shadow (1% of the baseline) we would need 30/50=600Ω/m.

Cures and considerations:

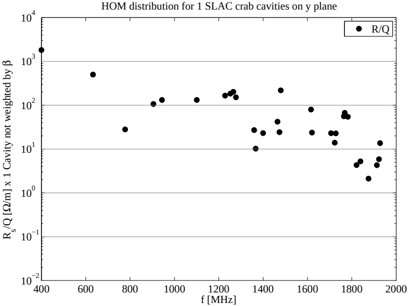
- A the last HiLumi workshop we recommended $(R_s/Q)_{tot}^{max}$ $\simeq$1kΩ/m that can be kept as a strict limit (E.Métral talk in Hilumi 2014, KEK)
- Machine operation optimization: working with Mo collimators operating at $Q' = 3$, the stabilty limits are pushed further and beams have margin of stability. →we can take a factor 2 margin from there: $(R_s/Q)_{tot}^{max}$ $\simeq$2 kΩ/m.
- Factor 1.5 gain when increasing to 100 mm the beam pipe aperture (see yesterday talks from B. Xiao and S. De Silva): $(R_s/Q)_{tot}^{max}$ $\simeq$3 kΩ/m if gain similar for all the HOMs (relaxed limit).
- ...

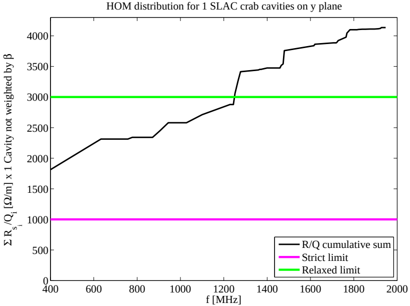
BNL crab cavity design single bunch limits



→ We need to decrease by at least a factor of 2 the total cumulated R_s/Q.

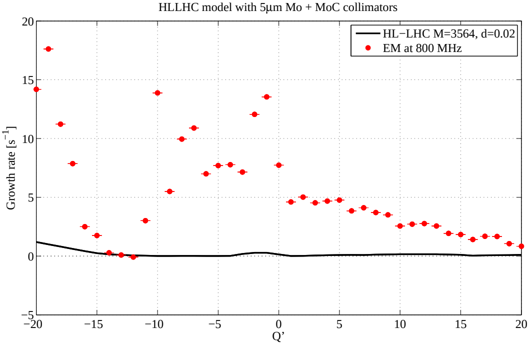
SLAC crab cavity design single bunch limits





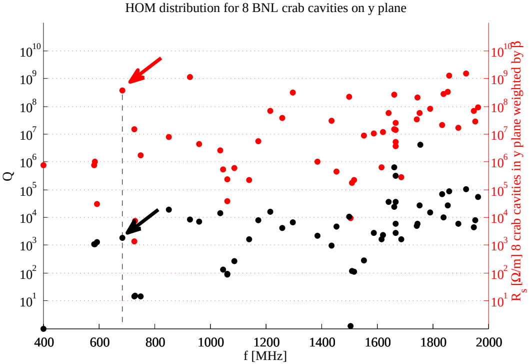
→ We need to decrease by at least a factor of 2 the total cumulated R_s/Q.

- **Coupled bunch** growth rates for the EM.
- Only one statistical process realization is shown (full statistics studies on going...)



→ Significant effect on the rise time: is this the case also for the crab cavities?

- **Coupled bunch** growth rates for a crab cavity HOM close to the EM (f_r =680 MHz, $R_s \simeq 1G\Omega/m$, $Q \simeq 1000$).
- Only one statistical process realization is shown (full statistics studies on going...)



- **Coupled bunch** growth rates for the a crab cavity HOM close to the EM (f_r =680 MHz, $R_s \simeq 1G\Omega/m$, $Q \simeq 1000$).
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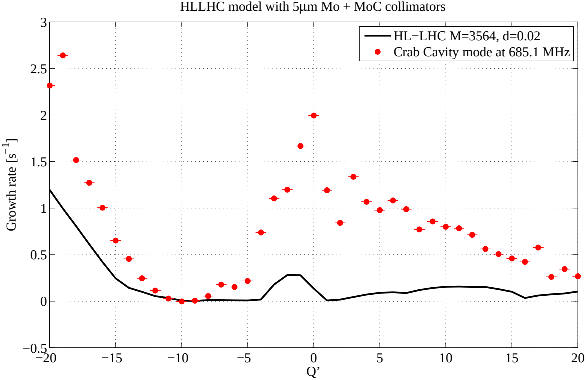


→ Up to factor ≃10 growth rates higher than baseline for $Q' > 0$.

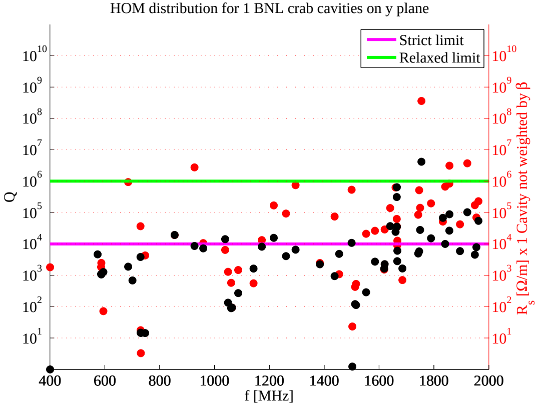
Coupled bunch observations:

- A single crab cavity mode introduces up to a **factor 10** in growth rate higher than the contribution of the HL-LHC machine for $Q' > 0$.
- The chosen mode has $R_s \simeq$1 GΩ/m accounting for the β function and for N=8 cavities.
- Dividing by $\beta_y/\beta_y^{av} = 50$ and accounting for a **factor 4** of impedance reduction due to the spread, each cavity introduces 5 MΩ/m (it would be 2.5 MΩ/m if the mode is well separated).
- To be in the shadow (1% of the baseline) we would need 5M/10/100=5kΩ/m.

Cures and considerations:

- At the last HiLumi workshop we recommended ${R_s}^{max}_{HOM/CC} \simeq 10 - 20k\Omega/\text{m}$ that can be kept as a strict limit.
- Accounting for 8 *well separated* mode we have ${R_s}^{max}_{HOM/CC}$ ≃160 kΩ/m.
- Colliding at 45 cm to 15 cm (ultimate scenario) we gain a **factor 3** from the β function decrease: ${R_s}^{max}_{HOM/CC}$ ≃0.5 MΩ/m.
- Machine operation optimization: working with Mo collimators operating at $Q' = 3$, the stabilty limits are pushed further and beams have margin of stability. →we can take a **factor 2** margin from there: ${R_s}^{max}_{HOM/CC}$ ≃1 MΩ/m (relaxed limit).
- ...

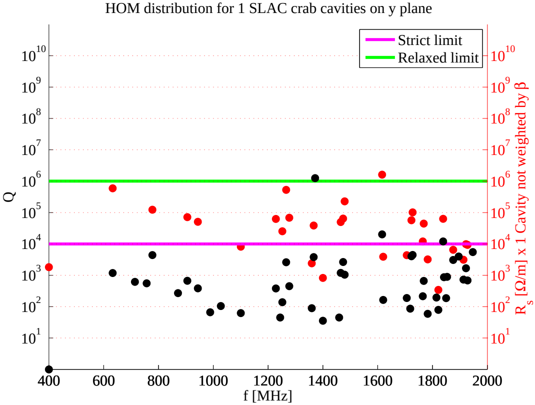
Coupled bunch limits:



→ The 927 MHz, 1.86 GHz and 1.92 GHz modes should be reduced by a factor 3 (or 2 times more if the modes start to be well separated).

→ The mode at 1.75 GHz should be reduced by more than two orders of magnitude.

Coupled bunch limits:



→ The mode at 1.6 GHz should be decreased by a factor 2.

Conclusions I

The HLLHC beam stability can be improved reducing the collimator impedance.
Different scenarios have been studied.

- The TCSGs collimators in IP3 and IP7 coated with 5 μm Mo over MoC.
  - → The impedance is reduced up to 40 % of the baseline one (all TSGS in CFC).
  - → Stability ensured for all type of beams.
- The TCSGs collimators only in IP7 coated with 5 μm Mo over MoC.
  - → The impedance is reduced up to 55 % of the baseline one (all TSGS in CFC). .
  - → Stability margins still available with negative polarity.
- The TCSGs collimators only in IP7 coated with 5 μm Mo over MoC and IP3 settings more open.
  - → The impedance is reduced up to 45 % of the baseline one (all TSGS in CFC). .
  - → Increased stability margin for both negative polarity.

Conclusions II

- The TCSGs collimators only in IP7 coated with 5 μm of TiB2 or TiN over MoC.
  - → TiN coating is 30% less effective than Mo coating.
  - → TiB2 coating is 10% less effective than Mo coating.
  - → Beams unstable except for TiB2 coating and negative octupole polarity (but at the edge of instability).
- Stability studies with Q'=+3 instead of +15:
  - → The stability curves are generally improved: all beams stable. But...
  - → Thiny region of stability predicted: requires good Q' control (within 1 unit).
  - → The coating can be reduced to 1 μm with small differences within Mo, TiB2 or TiN.
- Crab cavities observations:
  - → In single bunch all the crab cavities increase the machine growth rate by a factor 1.5.
  - → Both BNL and SLAC design should at least half the total cumulated R_s/Q.
- Crab cavities threshold:
  - → In the coupled bunch regime a chosen HOM (690 MHz) shows increase in the growth rate up to a factor 10.
  - → BNL design: 927 MHz, 1.86 GHz and 1.92 GHz modes to be reduced by a factor 3. Mode 1.75 GHz to be reduced by more than 2 orders of magnitude for relaxed limits.
  - → SLAC design: the mode at 1.6 GHz should be decreased by a factor 2.

Thank you for your attention!