Safe Beam Tests

R. Assmann, CERN

Thanks to Stefano Redaelli for presenting this talk on my behalf (criticism and complaints please to my address…)

Reference

- Very complete study by Yi-Peng Sun *et al* (presented yesterday)
- Addresses many issues with a lot of detailed simulations and interesting insights, answering many of the previous questions.
- Details see this paper:

Beam Dynamics Aspects of Crab Cavities in the Large Hadron Collider

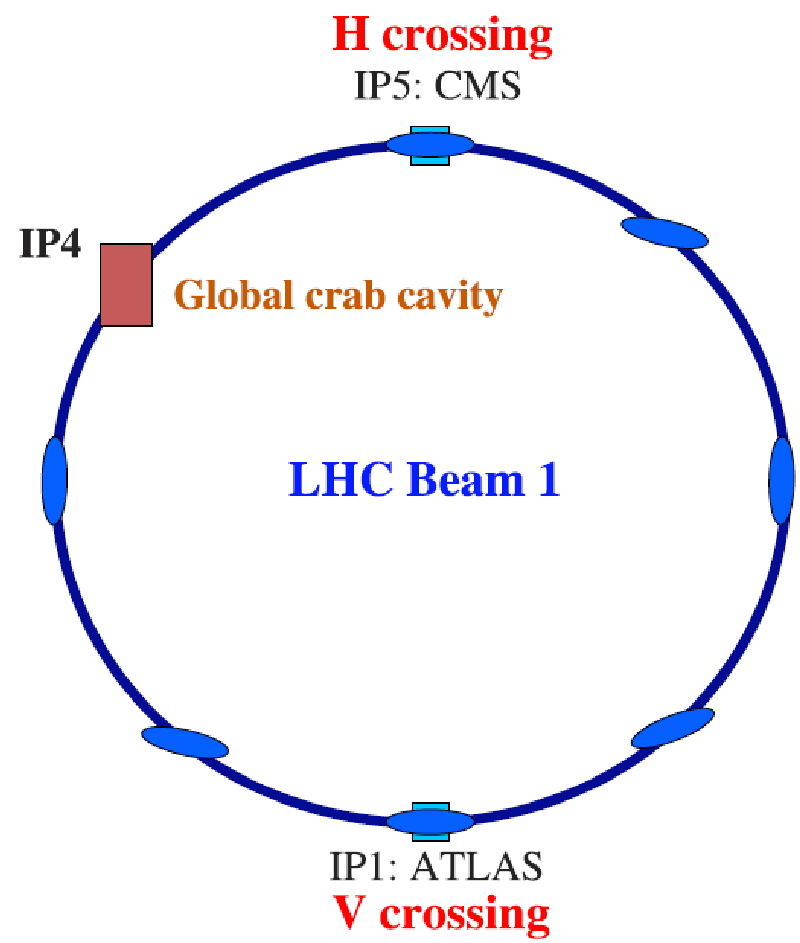
Yi-Peng Sun,* Ralph Assmann, Javier Barranco, Rogelio Tomás, Thomas Weiler, and Frank Zimmermann
European Organization for Nuclear Research (CERN), Geneva, Switzerland

Rama Calaga
BNL, Upton, New York 11973, USA

Akio Morita
High Energy Accelerator Research Organization, KEK,
1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

The Global Crab Cavity in IR4

- Explained before in detail…
- Meant as a demonstration experiment. Goals:
  - **Show that crab cavities do not disturb the beam.**
  - **Show that the predicted gain is really achieved.**
- Some price to be paid:
  - Not closed solution, so beam changed all around the ring.
  - Have to address issues that would be no problem for a closed solution, e.g. collimation and MP.
  - Additional issues can cause problems…



Goal of this Presentation

- Assess the tests and challenges to be mastered for the global crab cavity program.
- Assess if there are evident show-stoppers.
- Assess implications for doing the crab cavity test program.
- This presentation cannot propose a detailed beam test program with time estimates, detailed beam parameters, … Requires much more work.
- Cannot present a failure analysis, as proposed in the abstract. This should be driven by the RF specialists.

β^*=0.55m → Present triplets

β^*=0.25m → Phase I triplet upgrade

Global Crab Cavity Program on One Slide

- Main machine changes:
  - One 800 MHz crab cavity installed in IR4, optimized for IP5.
  - Crab cavity detuned during injection, ramp & squeeze.
  - Ramped up after squeeze for ≥ 10 turns to ≈ 2.3 MV.
  - Compensation for limited voltage with (*one for β^*=0.55m, both for β^*=0.25m*):
    - Option 1: Decrease fractional horizontal tune to 0.05.
    - Option 2: Increase beta at IR4 crab location to 3 km.
  - Compensation for 0.5-1.0 σ decrease in aperture with either:
    - Option 1: Correct orbit to smaller maximum excursion (smaller margin).
    - Option 2: No squeeze in IR1, IR2, IR8.
  - Collimate head and tail of beam at 0.5-1.0 σ below the canonical 6 σ.
  - Slightly smaller tolerances for dynamic changes in orbit and beta beat (respect of collimation hierarchy).
  - Predicted 1-2 σ loss in dynamic aperture.
- Increase in luminosity to be measured in IP5 (decrease in IP1):
  - **4% (β^*=0.55m) or 14% (β^*=0.25m)**

General Remarks

- There is no clear show-stopper in the proposed crab cavity program, for program as summarized in the previous slide.
- Many questions have been addressed and answers have been provided over the last year. Good progress…
- Some of the machine changes must be considered as major changes and they require **significant beam time for testing**.
- Will come back to these tests…
- However, before this let's comment on some more advanced proposals:
  - Low emittance option.
  - Replacement of momentum cleaning system with crab cavities

Comments on Low Emittance Option

- It is proposed to use a low emittance beam to enhance the luminosity gain at top energy.
- We must note:
  - This idea relies on gaining normalized aperture with smaller beam size.
  - The gain in aperture is then used to increase the crossing angle, reducing the luminosity.
  - The increased crossing angle is then compensated with the crab cavities, resulting in larger luminosity gain to be observed (25%).
  - Requires that collimators sit at same normalized settings, meaning factor 2 smaller real gaps with low emittance (factor 1.4 with phase I triplet).
- As for the TOTEM beam, this low emittance option cannot be guaranteed from the collimation side.
- The low emittance option imposes much tighter collimation and machine stability tolerances and is very difficult.
- Clear <u>NO to rely on this option </u>(should still try it).

Comments on Proposal of Momentum Cleaning with Crab Cavities

- This idea relies on using crab cavities to convert energy offsets into horizontal offsets such that particles are cleaned in the betatron cleaning system. Nice concept in principle.
- However, the LHC momentum cleaning system is most needed at the start of the energy ramp, to intercept un-captured beam as specified by the RF group.
- I assume that nobody proposes using crab cavities in the LHC at injection!? This would not work.
- Clear message: Crab cavities cannot replace the momentum cleaning system of the LHC.
- Explained benefit at top energy for such a system: Allows smaller β^* with phase II triplets if limited by off-momentum β beat...
- Let's see top energy losses…

Standard Global Crab Cavity Program

- Main machine changes:
  - One 800 MHz local crab cavity installed in IR4, optimized for IP5.
  - Crab cavity detuned during injection, ramp & squeeze.
  - Ramped up after squeeze for ≥ 10 turns to ≈ 2.3 MV.
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Stick to the standard global crab cavity program, even if luminosity gain is lower (more realistic)

Safe Beam Tests

- Safe → **Minimize intensity during tests as much as possible and proceed very systematically**.
- Propose three categories of beam tests:
  1. **Beam tests before installation of the IR4 crab cavity**
  2. **Beam tests after installation of the IR4 crab cavity, before squeeze and with low intensity**
  3. **Beam tests with crab cavity in collision**
- Some major machine changes can be tested without crab cavities and should be tested to avoid later failure.

Beam Tests Before Installation IR4 Crab Cavity I

- Tests should be performed at top energy with a pilot bunch to minimize risks.
- Test 1: **Feasibility of high beta option in IR4 at top energy.**
  - Verify high beta at proposed crab cavity location.
  - Verify that RF system and beam instrumentation is not disturbed.
  - Verify the local change at top energy without changing beam all around the ring.
  - Verify local IR4 protection against beam/halo losses (e.g. from IR3).
- Test 2: **Feasibility of low fractional tune.**
  - Set up machine for injection with $Q_x = 0.05 – 0.1$
  - Set up machine for energy ramp with $Q_x = 0.05 – 0.1$
  - Set up machine for squeeze with $Q_x = 0.05 – 0.1$
  - Verify that low fractional tune is a feasible working point with good stability, acceptable lifetime, good beam-beam, …

Beam Tests Before Installation IR4 Crab Cavity II

- Test 3: **Feasibility to collimate at lower gaps.**
  - Reduce collimation in steps from 6 σ to 5 σ for different intensities.
  - Verify that beam lifetime, impedance, stability, background, etc remain acceptable for lower collimation gaps.
- Test 4: **Feasibility to work with reduced orbit margin.**
  - Correct orbit to smaller tolerance such that more aperture is available.
  - Check stability with smaller horizontal tune.
- Test 5: **Feasibility to work with reduced dynamic aperture.**
  - Measure dynamic aperture with increased IR4 beta and lower fractional tune.
  - Assess room in dynamic aperture, e.g. by reducing the achieved dynamic aperture by 2 σ.
- Test 6: **Feasibility of slightly reduced operational margins.**
  - Understand operational margins and assess if critical at the 0.1 σ level.

Standard Global Crab Cavity Program

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  - Ramped up after squeeze for ≥ 10 turns to ≈ 2.3 MV.
  - Compensation for limited voltage with (both for β^*=0.25m):
    - Option 1: Decrease fractional horizontal tune to 0.05.
    - Option 2: Increase beta at IR4 crab location to
  - Compensation for 0.5-1.0 σ decrease i .
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Many important issues can be checked before installation of the crab cavity!

Beam Tests After Installation IR4 Crab Cavity

- Tests are done without collision.
- Test 1: **Feasibility of detuned crab cavity.**
  - Verify that impedance is OK during injection and ramp.
  - Measure impedance.
- Test 2: **Feasibility of voltage ramp up and down** (single bunch, low I)
  - Ramp up voltage over at least 10 turns to 2.3 MV. Ramp down.
  - Measure transverse emittance before and after.
- Test 3: **Feasibility of emittance preservation** (single bunch, low I)
  - Ramp up cavity voltage to 2.3 MV.
  - Measure emittance versus time and compare to no CC case.
- Test 4: **Feasibility of non-closed crabbing** (single bunch, low I)
  - Ramp up cavity voltage to 2.3 MV, low tune or high IR4 beta.
  - Verify that collimation and protection hierarchy is maintained.
  - Verify acceptable beam lifetime and background.

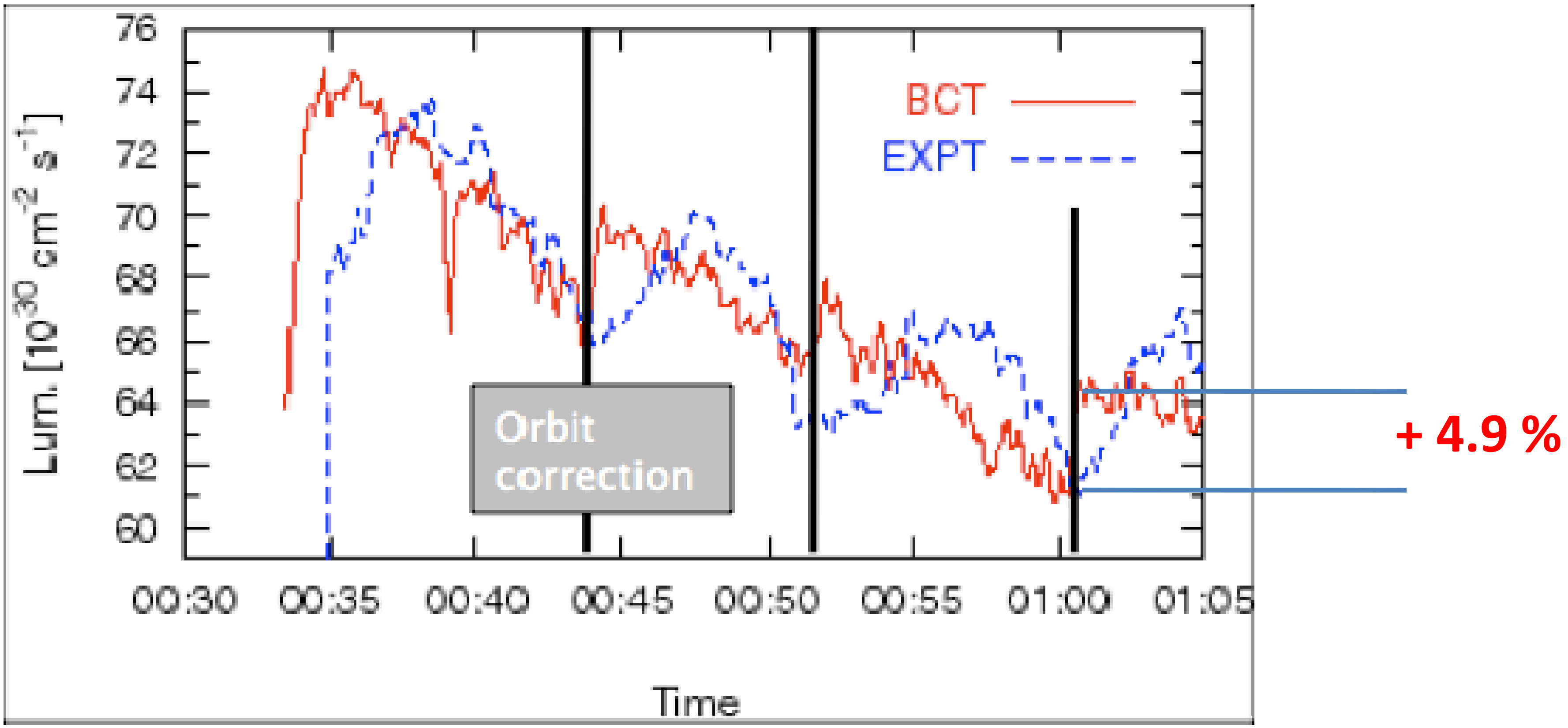
Collimation Hierarchy Test

- Up to 1 σ changes of horizontal orbit along a bunch would normally be incompatible with collimation hierarchy.
- This was the reason for the strong concerns put up from our side.
- Latest results show that the retraction is not much reduced by this x-z correlation.
- This is due to a cancellation between the crab induced x-z correlation and the dispersion offset of off-energy particles at the collimators (particles with z offset have also energy offset).
- This is very good news for crab cavities but needs to be confirmed in detailed measurements (effect of phase, optics, … errors?).
- Normalized distance between collimator families should be measured versus crab cavity voltage.

Beam Tests with Crab Cavity in Collision

- Beam parameters depend on the luminosity measurement resolution for various intensities, …. To be defined later.
- **This crucial test will aim at measuring between 4% and 14% of improvement in luminosity in IP5.**
- Careful previous beam tests and optimizations must have resulted in maintaining the beam quality with the crab cavity at 2.3 MV.
- A 4% gain in luminosity seems a priori small to be measured.
- However, we could do it for LEP why not for LHC?
  Crab cavities provide well controlled parameters that can be changed back and forth.
- See **LEP examples on next slides on measured luminosity…**
- Would worry more about machine changes than measuring luminosity at the few % level.

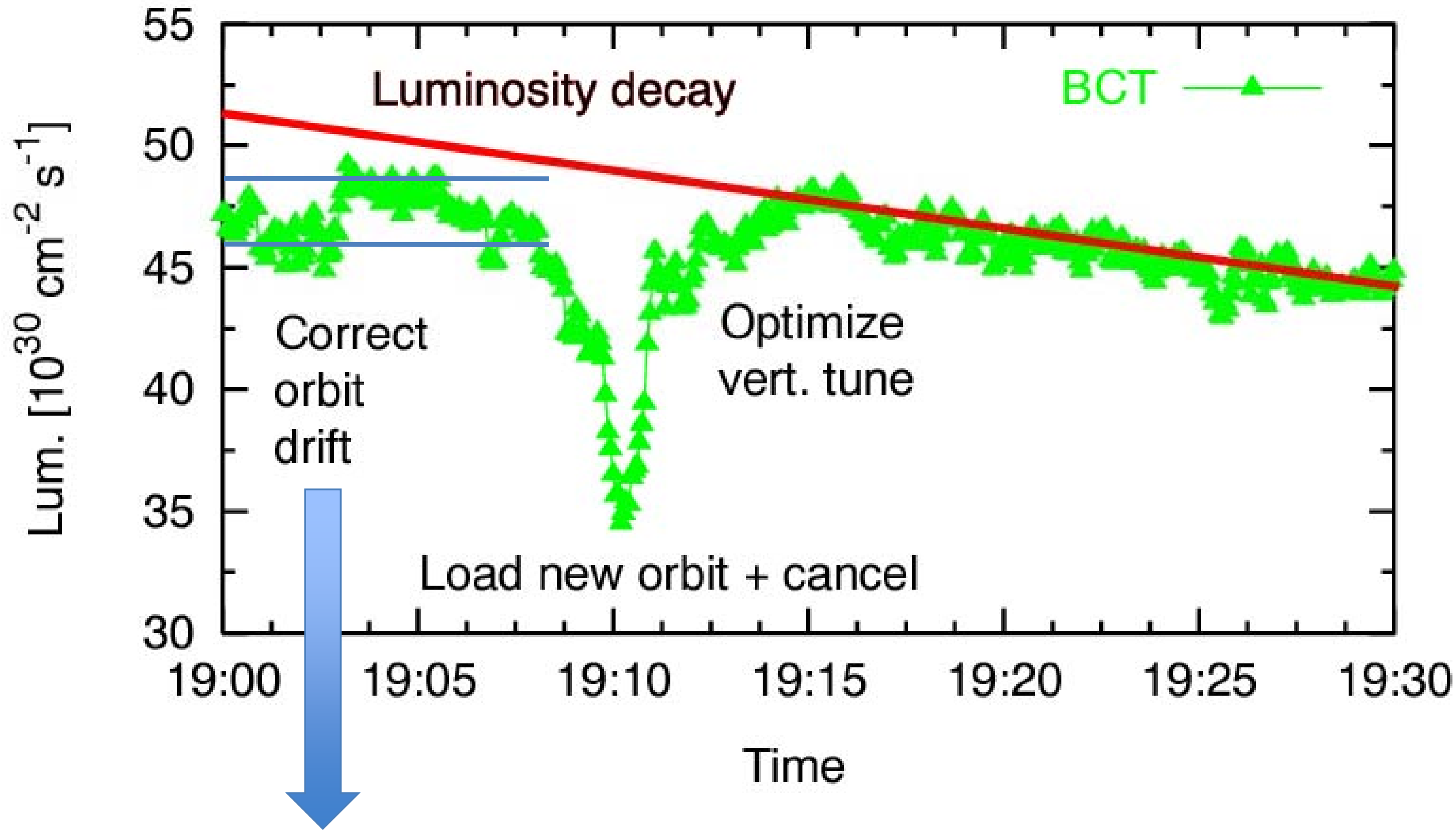
LEP Luminosity Resolution – Example 1



At LEP we resolved luminosity changes reproducibly at the few % level without problems. Machine signals better than experiments!

Should also be possible for the LHC with more modern technology!

LEP Luminosity Resolution – Example 2



+ 5.4 %

Conclusion

- The global crab cavity test in the LHC imposes major machine changes (high beta IR4, low Q_x, collimation at 5σ for head/tail, …).
- Should stick to the less demanding baseline scenario even if luminosity gain is smaller (no small ε, no "crab collimation").
- **No a priori show-stopper visible anymore** after quite impressive work progress over the last year. See paper by Yipeng Sun et al.
- Only beam tests will show whether crab cavities are feasible for LHC or not. Clear risks are still visible but also good potential.
- Many machine changes can be tested and proven even without a crab cavity. **Time consuming tests mean that heavy investment is necessary** (effort & beam time). List provided.
- Several tests of crab cavity without collisions are required and possible.
- **Final measurement of luminosity change is demanding (4%) but we could do it in LEP, so why not in LHC?** Would not worry too much about this…