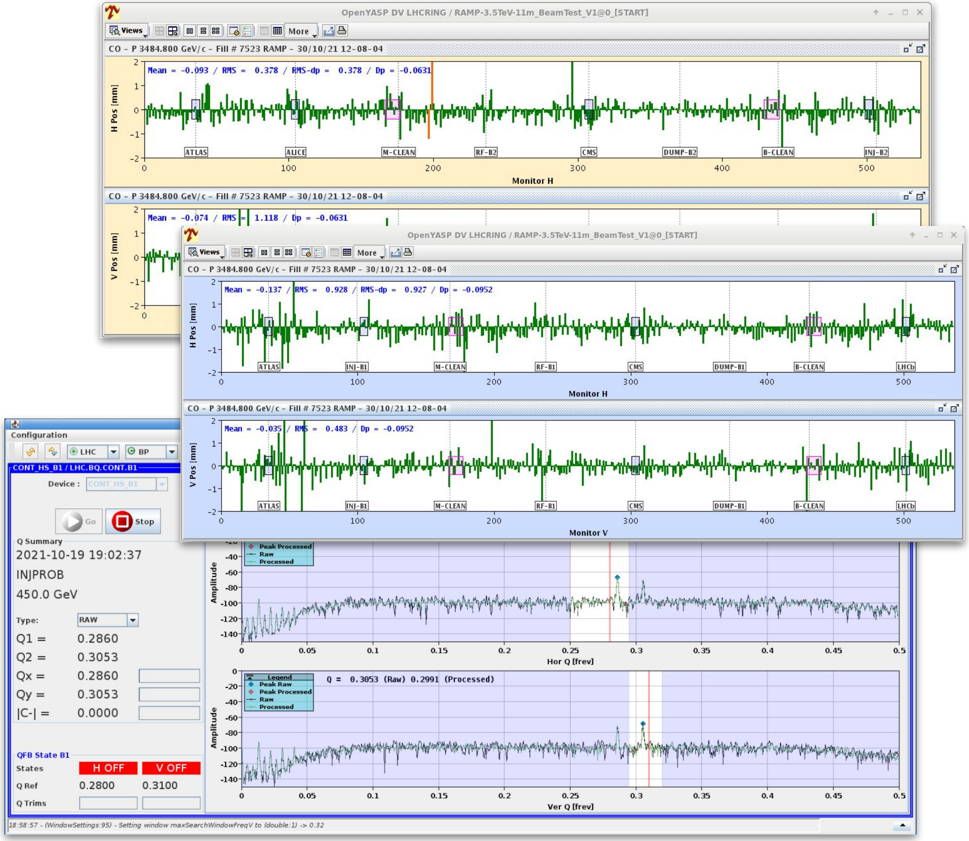
BI feedbacks

SY-BI: D. Louro Alves, L. Grech, S. Jackson
BE-OP: A. Calia, M. Hostettler, D. Jacquet, J. Wenninger

Beam-Based Feedback introduction

- Fast feedback loop with FESA class
  - ○ Beam Feedback Controller (BFC)
  - ○ Developed by SY-BI
- Keep orbit & tune @ reference
  - ○ Orbit Feedback (OFB)
  - ○ Tune Feedback (QFB)
- Critical LHC system
  - ○ Especially during dynamic phases (e.g. Ramp)



OpenYASP DV LHCRING / RAMP-3.5TeV-11m_BeamTest_V1@0_[START]

CO – P 3484.800 GeV/c – Fill # 7523 RAMP – 30/10/21 12-08-04

Mean = -0.093 / RMS = 0.378 / RMS-dp = 0.378 / Dp = -0.0631

CO – P 3484.800 GeV/c – Fill # 7523 RAMP – 30/10/21 12-08-04

Mean = -0.074 / RMS = 1.118 / Dp = -0.0631

OpenYASP DV LHCRING / RAMP-3.5TeV-11m_BeamTest_V1@0_[START]

CO – P 3484.800 GeV/c – Fill # 7523 RAMP – 30/10/21 12-08-04

Mean = -0.137 / RMS = 0.928 / RMS-dp = 0.927 / Dp = -0.0952

CO – P 3484.800 GeV/c – Fill # 7523 RAMP – 30/10/21 12-08-04

Mean = -0.035 / RMS = 0.483 / Dp = -0.0952

Configuration

CONT_HS_B1 / LHC.BQ.CONT.B1

Device : CONT_HS_B1

Q Summary

2021-10-19 19:02:37

INJPROB

450.0 GeV

Type: RAW

Q1 = 0.2860

Q2 = 0.3053

Qx = 0.2860

Qy = 0.3053

|C-| = 0.0000

QFB State B1

States H OFF V OFF

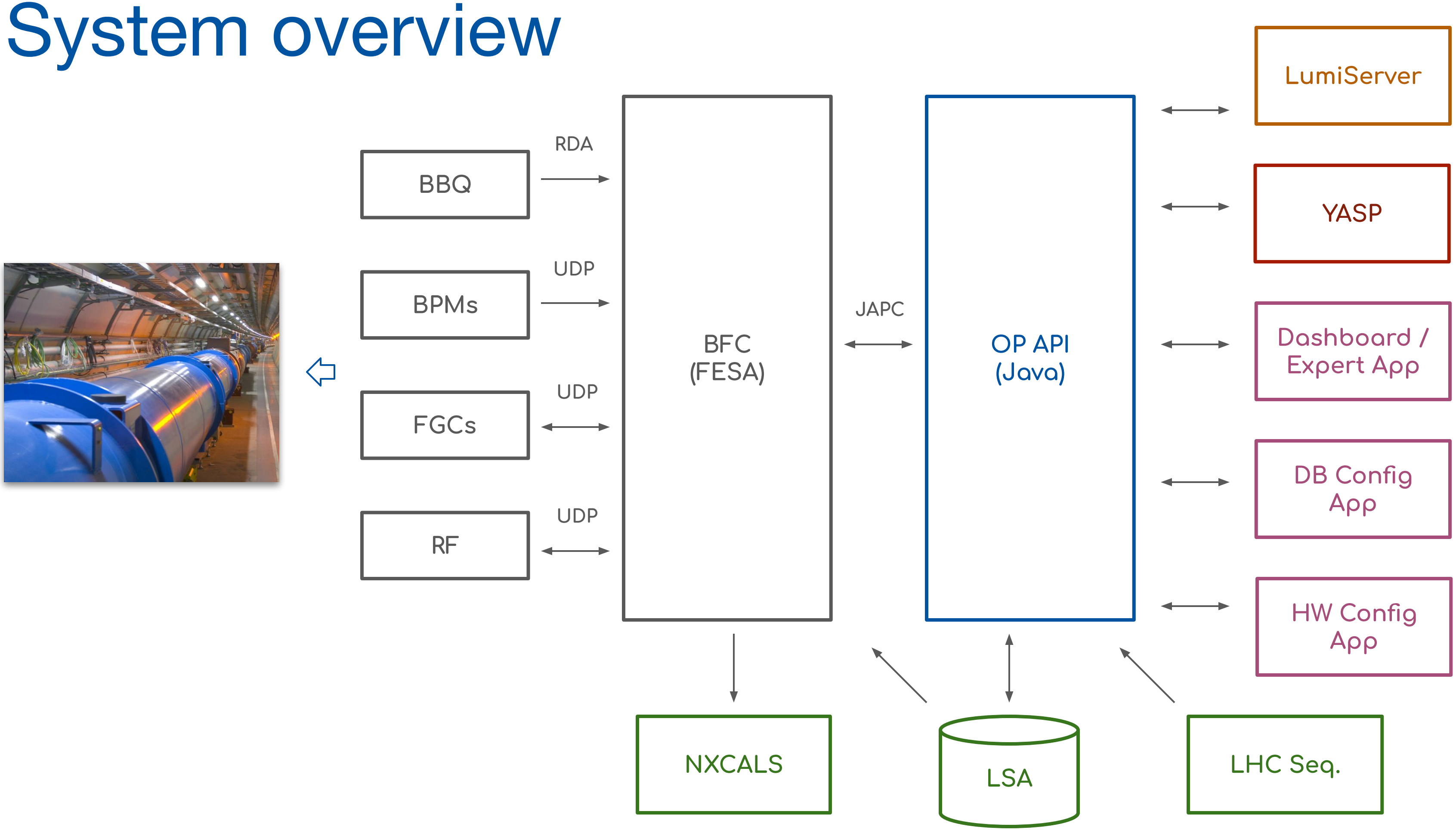
Q Ref 0.2800 0.3100

Q Trims

Q = 0.3053 (Raw) 0.2991 (Processed)

18:58:57 - (WindowSettings:95) - Setting window maxSearchWindowFreqV to (double:1) -> 0.32

System overview



BBQ

RDA

BPMs

UDP

FGCs

UDP

RF

UDP

BFC
(FESA)

JAPC

OP API
(Java)

LumiServer

YASP

Dashboard /
Expert App

DB Config
App

HW Config
App

NXCALS

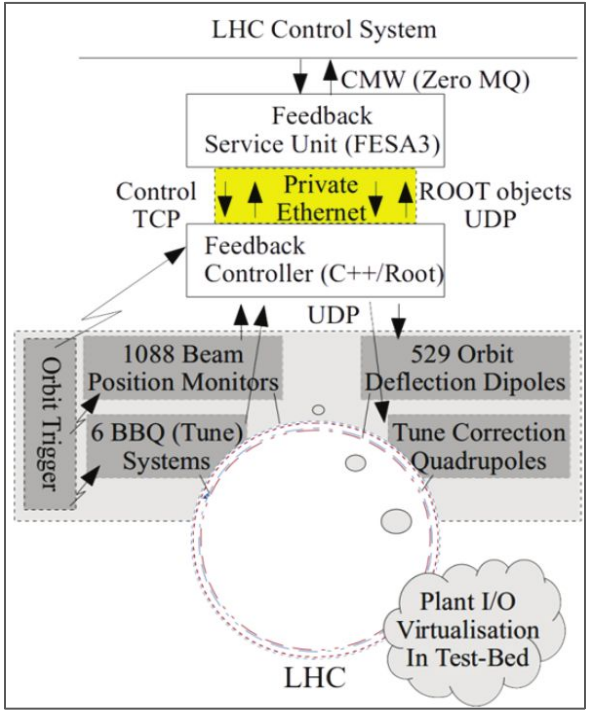
LSA

LHC Seq.

HW & FESA API renovation

- Significantly faster HW
  - 64-core CPU & 200 GB RAM
  - Operational + spare (testbed) machines
- Major architecture refactoring, of note
  - Eradicated initial Root obj. initialization
  - Removed internal Ethernet link
  - Merged *Service Unit* & *Controller*
- New architecture based on FESA3
  - ✓ Simpler and more maintainable

Old architecture


LHC Control System
CMW (Zero MQ)
Feedback Service Unit (FESA3)
Control TCP
Private Ethernet
ROOT objects UDP
Feedback Controller (C++/Root)
UDP
Orbit Trigger
1088 Beam Position Monitors
529 Orbit Deflection Dipoles
6 BBQ (Tune) Systems
Tune Correction Quadrupoles
Plant I/O Virtualisation In Test-Bed
LHC

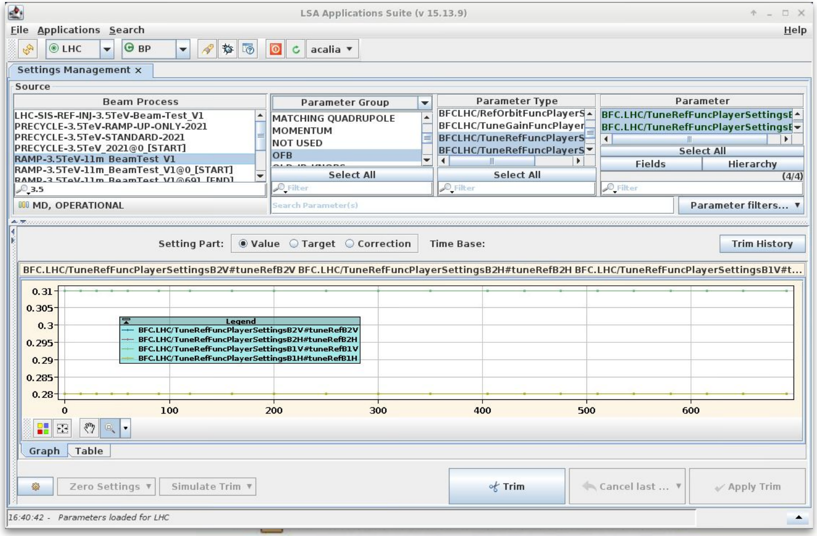
[1] TESTING FRAMEWORK FOR THE LHC BEAM-BASED FEEDBACK SYSTEM (S. Jackson et al.)

HW & FESA API renovation

- New features
  - Function-driven behavior
  - Reimplemented optics (twiss) handling
  - Faster and parallelized Response Matrices calculations
  - Better integration with LHC control system
- Studies and prototypes (*L. Grech et al.*)
  - “Feasibility of Hardware Acceleration in the LHC Orbit Feedback Controller”
  - “An Alternative Processing Algorithm for the Tune Measurement System in the LHC”
  - “A Machine Learning Approach for the Tune Estimation in the LHC”

Operational-side improvements

- Settings were a bit spread out ...
  - ○ LSA, Sequences and BFC init values
  - ○ Confusion & inconsistencies
- Consolidation and simplification
  - ✓ LSA as source of truth
    - ■ Make Rules & Value Generators
  - ✓ References from operational settings
    - ■ Orbit ref. from BPM ref.
    - ■ Tune ref. from new *TUNE_TARGET* knob
- Nominal operations via LHC Sequencer



Beam Process:
LHC-SIS-REF-INJ-3.5TeV-Beam-Test_V1
PRECYCLE-3.5TeV-RAMP-UP-ONLY-2021
PRECYCLE-3.5TeV-STANDARD-2021
PRECYCLE-3.5TeV_2021@0_[START]
RAMP-3.5TeV-11m_BeamTest_V1
RAMP-3.5TeV-11m_BeamTest_V1@0_[START]
RAMP-3.5TeV-11m_BeamTest_V1@691_[END]
3.5
MD, OPERATIONAL

Parameter Group:
MATCHING QUADRUPOLE
MOMENTUM
NOT USED
OFB

Parameter Type:
BFCLHC/RefOrbitFuncPlayerS
BFCLHC/TuneGainFuncPlayer
BFCLHC/TuneRefFuncPlayerS
BFCLHC/TuneRefFuncPlayerS

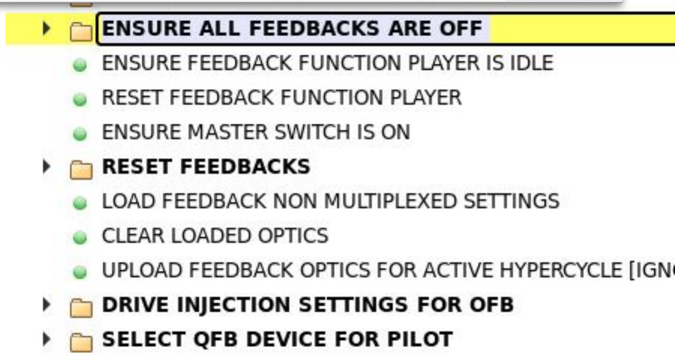
Parameter:
BFC.LHC/TuneRefFuncPlayerSettingsE
BFC.LHC/TuneRefFuncPlayerSettingsE

Setting Part: ● Value ○ Target ○ Correction Time Base:

BFC.LHC/TuneRefFuncPlayerSettingsB2V#tuneRefB2V BFC.LHC/TuneRefFuncPlayerSettingsB2H#tuneRefB2H BFC.LHC/TuneRefFuncPlayerSettingsB1V#t...

BFC.LHC/TuneRefFuncPlayerSettingsB2V#tuneRefB2V
BFC.LHC/TuneRefFuncPlayerSettingsB2H#tuneRefB2H
BFC.LHC/TuneRefFuncPlayerSettingsB1V#tuneRefB1V
BFC.LHC/TuneRefFuncPlayerSettingsB1H#tuneRefB1H

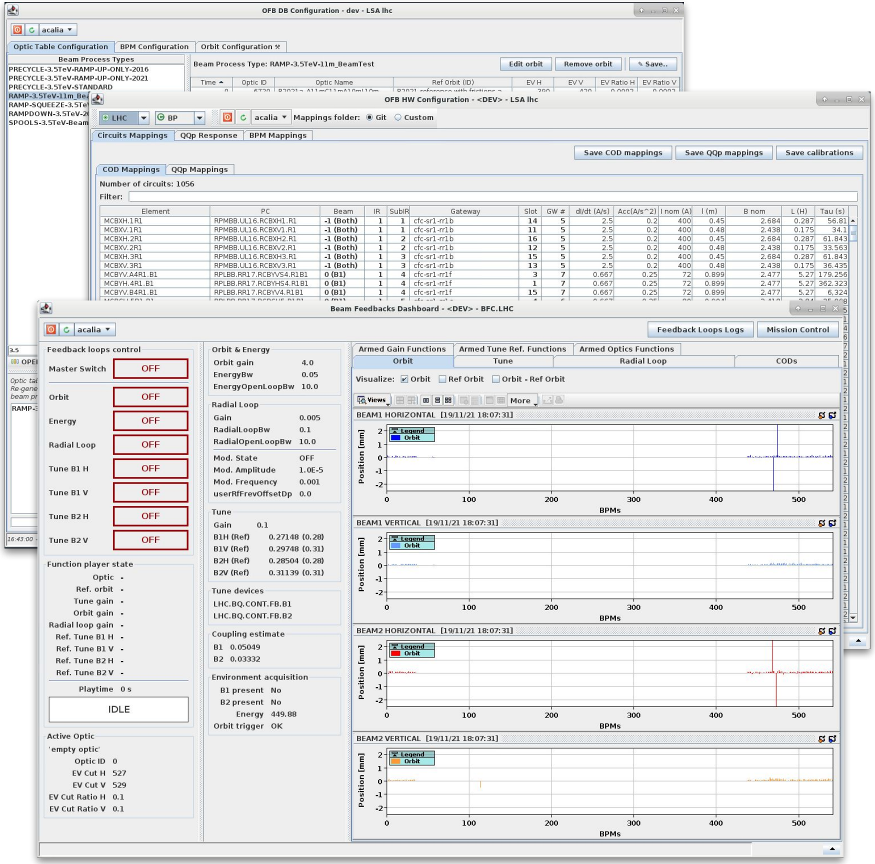
16:40:42 - Parameters loaded for LHC



ENSURE ALL FEEDBACKS ARE OFF
ENSURE FEEDBACK FUNCTION PLAYER IS IDLE
RESET FEEDBACK FUNCTION PLAYER
ENSURE MASTER SWITCH IS ON
RESET FEEDBACKS
LOAD FEEDBACK NON MULTIPLEXED SETTINGS
CLEAR LOADED OPTICS
UPLOAD FEEDBACK OPTICS FOR ACTIVE HYPERCYCLE [IGN
DRIVE INJECTION SETTINGS FOR OFB
SELECT QFB DEVICE FOR PILOT

Operational-side improvements

- Operational apps & projects zoo …
  - Requirements evolved with experience
- New & heavily refactored apps
  - ✓ HW Configuration app
    - Mapping files & Tune RM generation
  - ✓ DB Configuration app
    - LSA Trims, Optic & Ref. Orbit management
  - ✓ Dashboard & Expert GUI
    - Dashboards & tools for MDs/commissioning
- Simplified YASP-OFB integration



OFB DB Configuration - dev - LSA lhc

Optic Table Configuration | BPM Configuration | Orbit Configuration

Beam Process Types: PRECYCLE-3.5TeV-RAMP-UP-ONLY-2016, PRECYCLE-3.5TeV-RAMP-UP-ONLY-2021, PRECYCLE-3.5TeV-STANDARD, RAMP-3.5TeV-11m_Bea…, RAMP-SQUEEZE-3.5Te…, RAMPDOWN-3.5TeV-2…, SPOOLS-3.5TeV-Beam…

Beam Process Type: RAMP-3.5TeV-11m_BeamTest

Time	Optic ID	Optic Name	Ref Orbit (ID)	EV H	EV V	EV Ratio H	EV Ratio V

OFB HW Configuration - <DEV> - LSA lhc

LHC | BP | acalia | Mappings folder: ● Git ○ Custom

Circuits Mappings | QQp Response | BPM Mappings

COD Mappings | QQp Mappings

Number of circuits: 1056

Filter:

Element	PC	Beam	IR	SubIR	Gateway	Slot	GW #	dI/dt (A/s)	Acc(A/s^2)	I nom (A)	I (m)	B nom	L (H)	Tau (s)
MCBXH.1R1	RPMBB.UL16.RCBXH1.R1	-1 (Both)	1	1	cfc-sr1-rr1b	14	5	2.5	0.2	400	0.45	2.684	0.287	56.81
MCBXV.1R1	RPMBB.UL16.RCBXV1.R1	-1 (Both)	1	1	cfc-sr1-rr1b	11	5	2.5	0.2	400	0.48	2.438	0.175	34.1
MCBXH.2R1	RPMBB.UL16.RCBXH2.R1	-1 (Both)	1	2	cfc-sr1-rr1b	16	5	2.5	0.2	400	0.45	2.684	0.287	61.843
MCBXV.2R1	RPMBB.UL16.RCBXV2.R1	-1 (Both)	1	2	cfc-sr1-rr1b	12	5	2.5	0.2	400	0.48	2.438	0.175	33.563
MCBXH.3R1	RPMBB.UL16.RCBXH3.R1	-1 (Both)	1	3	cfc-sr1-rr1b	15	5	2.5	0.2	400	0.45	2.684	0.287	61.843
MCBXV.3R1	RPMBB.UL16.RCBXV3.R1	-1 (Both)	1	3	cfc-sr1-rr1b	13	5	2.5	0.2	400	0.48	2.438	0.175	36.435
MCBYV.A4R1.B1	RPLBB.RR17.RCBYVS4.R1B1	0 (B1)	1	4	cfc-sr1-rr1f	3	7	0.667	0.25	72	0.899	2.477	5.27	179.256
MCBYH.4R1.B1	RPLBB.RR17.RCBYHS4.R1B1	0 (B1)	1	4	cfc-sr1-rr1f	1	7	0.667	0.25	72	0.899	2.477	5.27	362.323
MCBYV.B4R1.B1	RPLBB.RR17.RCBYV4.R1B1	0 (B1)	1	4	cfc-sr1-rr1f	15	7	0.667	0.25	72	0.899	2.477	5.27	6,324

Beam Feedbacks Dashboard - <DEV> - BFC.LHC

Feedback loops control

Master Switch	OFF
Orbit	OFF
Energy	OFF
Radial Loop	OFF
Tune B1 H	OFF
Tune B1 V	OFF
Tune B2 H	OFF
Tune B2 V	OFF

Function player state

Optic	-
Ref. orbit	-
Tune gain	-
Orbit gain	-
Radial loop gain	-
Ref. Tune B1 H	-
Ref. Tune B1 V	-
Ref. Tune B2 H	-
Ref. Tune B2 V	-
Playtime	0 s

IDLE

Active Optic

'empty optic'

Optic ID	0
EV Cut H	527
EV Cut V	529
EV Cut Ratio H	0.1
EV Cut Ratio V	0.1

Orbit & Energy

Orbit gain	4.0
EnergyBw	0.05
EnergyOpenLoopBw	10.0

Radial Loop

Gain	0.005
RadialLoopBw	0.1
RadialOpenLoopBw	10.0
Mod. State	OFF
Mod. Amplitude	1.0E-5
Mod. Frequency	0.001
userRfFrevOffsetDp	0.0

Tune

Gain	0.1
B1H (Ref)	0.27148 (0.28)
B1V (Ref)	0.29748 (0.31)
B2H (Ref)	0.28504 (0.28)
B2V (Ref)	0.31139 (0.31)

Tune devices

LHC.BQ.CONT.FB.B1
LHC.BQ.CONT.FB.B2

Coupling estimate

B1	0.05049
B2	0.03332

Environment acquisition

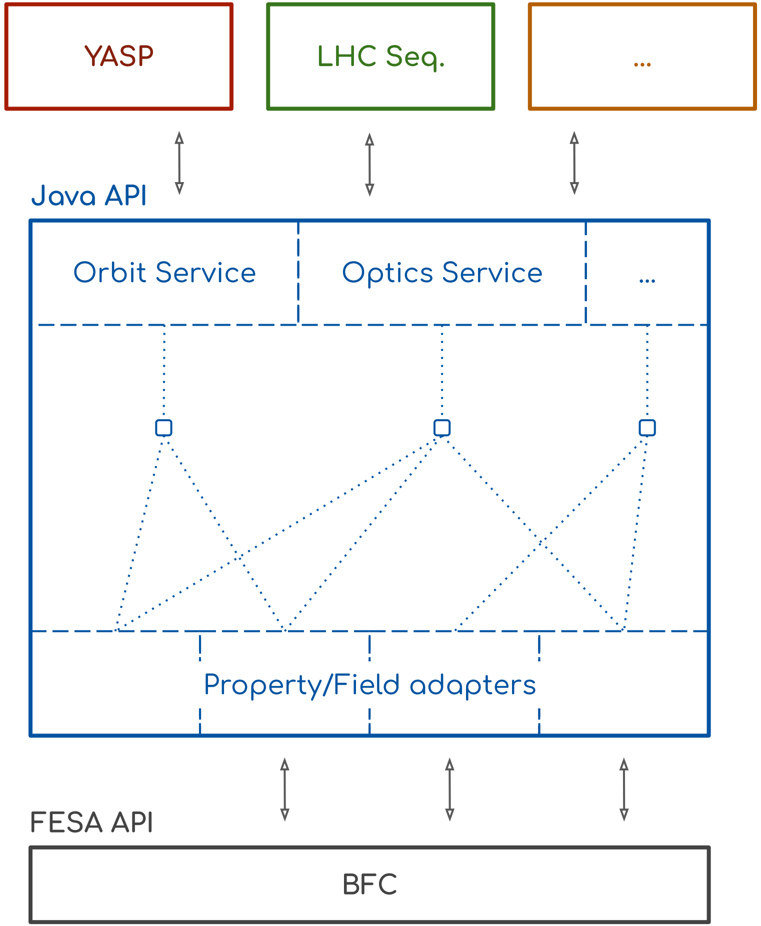
B1 present	No
B2 present	No
Energy	449.88
Orbit trigger	OK

Visualize: ☑ Orbit □ Ref Orbit □ Orbit - Ref Orbit

OP API renovation

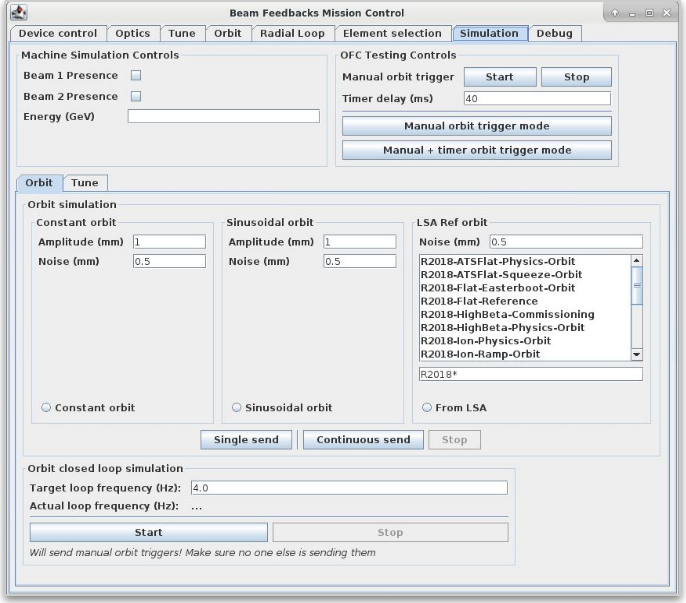
- Java API on top of BFC FESA class
  - Integration with CCC ecosystem
  - Ensure correct usage of FESA API
  - Move complexity away from apps

    E.g. LHC Seq. agent from 3k+ loc to ~600
  - Flexible abstraction layer for OP
- Extends BFC API
  - *E.g. “load LSA orbit as reference”*
- Opens the door to testing
  - New specific testing framework



Automatic testing

- Goals
  - ➜ Peace of mind when refactoring
  - ➜ Reduce commissioning time
  - ➜ Requirement validation
  - ➜ Encourage “good programming practices”
- Reproducible environment
  - ○ Gitlab CI
  - ○ Testbed machine in simulation
- Closed loop simulation tests
  - ○ Behavior verification (“*Does it converge?*”)



Beam Feedbacks Mission Control

Machine Simulation Controls

Beam 1 Presence □

Beam 2 Presence □

Energy (GeV)

OFC Testing Controls

Timer delay (ms): 40

Orbit simulation

Constant orbit

Amplitude (mm): 1

Noise (mm): 0.5

○ Constant orbit

Sinusoidal orbit

Amplitude (mm): 1

Noise (mm): 0.5

○ Sinusoidal orbit

LSA Ref orbit

Noise (mm): 0.5

R2018-ATSFlat-Physics-Orbit
R2018-ATSFlat-Squeeze-Orbit
R2018-Flat-Easterboot-Orbit
R2018-Flat-Reference
R2018-HighBeta-Commissioning
R2018-HighBeta-Physics-Orbit
R2018-Ion-Physics-Orbit
R2018-Ion-Ramp-Orbit

R2018*

○ From LSA

Orbit closed loop simulation

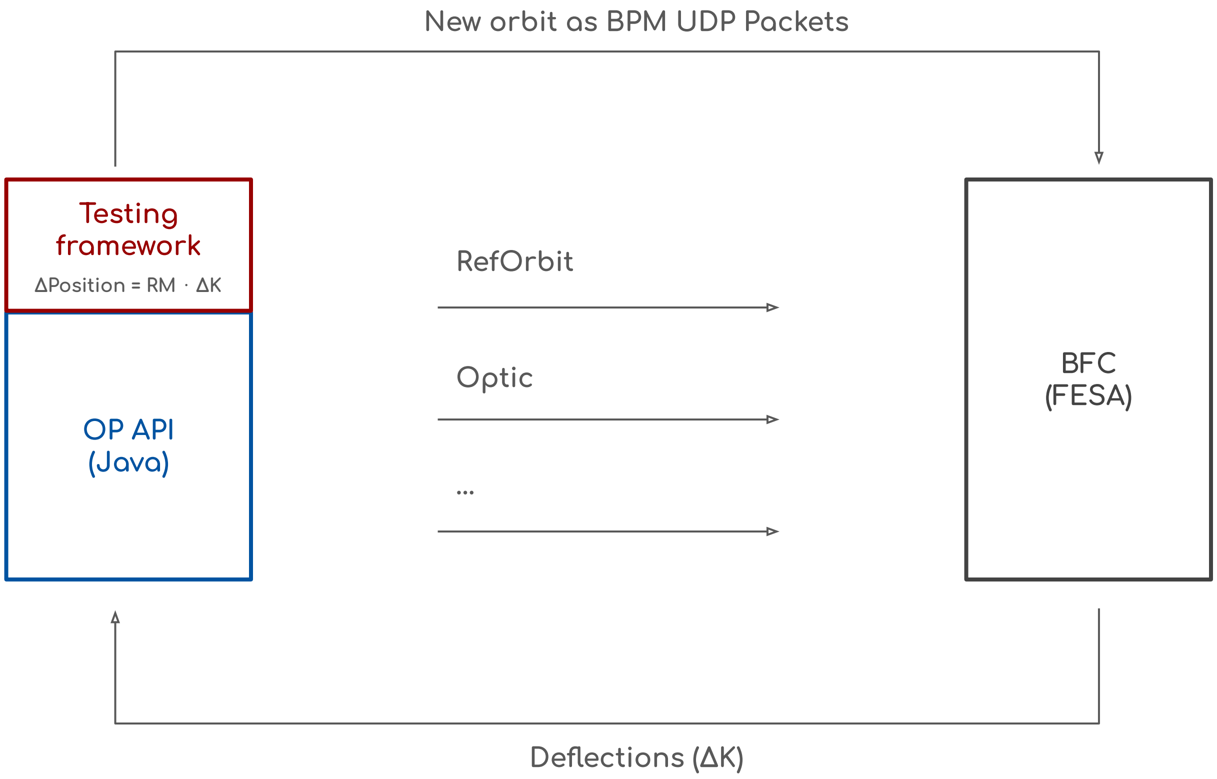
Target loop frequency (Hz): 4.0

Actual loop frequency (Hz): ...

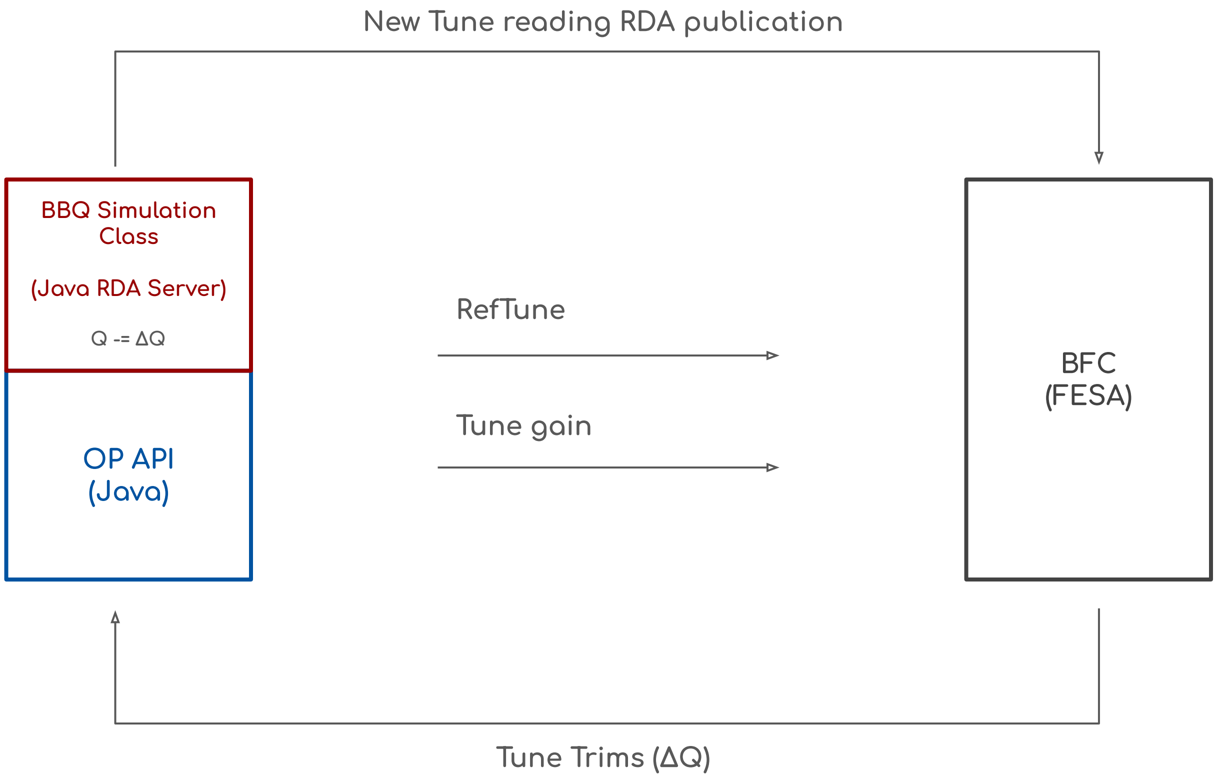
Will send manual orbit triggers! Make sure no one else is sending them

```
@Test
public void whenRunning_sendingPauseAndResume_shouldPauseAndResume() {
   ensureRunningFor(Duration.ofSeconds(15), () -> {
        sendFunctionPlayerEvent(PAUSE);
        awaitState(functionPlayerState(), PAUSED);
        sendFunctionPlayerEvent(RESUME);
        awaitState(functionPlayerState(), RUNNING);
   });
}
```

Orbit closed loop simulation

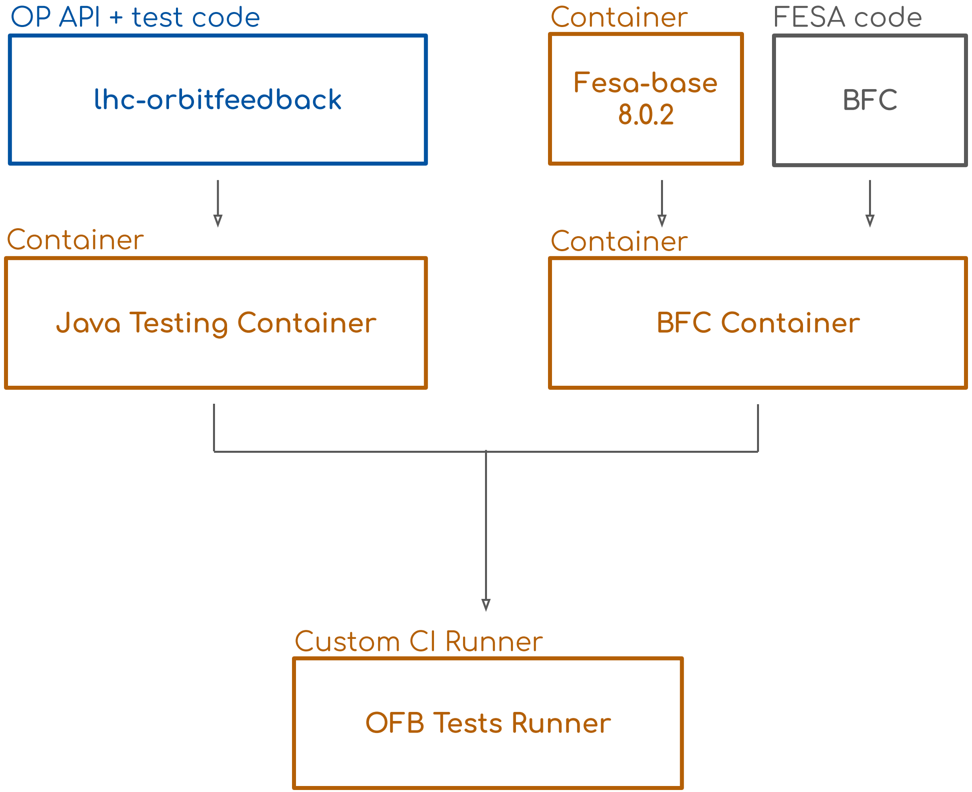


Tune closed loop simulation



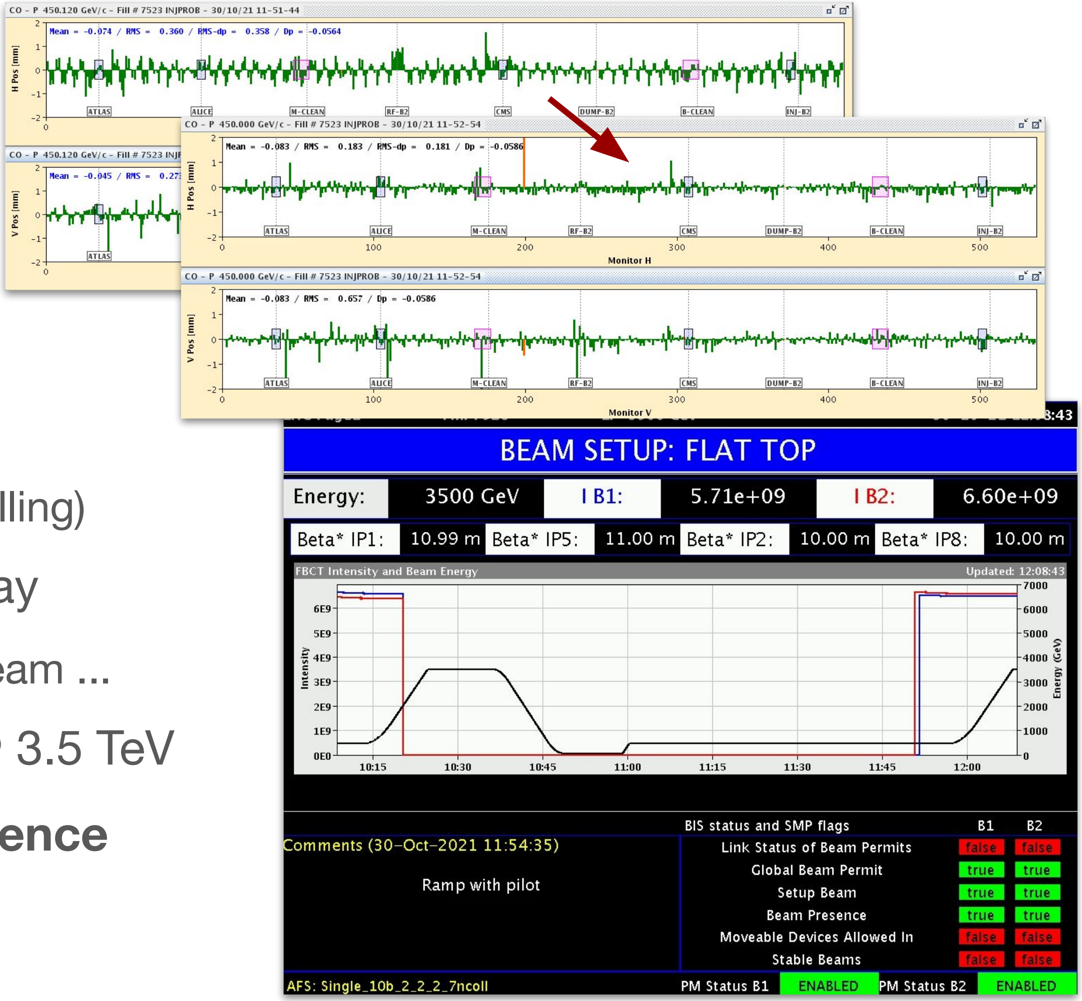
Continuous integration

- Automatic full-stack validation
  - Run on commit and daily
  - Based on Gitlab CI Pipelines
  - Currently ~100 unit tests
  - Report in case of errors
- Detailed history of issues
  - *“This happened before… ”*
- Better development cycle
  - *“It worked on my machine… ”*



Beam test results

- Successfully commissioned !
  - ✓ New BFC FESA class
  - ✓ OP API + applications
  - ✓ LSA settings + sequencer tasks
  - ✓ Trim orchestration (e.g. lumi levelling)
- Some issues ironed out on the way
  - ○ Mostly only discoverable with beam ...
- Excellent behavior during ramp @ 3.5 TeV
- **Invaluable feedback and experience**
  - ➜ Smooth start of Run3


CO - P 450.120 GeV/c - Fill # 7523 INJPROB - 30/10/21 11-51-44
Mean = -0.074 / RMS = 0.360 / RMS-dp = 0.358 / Dp = -0.0564
H Pos [mm]
CO - P 450.120 GeV/c - Fill # 7523 INJP
Mean = -0.045 / RMS = 0.27
V Pos [mm]
CO - P 450.000 GeV/c - Fill # 7523 INJPROB - 30/10/21 11-52-54
Mean = -0.083 / RMS = 0.183 / RMS-dp = 0.181 / Dp = -0.0586
H Pos [mm]
Monitor H
CO - P 450.000 GeV/c - Fill # 7523 INJPROB - 30/10/21 11-52-54
Mean = -0.083 / RMS = 0.657 / Dp = -0.0586
V Pos [mm]
Monitor V
ATLAS
ALICE
M-CLEAN
RF-B2
CMS
DUMP-B2
B-CLEAN
INJ-B2
2
1
0
-1
-2
0
100
200
300
400
500
FBCT Intensity and Beam Energy
Updated: 12:08:43
Intensity
Energy (GeV)
6E9
5E9
4E9
3E9
2E9
1E9
0E0
7000
6000
5000
4000
3000
2000
1000
0
10:15
10:30
10:45
11:00
11:15
11:30
11:45
12:00

BEAM SETUP: FLAT TOP

Energy:	3500 GeV	I B1:	5.71e+09	I B2:	6.60e+09

Beta* IP1:	10.99 m	Beta* IP5:	11.00 m	Beta* IP2:	10.00 m	Beta* IP8:	10.00 m

Comments (30-Oct-2021 11:54:35)

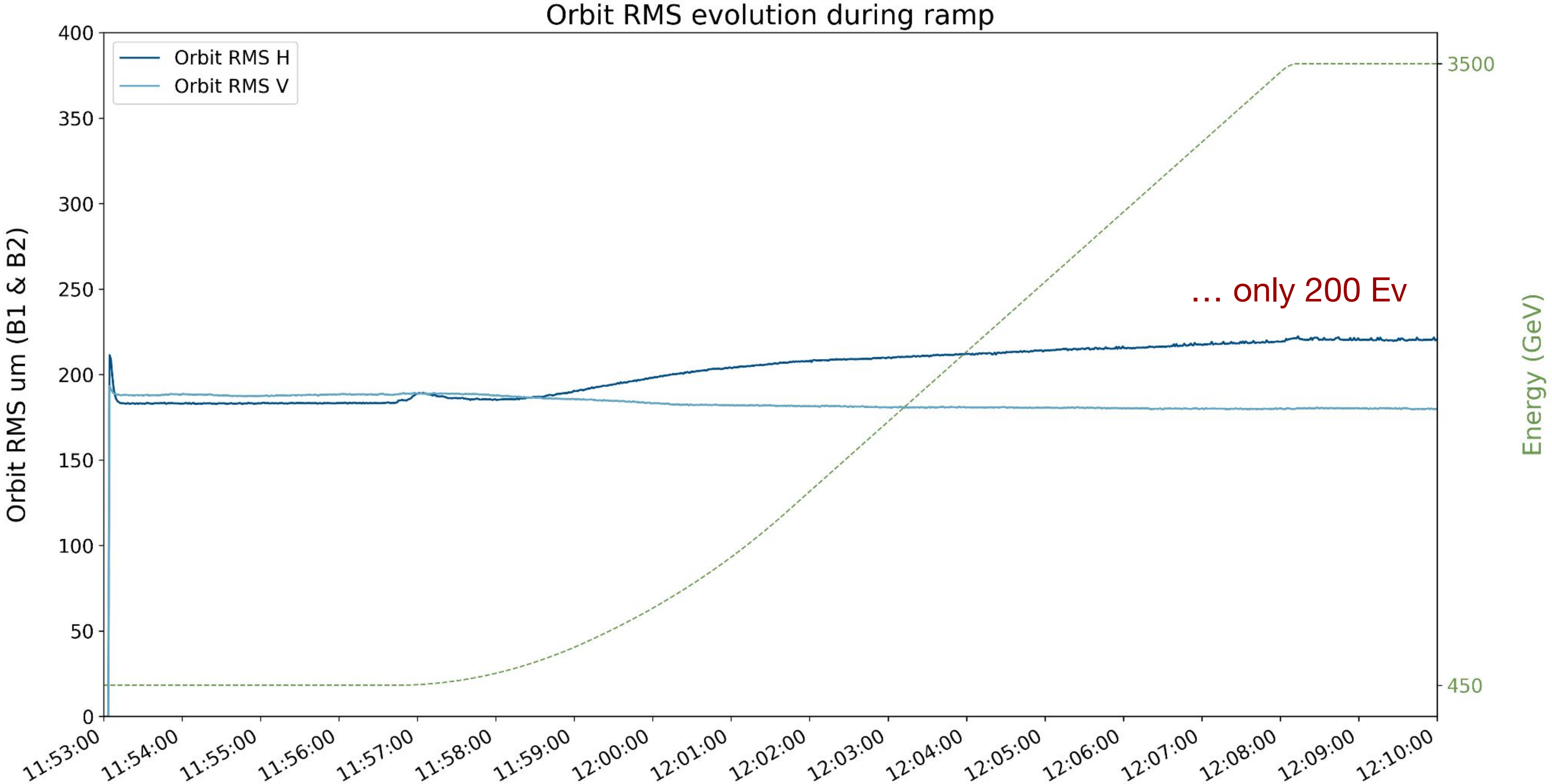
Ramp with pilot

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: Single_10b_2_2_2_7ncoll

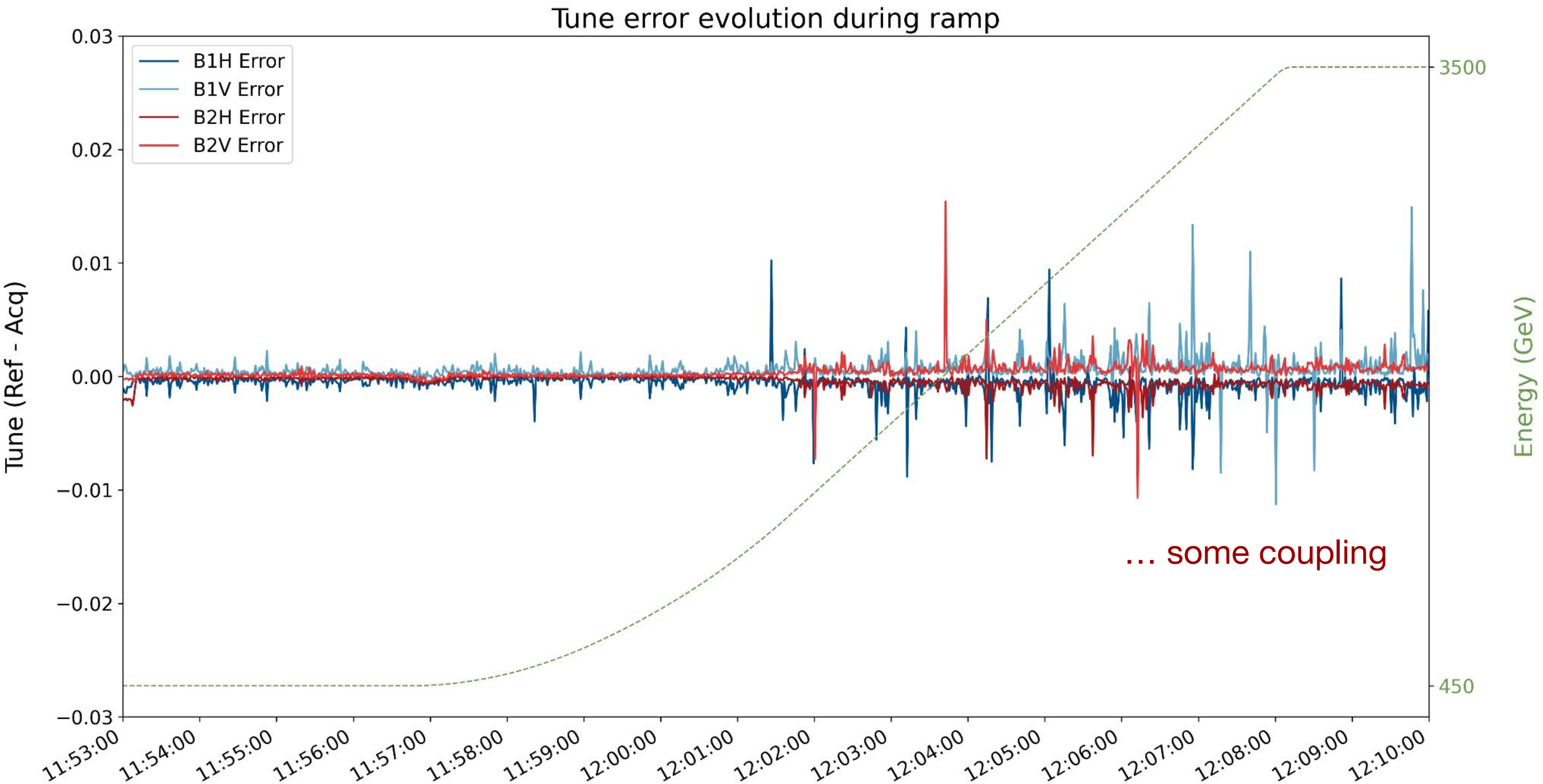
PM Status B1 ENABLED PM Status B2 ENABLED

Beam test results



… only 200 Ev

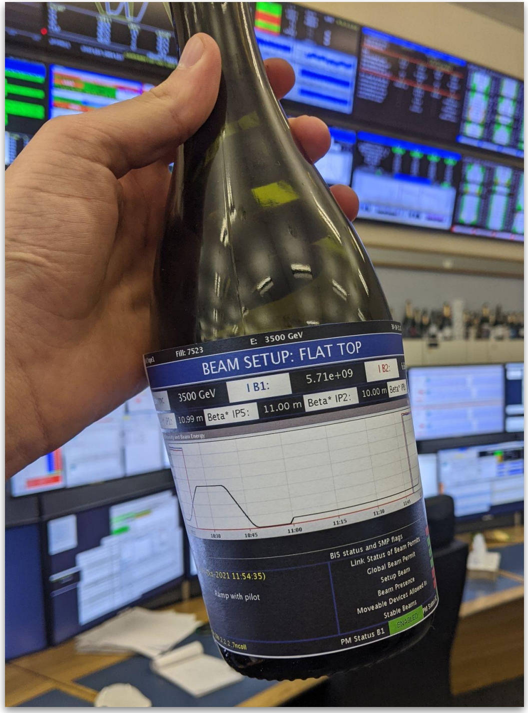
Beam test results



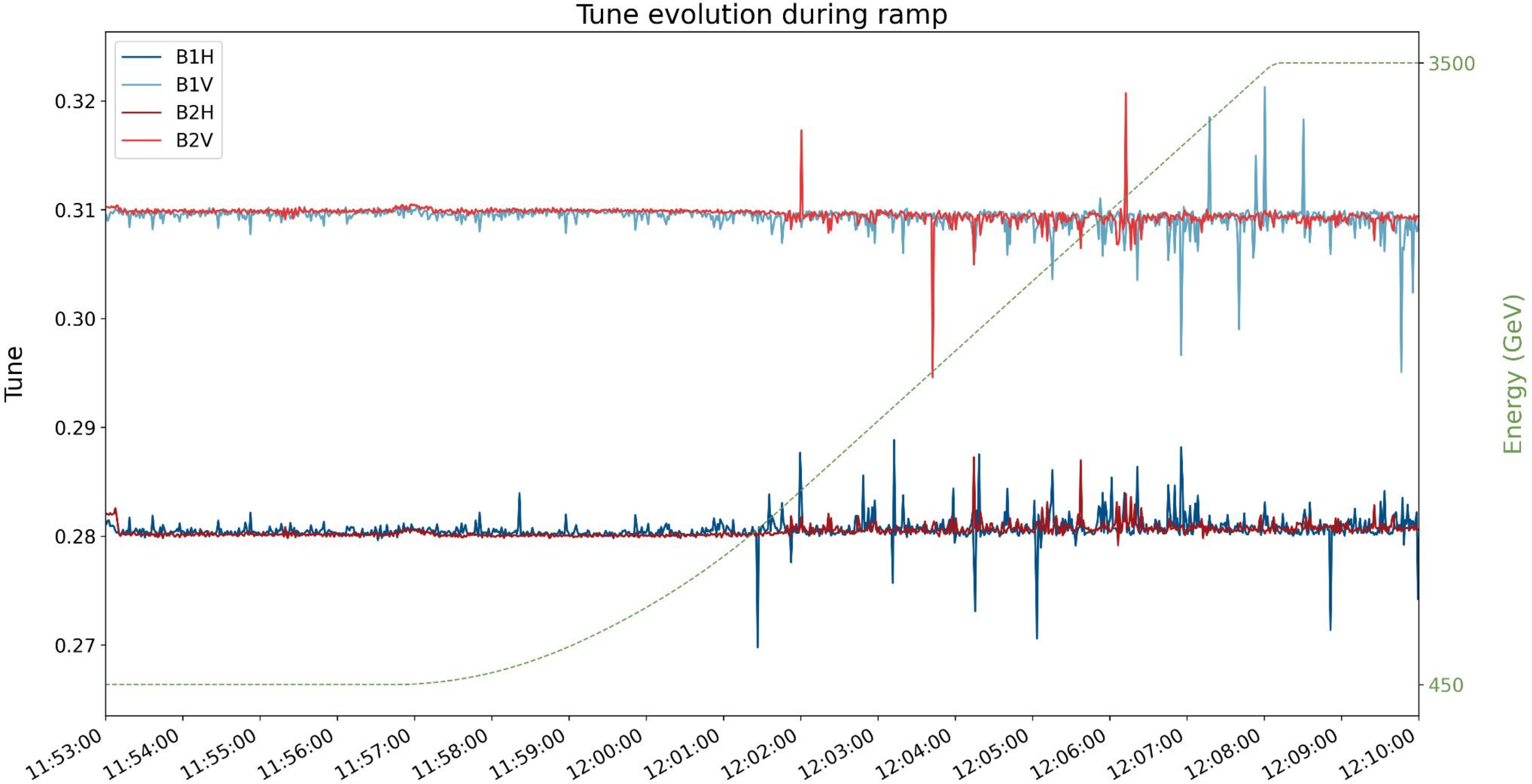
… some coupling

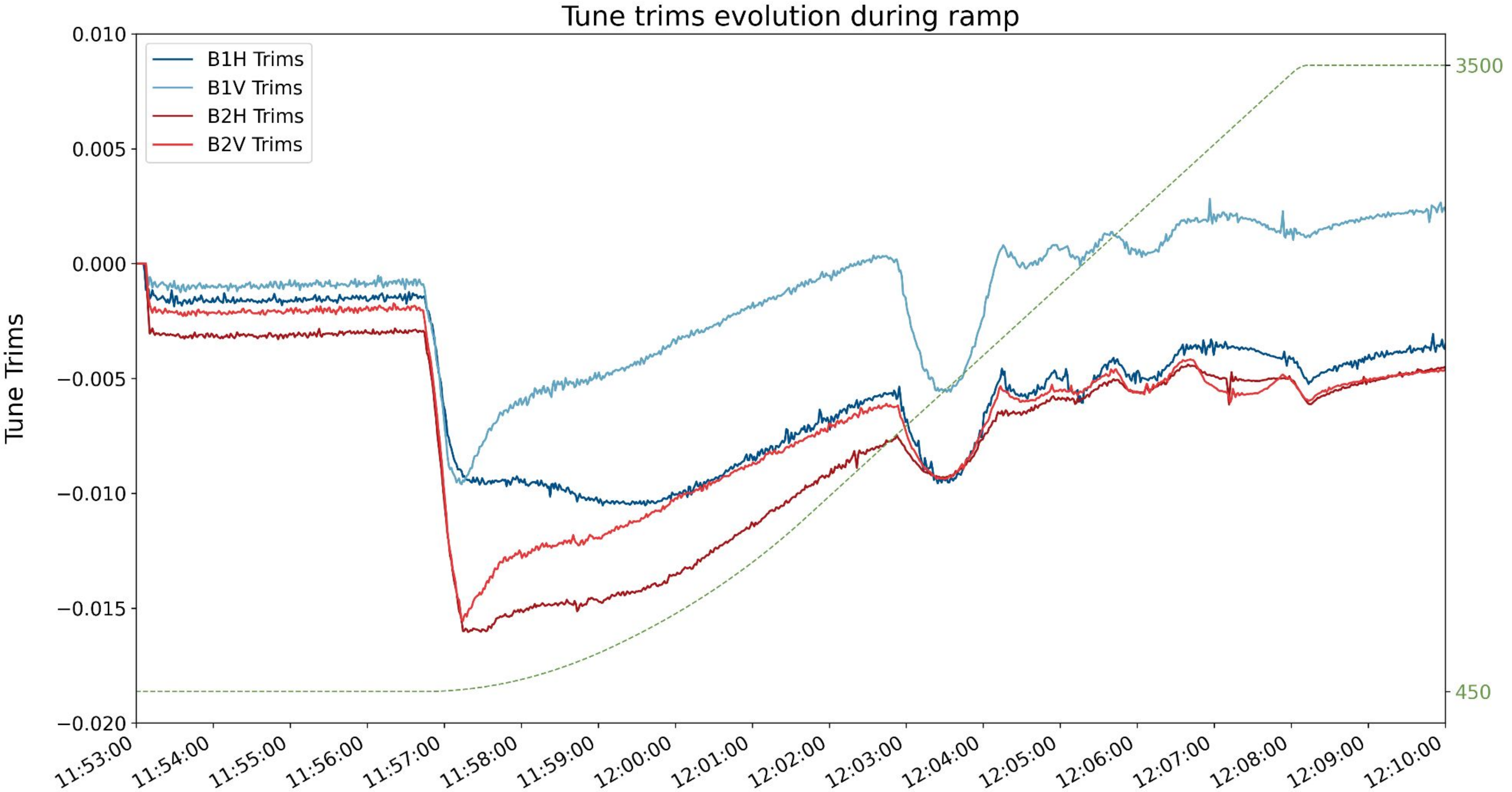
Conclusions

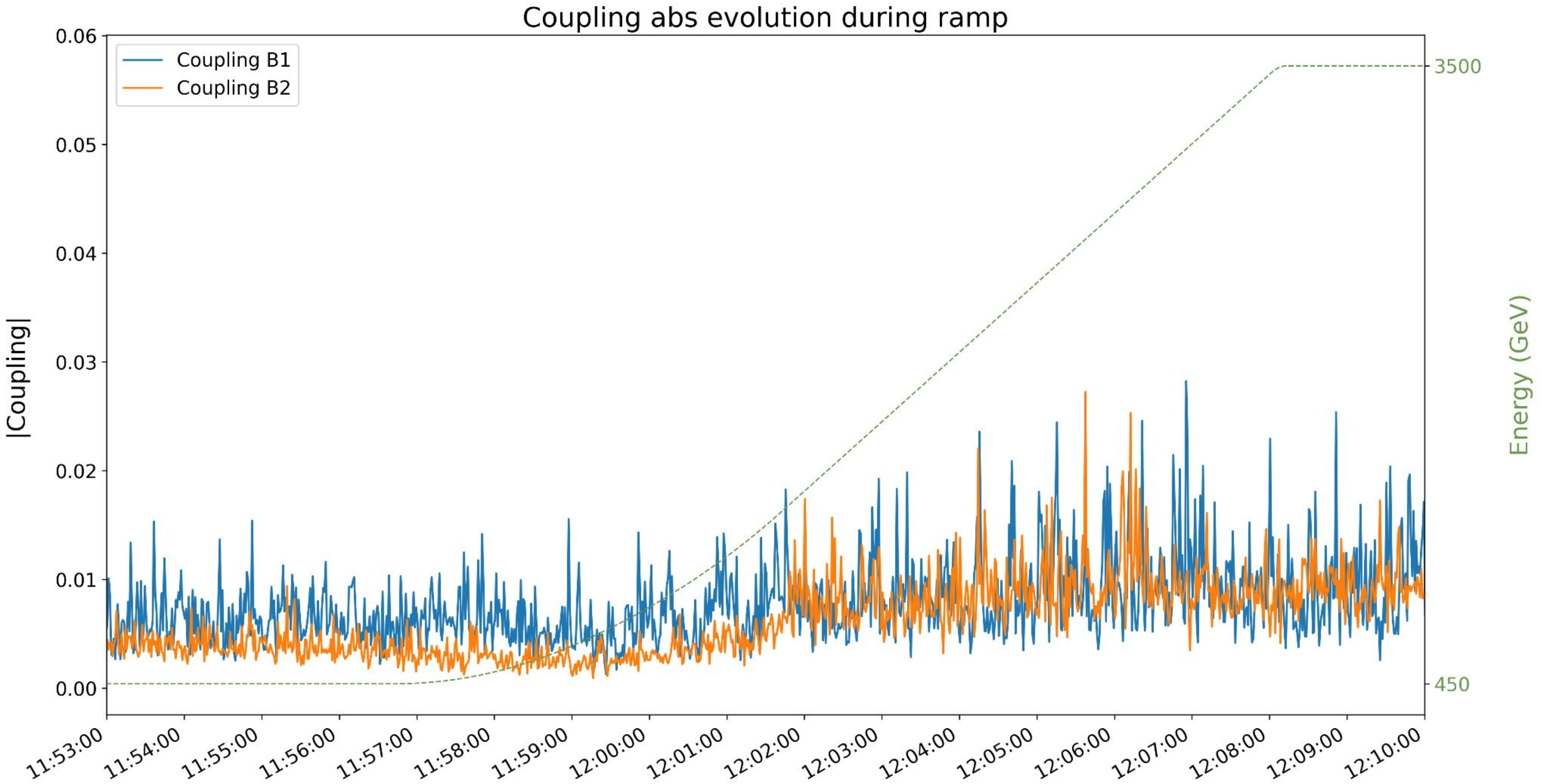
- Beam test was very important !
  - Minor issues fixed
  - Invaluable feedback
  - Significant head-start for 2022
- Success recipe
  - **Collaborations** & synergies are paramount
  - **Testing** & simulation are a MUST
  - Embrace change & **best-practices**
- No impact of 1-year extension of Run3

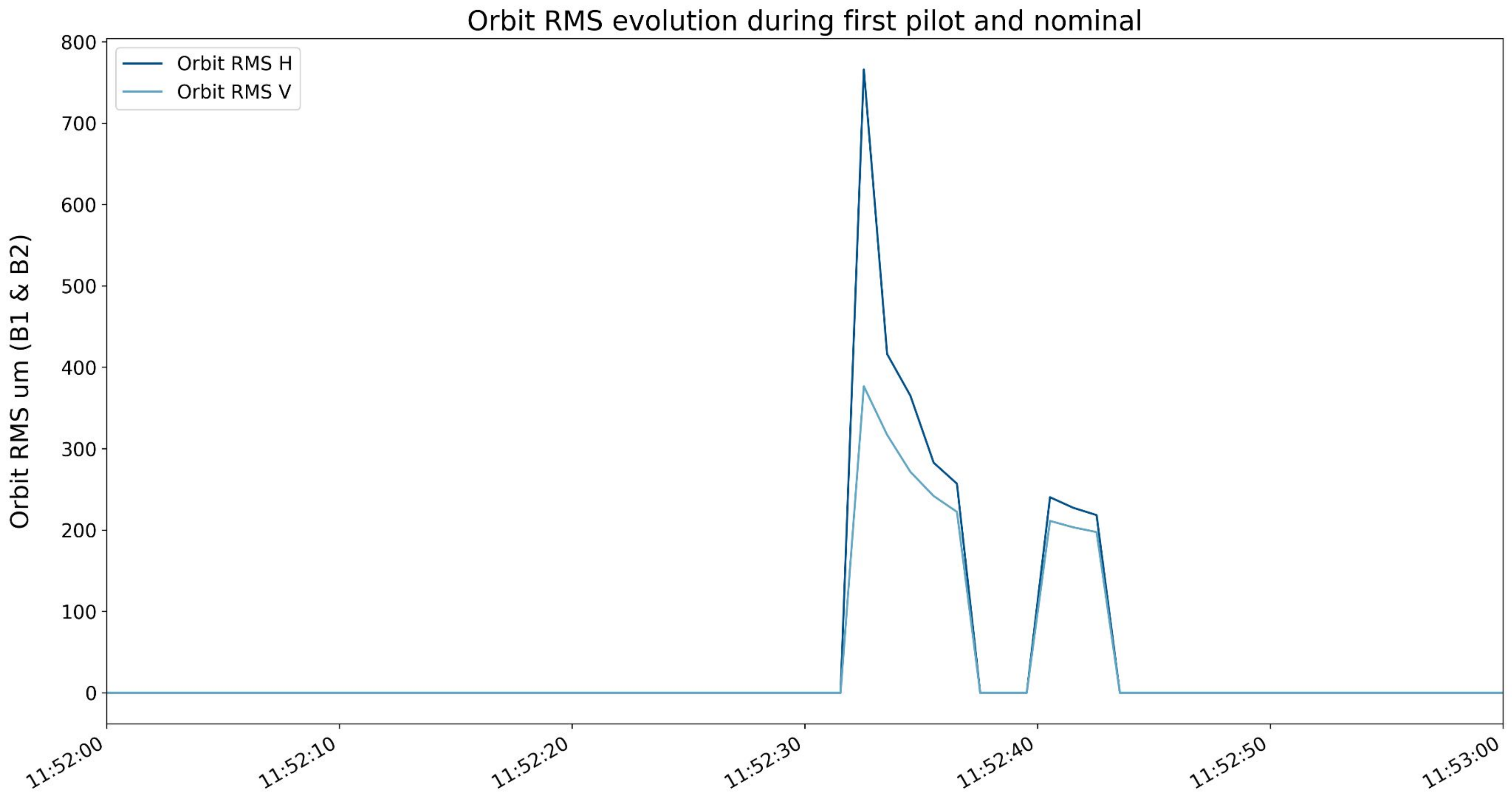


Extra

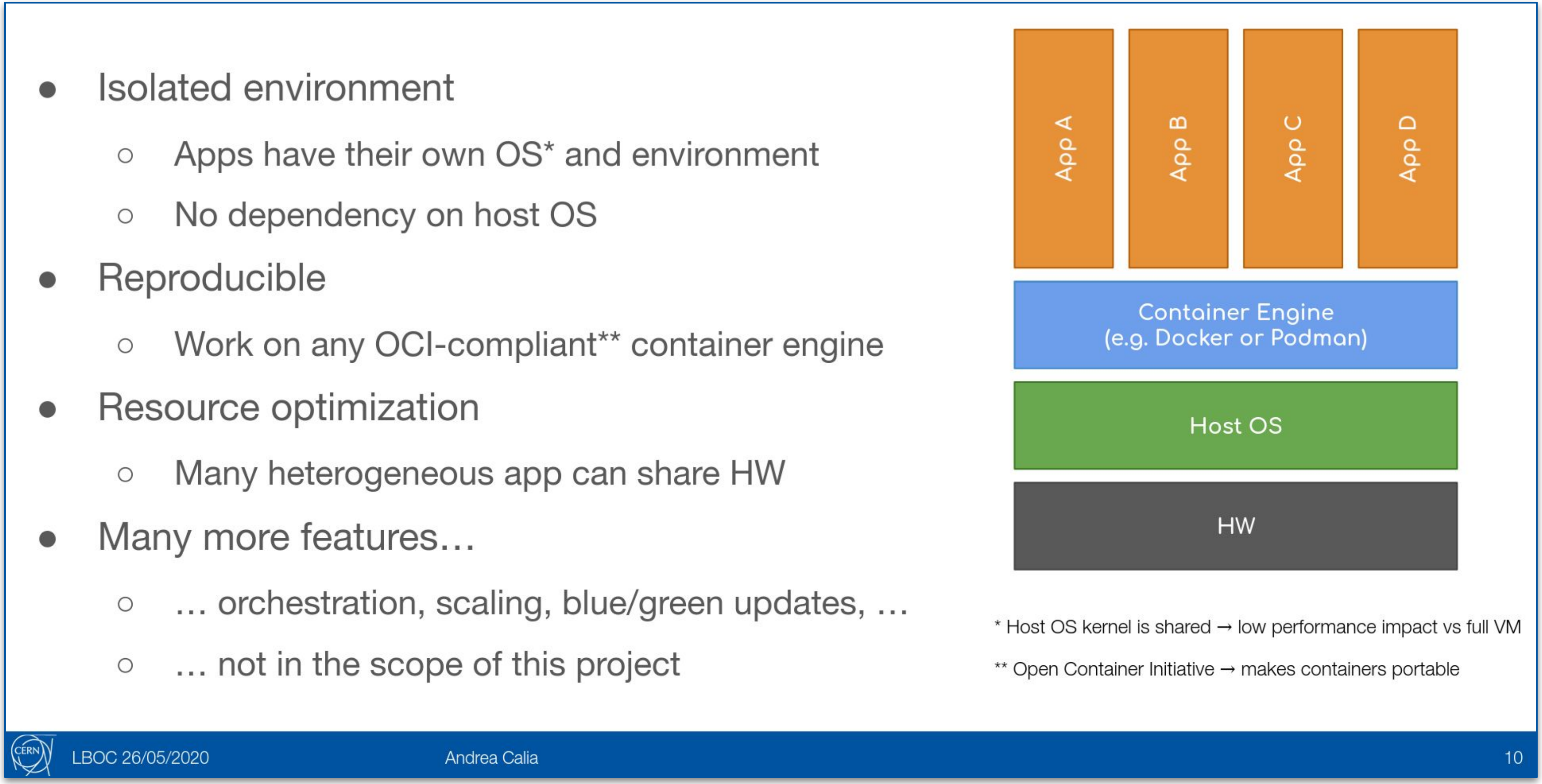

Tune evolution during ramp
B1H
B1V
B2H
B2V
Tune
0.32
0.31
0.30
0.29
0.28
0.27
Energy (GeV)
3500
450
11:53:00
11:54:00
11:55:00
11:56:00
11:57:00
11:58:00
11:59:00
12:00:00
12:01:00
12:02:00
12:03:00
12:04:00
12:05:00
12:06:00
12:07:00
12:08:00
12:09:00
12:10:00


Tune trims evolution during ramp
Tune Trims
Energy (GeV)
B1H Trims
B1V Trims
B2H Trims
B2V Trims
0.010
0.005
0.000
−0.005
−0.010
−0.015
−0.020
3500
450
11:53:00
11:54:00
11:55:00
11:56:00
11:57:00
11:58:00
11:59:00
12:00:00
12:01:00
12:02:00
12:03:00
12:04:00
12:05:00
12:06:00
12:07:00
12:08:00
12:09:00
12:10:00


Coupling abs evolution during ramp
Coupling B1
Coupling B2
|Coupling|
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Energy (GeV)
3500
450
11:53:00
11:54:00
11:55:00
11:56:00
11:57:00
11:58:00
11:59:00
12:00:00
12:01:00
12:02:00
12:03:00
12:04:00
12:05:00
12:06:00
12:07:00
12:08:00
12:09:00
12:10:00


Orbit RMS evolution during first pilot and nominal
Orbit RMS H
Orbit RMS V
Orbit RMS um (B1 & B2)
800
700
600
500
400
300
200
100
0
11:52:00
11:52:10
11:52:20
11:52:30
11:52:40
11:52:50
11:53:00

Container ??



- Isolated environment
  - Apps have their own OS* and environment
  - No dependency on host OS
- Reproducible
  - Work on any OCI-compliant** container engine
- Resource optimization
  - Many heterogeneous app can share HW
- Many more features…
  - … orchestration, scaling, blue/green updates, …
  - … not in the scope of this project

App A
App B
App C
App D
Container Engine
(e.g. Docker or Podman)
Host OS
HW

* Host OS kernel is shared → low performance impact vs full VM

** Open Container Initiative → makes containers portable

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Another test example

```java
@Test
public void arm_validRefOrbitTimeEvolution_shouldPlay() {
   RefOrbitTimeEvolution refOrbitTimeEvolution = ...
   sendRefOrbitTimeEvolution(refOrbitTimeEvolution);
   ...
   sendFunctionPlayerEvent(ARM);
   awaitState(functionPlayerState(), ARMED);
   ...
   runWhileSendingOrbitTriggersEvery(Duration.ofMillis(80), () -> {
       sendFunctionPlayerEvent(TRIGGER);
       awaitState(functionPlayerState(), RUNNING);
       awaitState(functionPlayerState(), IDLE);
   });
   assertThat(referenceOrbit().get()).isEqualTo(refOrbitT2);
}
```

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