FCC-hh Instrumentation overview and challenges

L. Ponce on behalf of the Beam Instrumentation
for FCC-hh study team

Context

- First attempt to define observables and requirements to identify instruments where R&D will be needed
- Objective is to document the collected information at a level of details which will allow first cost estimate and present Spring 2018
- Status of the study presented tomorrow by H. Schmickler

Outline

- Reminder of the main FCC-hh parameters relevant for instrumentation
- LHC-like beam operation schedule and scenarios
- Definition of SAFE beam for FCC-hh
- Review of instrumentation specifications

Beam parameters

	(HL)-LHC	FCC-hh baseline	FCC-hh ultimate
Collision energy [TeV]	14	100	100
Dipole field [T]	8.3	16	
Luminosity L [10^34 cm^{-2}s^{-1}]	(5) 1	5	20-30
Normalized emittance [um]	(2.5) 3.5	2.2 (0.44)	
Bunch intensity [10^11]	(2.2) 1.15	1 (0.2)	
Bunch spacing [ns] (option)	25	25 (5)	
Beta* [m]	(0.15) 0.55	1.1	0.3
Number of bunch	2808	10400 (53000)	
IP beam size [um]	16.7	6.8 (3)	3.5 (1.6)
Rms bunch length [cm]		8	
Stored energy/beam [GJ]	(0.7) 0.36	8.4	
Synchrotron rad. [W/m/beam]	(0.35) 0.18	30	
Dipole coil aperture [mm]	56	50	

FCC Run Schedule

M. Benedikt, FCC week 2016

- 5 Year-long operation periods:
  - 3.5 years operation period with:
    - 1 year HW commissioning, MDs, short stops
    - 2.5 years lumi run with 70% availability
  - 1.5 year shutdown

- Commissioning with beam:
  - Full cycle setting up with low intensity => typ. 4 weeks for LHC
  - Intensity ramp-up (inc. scrubbing period) => couple of weeks for LHC

- Sequence to be repeated :
  - After long shutdown
  - After short stop
    - Shorter setup periods, mini intensity ramp-up (no scrubbing)
  - *After Machine Developments:*
    - *If not joined with a Short stop*

LHC-like Beam Operation

- Initial Beam Commissionning:
  - Beam threading, establish circulating beams
  - First cycle ramp/squeeze
  - Optics measurements and corrections, feedforward in functions

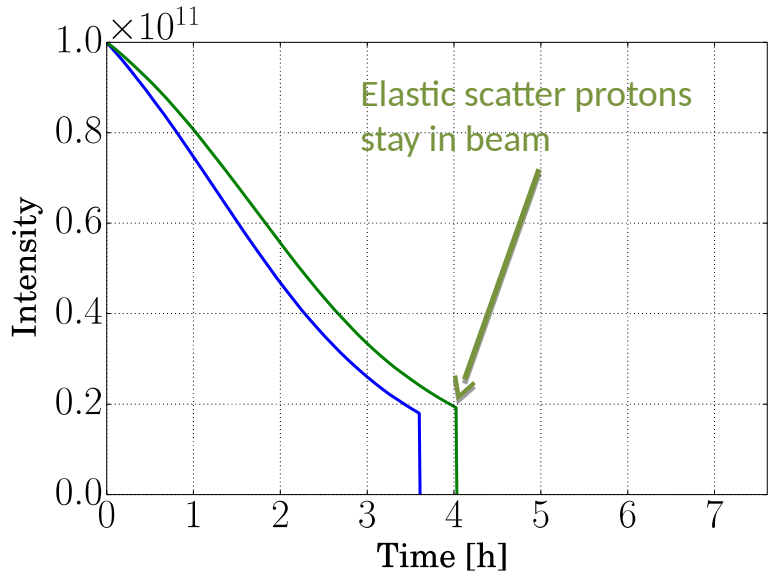
  => Single bunch, low intensity = PILOT BEAM
- With reference orbit established:
  - Collimators setting-up
  - Machine protection validation (injection, beam dump system, loss maps...)

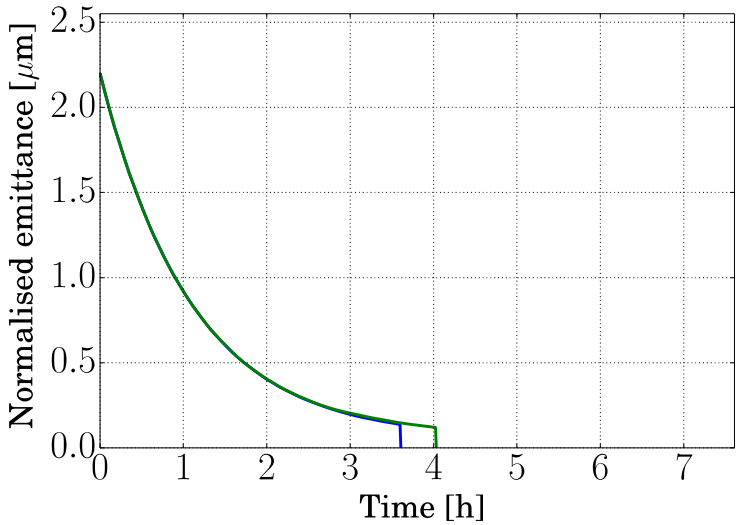
  => Single bunch, nominal bunch intensity = SETUP BEAMS

- Operation with nominal/ultimate beams:
  - Injection of trains
  - Intensity ramp up/ scrubbing
  - Feedback on tune, orbit, chromaticity…
  - Rest of the cycle rely on machine reproducibility

  => Monitoring of beam parameters evolution with different bunch patterns

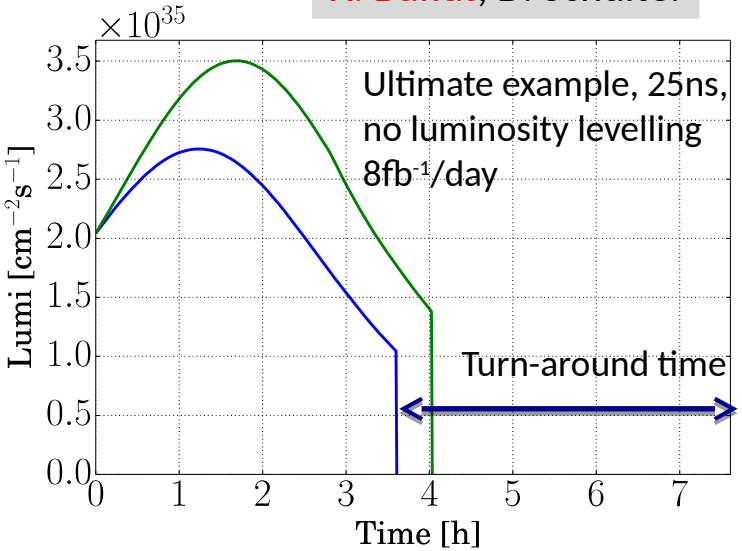
Parameters evolution during a fill



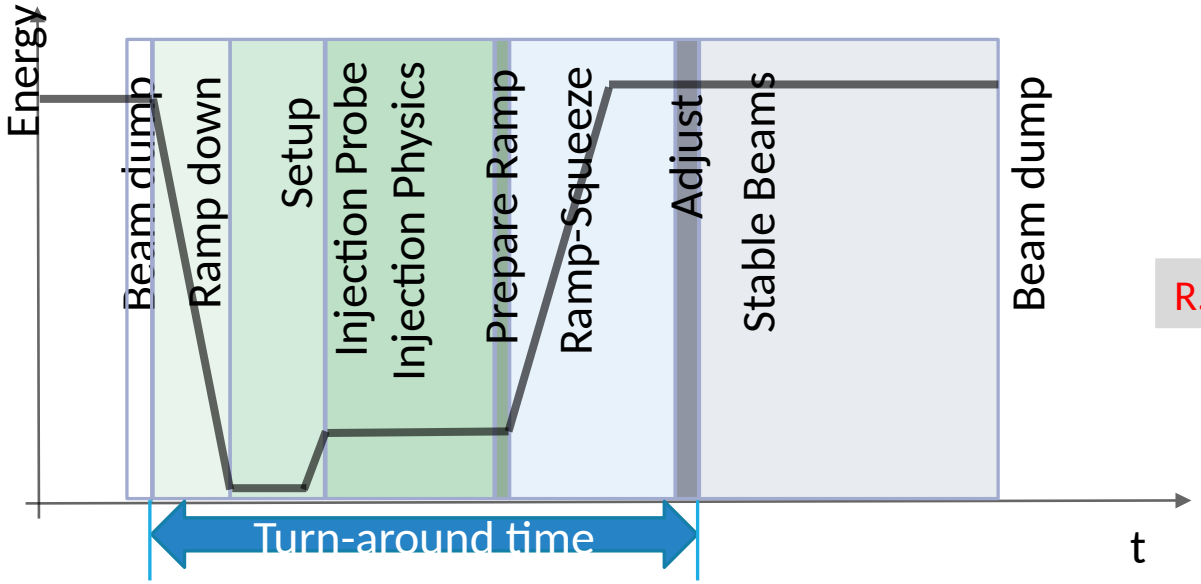


X. Buffat, D. Schulte.

- Intensity decrease by a factor 5 and emittance by a factor 10 (same equilibrium for 5 ns)
- Example with ultimate parameters shown
  - Turn-around time reduction crucial
  - Performant injection diagnostics (see talk from F. Buckart)



FCC Operationnal cycle



R. Alemany, FCC week 2016

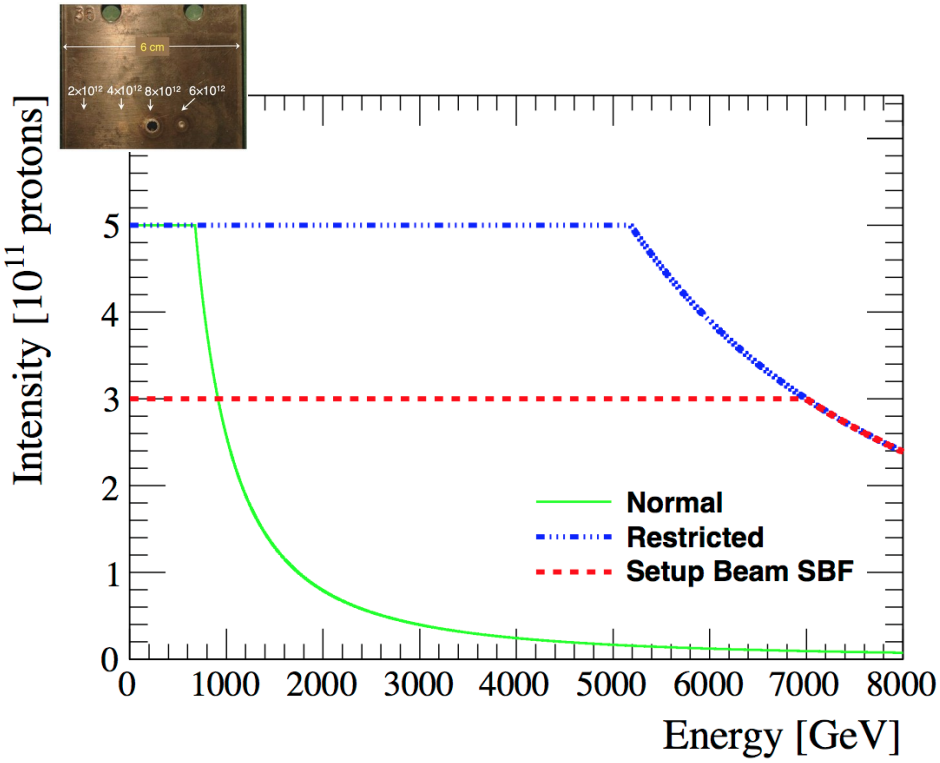
- LHC-like operational cycle:
  - Setting-up of the machine parameters with “pilot” beam at injection
  - Injection pf intermediate intensity (12 bunches in LHC) for machine protection
    - Never inject unsafe beam into an empty machine
  - Filling with physics beams (trains of nominal bunches)

  => within a cycle, switch of instrumentation sensitivity

- Total time highly dependent on injection phase length => high performance of diagnostics

Safe/Setup Beams definition

- Both LHC and SPS have a definition of “setup beam” considered as an intensity that can never harm any machine component
- For LHC, SETUP beam is 5e11 protons at 450 GeV and 1e10 at 7TeV



Safe Beams for FCC

Thanks to M.Zerlauth

- Study of the whole hadron complex at CERN:
  - Assuming injection energy 3.3 TeV, flat top of 50 TeV
  - Emittance 2.2 um, i.e. beam size of 0.1 mm at beta=100m

- Recommandation MPP:
  - Safe Beam in the order of 5e8 protons at 50 TeV and 1e10 protons for 3.3 TeV
  - i.e. comparable to current dynamic range of the LHC BPM system

- Setup of FCC beams can be done with such intensitites at flat top provided systematics ("pilot", nominal and train sensitivity) are less dominant than in LHC or at least deterministic

Melting of copper as f(E,ε)

TABLE IV. Number of protons and proton bunches needed to melt the copper target at the maximum energy deposition point as well as at the target front surface.

Energy [GeV]	RMS beam size [mm]	$n_{p,max}$	$N_{p,max}$	$n_{p,entrance}$	$N_{p,entrance}$
0.05	0.2	5.0×10^{11}	0.3	1.3×10^{12}	0.8
	0.4	1.2×10^{12}	0.8	5.1×10^{12}	3.2
	1.0	6.3×10^{12}	3.9	3.1×10^{13}	18.9
0.16	0.2	2.9×10^{12}	1.8	3.0×10^{12}	1.9
	0.4	1.1×10^{13}	6.7	1.2×10^{13}	7.5
	1.0	5.6×10^{13}	34.8	7.3×10^{13}	44.8
1.4	0.2	6.6×10^{12}	4.1	6.8×10^{12}	4.2
	0.4	2.5×10^{13}	15.5	2.5×10^{13}	15.5
	1.0	1.5×10^{14}	89.6	1.5×10^{14}	89.6
26	0.2	5.6×10^{12}	41.1	6.0×10^{12}	44.4
	0.4	2.0×10^{13}	147.2	2.2×10^{13}	159.8
	1.0	9.0×10^{13}	665.7	1.1×10^{14}	822.3
450	0.1	6.4×10^{11}	5.5	1.4×10^{12}	11.9
	0.2	1.1×10^{12}	9.4	5.0×10^{12}	43.8
	0.8	3.1×10^{12}	26.7	6.7×10^{13}	586.1
3300	0.1	4.6×10^{10}	0.5	1.4×10^{12}	13.7
	0.2	8.0×10^{10}	0.8	4.1×10^{12}	40.6
	0.4	1.5×10^{11}	1.5	1.3×10^{13}	134.8
7000	0.1	1.8×10^{10}	0.2	1.3×10^{12}	10.9
	0.2	3.3×10^{10}	0.3	4.1×10^{12}	35.7
	0.4	6.2×10^{10}	0.5	1.5×10^{13}	131.3
50000	0.1	1.9×10^{9}	0.02	8.3×10^{11}	8.3
	0.2	3.9×10^{9}	0.04	3.3×10^{12}	32.7
	0.4	7.5×10^{9}	0.07	1.2×10^{13}	120.2

➢ *Yuancun Nie, R. Schmidt, et al.: "Interaction of 50 MeV- 50 TeV protons with solid copper and graphite targets in hadron aceelerator complex at CERN"*

Expected range of beam parameters

- Nominal bunch: 1e11 proton per bunch (25ns) (2e10 proton per bunch for 5 ns option):
  - Down to 2e10 per beam after 4 hours in collisions

- Setup intensity: 1e10 proton per bunch@injection, 5e8 p/b@ 50TeV
  - Setup of FCC beams should be done with 1 pilot of 5e8 protons per bunch

Particle	Bunch charge (q)	Number of bunches	Bunch spacing (ns)	RMS bunch length (ns)
p	5e8 → 1e11	1 → 10400 (53000)	5 → 25	1.07 (FT) → 1.8 (injection)
Pb	5e9 → 2e10	2072	100	?

- For Ions Beams: Ions beam setup done with proton pilot (steering, optics measurement), switch to ions directly with trains

Beam current

- Main challenge is the large dynamic range ~ 150000: from single pilot (5e8 p/bunch@ injection) to 0.5 A (10400 bunches of 1e11 p/b)
  - Even larger for the 5 ns options (5 times more bunches)
  - Factor 5 decrease within a fill with nominal intensity.

- Need total DC current as well as the individual bunch currents.

- **Loss rates** (lifetimes) must be provided on a **bunch by bunch** basis.
  - Tolerance of 1% relative on the bunch by bunch

- The total bunch current must also be used for **machine protection** purposes and trigger a beam abort when the total loss rate (for the entire beam) is too high.

Beam Position Monitor

Main Functionality:

- Single pass trajectory (beam positions versus machine azimuths)
  - First steering, injection oscillations
- Closed orbit (average beam positions versus machine azimuths)
  - Typically a 50 Hz averaging
- Beam oscillations (beam position versus time)
  - For optics measurement
- Closed orbit data should be integrated into real time orbit and radial position feedback for all intensities

<u>Few special BPMs:</u>

- Instability observation
  - High resolution bunch by buch and turn by turn data
- Machine protection functionnality
  - Beam abort in case of trajectory/orbit large excursions
  - Injection oscillations data used to interlock high intensity injection

Beam Position Monitor

- Performance for lattice BPM (more stringent for collimations and high lumi insertions)

Paremeter	LHC	Target	Beam	Comment
Alignment wrt quadrupoles	~300 um	<200 um	Pilot → Nominal trains	Vertical absolute position vs beam screen slits
Closed orbit precision long term	50um (20 um week)	20 um	Pilot → Nominal trains	Reproducibility Fill to fill over month
Closed orbit precision short term	<1um		Pilot → Nominal trains	Over few minutes
Turn by turn resolution	100 um	50-100 um	Pilot beam	Over 100k turns
Bunch by bunch and turn by turn	<1um	0.1 um	Nominal beam	For few BPM channels only for specific studies (instabilities)
Interlock response	10 turns	10 turns	any	Only couple of BPM channels for Machine protection
Interlock resolution	100 um	50 um	any	

- Systematics for LHC:
  - Dependance on bunch pattern ~ 200um
  - Temperature control: 10-20 um per 0.5 degree

Beam Position Monitor

- Main challenge :
  - Factor 10 to gain on minimum intensity
  - High resolution for optics measurment (pilot intensity, single bunch)
  - Control of the systematics : bunch pattern dependancy, temperature …
  - Alignment tolerance:
    - R&D needed to go much beyond 300um (LHC specification) on mechanics and/or beam-based alignement method

- New DOROS electronic with button BPM should be OK:
  - Tested in LHC
  - More details in H. Schmickler presentation

Transverse emittance

- Emittances derived from beam size evolution (optics info folded in)
  - Bunch by bunch data for time evolution
- Due to high intensities, should be non interceptive devices:
  - Interceptives device should be available for cross calibration with low intensity
- 5 ns options much more demanding:
  - Emittance growth in collisions permill level (relative)

Parameter	LHC	Target	Beam	Comment
beam emittance resolution	~50%	1%	Pilot->nominal	
Bunch by bunch profiles	Every 40 ms			

- Typical beam size in the arc ~ 10-50 um, enough Xray flux at top energy, visible light for the cycle
- For LHC, bunch by bunch profiles scan takes ~ 5min

Transverse profiles

- Challenges:
  - Typical beam size and size evolution during a fill, 5 ns option even more demanding
    - Emittance evolution in collisions permill level (relative)
  - Interceptives devices for cross calibration and matching
  - Bunch by bunch data in a reasonnable time for time evolution and eventually feedback

- Limits of existing technique at LHC:
  - Diffraction limit for the visible light

=> Different technics under study (seeToshiyuki Mitsuhashi's presentation)
=> special layout with higher beta (up to factor 10) would help

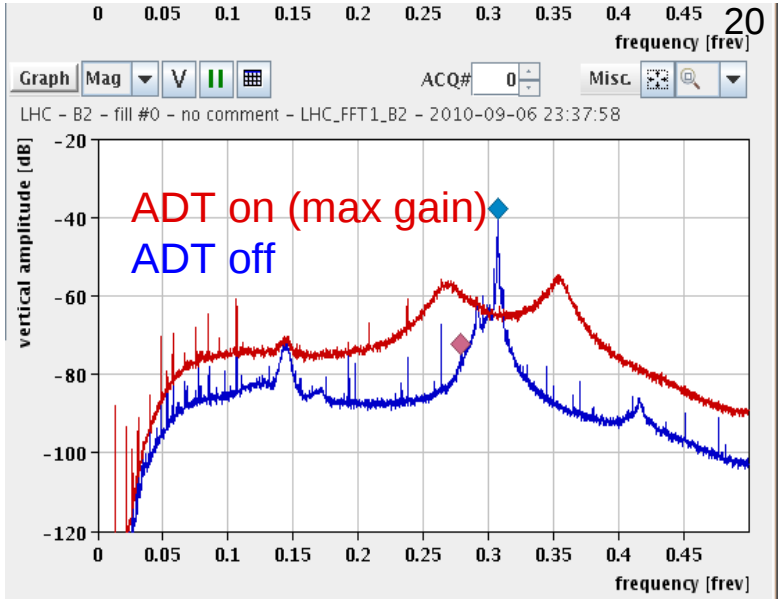
Tune measurement

- Tune measurements based on high sensitivity BPMs and the associated electronics.
- The tune measurement system must also provide a phased-lock loop (PLL) tune tracking functionality.
- Similar to the orbit case, the tune data should to be fed into a tune feedback system (~1 Hz)

- Challenge for FCC as for LHC:
  - Problem with high transverse damper activity regime
- Solution for LHC:
  1) Measurements and feedback with single bunch + feedforward and excellent reproducibility
  2) Gated signal on few bunches with lower ADT gain

=> Is it acceptable for FCC?

Tune spectra measured by BBQ system in LHC



Beam Loss monitor

- Detailed Machine protection specification may take time, for the moment we can “scale” the LHC system

- Machine Protection functionality:
  - Beam Loss Monitor in cold region to protect against quench
  - Beam Loss Monitor at each aperture restriction to protect against damage

- Machine operation functionality:
  - Collimation alignement, aperture measurement, threading, vacuum bump, etc…
  - Diagnostic of injection and post-mortem analysis

=> cohabitation of injection losses with losses from circulating beams difficult in LHC: special care at the design level for FCC

- Dynamic range, resolution and response time to be scaled from LHC experience

Summary

- With the actual FCC parameters, main challenges for instrumentation are:
  - Reach resolution with pilot intensity ~ 5e8 protons
    => Reduce systematics dependance on bunch pattern/bunch intensity
  - Alignement tolerance on the BPM vs quadrupole
  - Beam size measurements, espacially towards the end of a fill
  - Tune measurement quality in a high damper gain regime:
    => also for chroma, coupling, instabilities...

- Specification from Machine protection missing to get more in details into BLM design
  - Injection region instrumentation to be studied in details

Thank you for your attention