SHORT INTRODUCTION TO LINAC4

B. Mikulec

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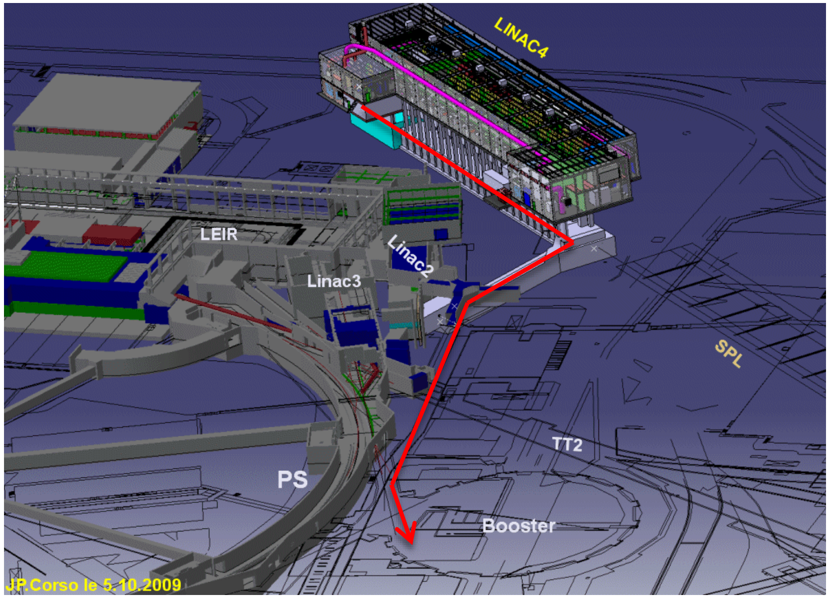
Outline

- Introduction to Interlock Design Considerations
- Linac4 Overview
- Linac4 Critical Elements for BIS
- Summary



Total distance from source to PSB entry point: ~260 m.

Interlock Design Considerations

Starting Points for Interlock Design (1)

- Linac4 has to provide different beams to the PSB every 1.2 s (or 0.9 s), where the intensity can vary by orders of magnitude.
- Interleaved can be cycles to measurement lines (in general: different destinations) for machine checks and improvements.

① Operational modes like in LHC not practicable

- The interlock system has to deal with different beam **destinations**; if a beam line to a certain destination is in fault, beam should still be provided to other destinations in case of valid conditions (destinations: L4Z, LBE, LBS, PSB, PS)

② Solved through analysis of acquisition values of bending magnets in the transfer lines (see presentation B. Puccio)

Starting Points for Interlock Design (2)

- The PSB is timing master of Linac4
  - 'Normal' and 'spare' cycles programmed in supercycle; if 'normal' cycle cannot be executed due to **PSB External Conditions**, the 'spare' cycle is automatically played for optimum use of facilities

③ Need to keep this operational flexibility and take into account PSB External Conditions (PSB user requests, ISOLDE watchdog, ISOLDE ventilation, BTY and BTP beam stoppers, beam inhibits)

- It has been shown (C. Maglioni, Linac4 BCC 10th Nov. 2011) that no damage to the beam pipe is expected after one worst case beam loss (although further damage to equipment in case a big beam fraction traverses the beam pipe and gets absorbed has not been investigated in detail)
- Certain dumps cannot stand more than one full beam pulse

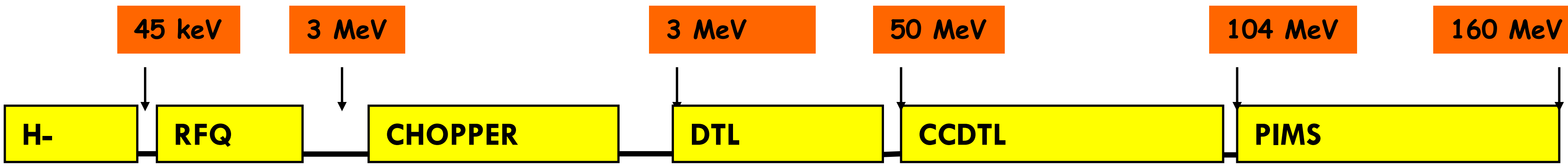
④ BIS designed to exclude more than one complete beam pulse loss

Linac4 Overview

Motivation for Linac4

- Ageing Linac2 equipment (Linac2 vacuum!)
- Allow an increase of LHC luminosity above PSB space-charge limits with 50 MeV injection → double intensity within same transverse emittances (160 MeV)
- H^- injection into PSB allows (horizontal) phase-space painting of transverse emittances; painting of longitudinal emittances through energy modulation also in baseline
- Originally foreseen to inject at a second stage into low-power SPL and PS2 to replace PSB and PS

Linac4 Layout



RF source	Radio Frequency Quadrupole	Chopper Line	Drift Tube Linac	Cell-Coupled Drift Tube Linac	Pi-Mode Structure
	352 MHz	352 MHz	352 MHz	352 MHz	352 MHz
	3 m	3.6 m	~19 m	25 m	22 m
	1 klystron	11 EMquad	3 tanks	21 tanks	12 tanks
	540 kW	3 cavities	3 klystrons	7 klystrons	8 klystrons
			5 MW	6.5 MW	~12 MW
			108 PMquads	**14 PMquads**	12 EMquads
				7 EMquads	

Expected ion current:
40 mA (avg. in pulse),
65 mA (bunch)

RF Duty cycle:
0.08% phase 1 (Linac4)
3-4% phase 3 (HP-SPL)

4 accelerating structures (RFQ, DTL, CCDTL, PIMS)

Total Linac4:
86 m, 19 klystrons

Linac4 Source

- Constraints for **H^- source**: should be pulsing continuously to assure intensity stability (also during tunnel access)
- Design: 65 mA peak current, 40 mA average current after chopper
  - Chopper will remove ~1/3 of Linac4 pulse (see later)
- Pulse duration: 400 (-600) µs
- Repetition rate: 0.83 (1.11) Hz

- HV of source: *USER_PERMIT* to source RF master BIC*

*The source BIC is the only BIC that stops the source in case of a false BEAM PERMIT.

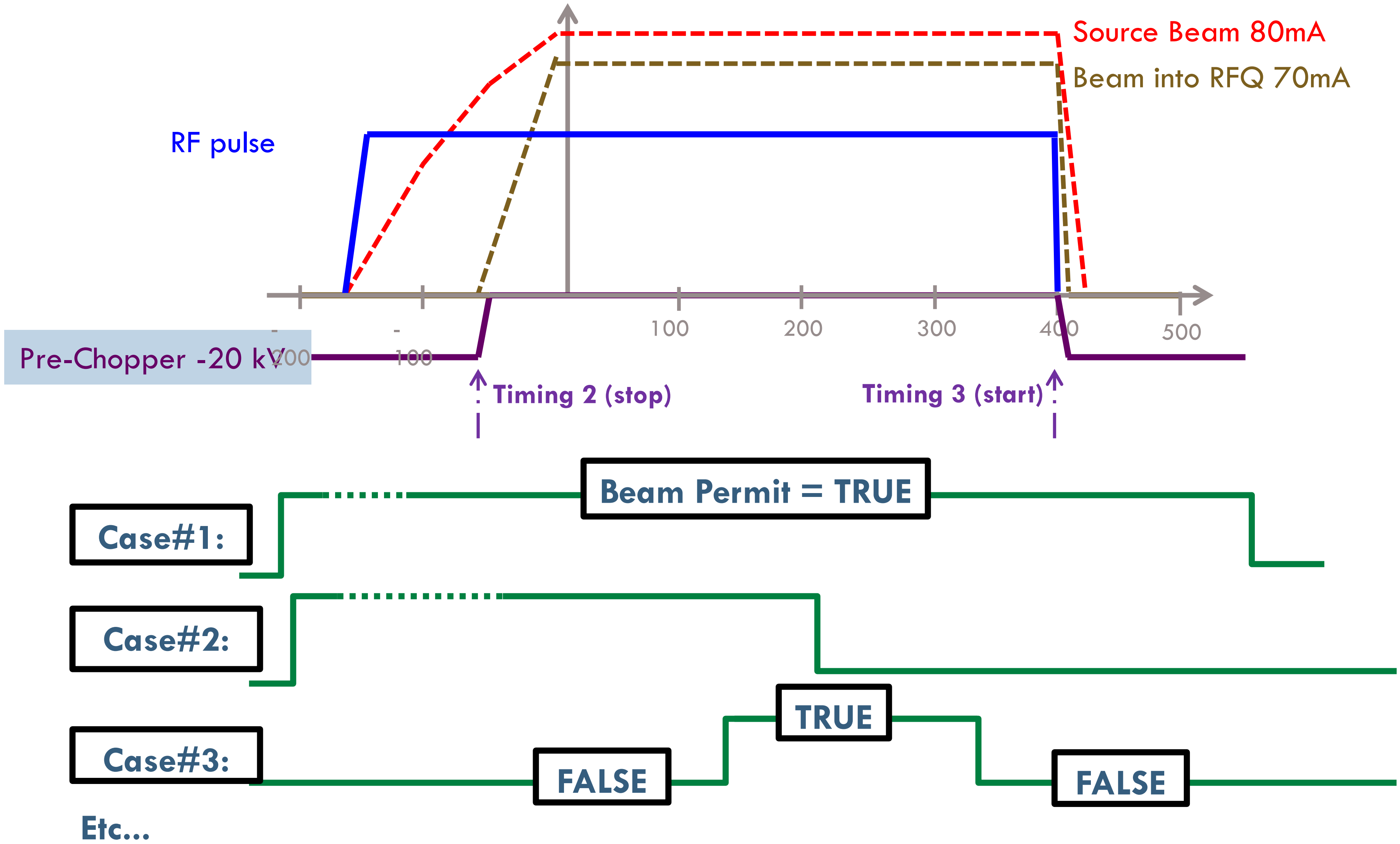
Pre-Chopper

- **Pre-chopper** regulates beam extraction (rise- and fall-time of ~2 μs, reaction time ~3 μs); -20 kV at deflecting plate
  - Controlled through four timings:

    (1) start ~1 ms before source RF; (2) stop for beam passage; (3) start to cut beam passage; (4) stop ~2 ms after source RF off
  - Timing (3) also used to shorten the Linac4 beam length for lower requested intensities (ppm control through 'number of turns' to be injected into the PSB)
    - Should also be used for BI instruments requiring reduced pulse length to avoid damage (wire scanners, SEM grids) → Linac4 'external conditions'

- **Main Linac4 BIS actor together with chopper**: loose beam at low energy (45 keV) in case of interlock; logic with timings (2) and (3) applied (EDMS 1166012); not fail-save (sparking!)
- Provides in addition *USER_PERMIT* to source RF master BIC

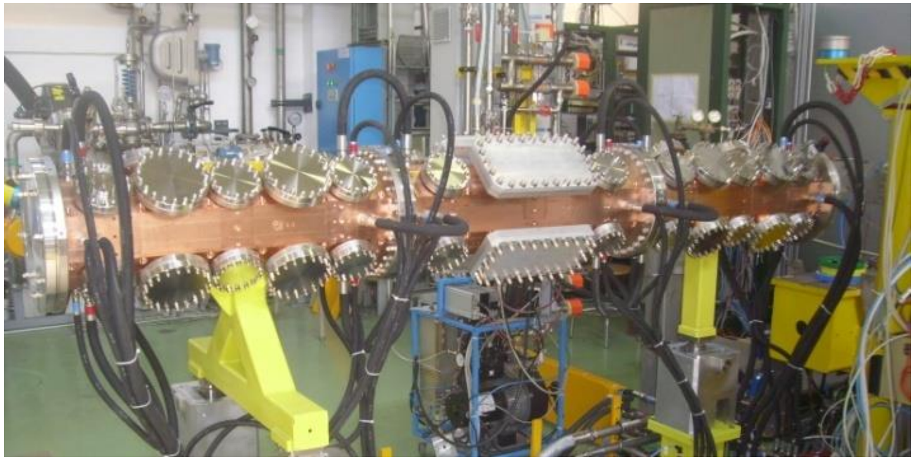
Timings of Pre-chopper



RFQ

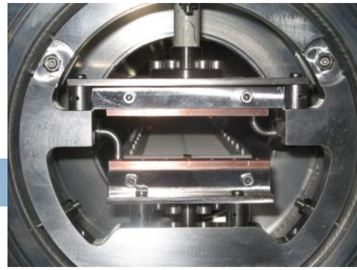
- Produced at CERN; brazed-copper 4-vane structure of 3 m length
- Acceleration of beam from 45 keV to 3 MeV + bunching
- Recently installed in 3 MeV Test Stand; installation in Linac4 tunnel planned for end summer 2013

- To be clarified if the RFQ could be added as *USER_PERMIT* to source RF master BIC.



Linac4 Beam Stopper

- Too slow for ppm action of BIS, but essential part of access system (if beam stopper IN, the source continues pulsing…)
  - Remark: Clear separation between personnel safety systems and BIS in interlock design



Chopper Line (1)

- 3 bunchers and matching section at entrance and exit
- Electrostatic beam deflector followed by **internal dump**; optics can be changed with 11 quads to loose beam there also without chopping
- Goal: chop holes into beam (~5 ns rise/fall-time)
  - to remove head/tail of the Linac4 pulse
  - during rise-time of ~1 µs between distributor levels
  - to match the PSB acceptance (for injection into PSB buckets including special longitudinal painting scheme)
- Installation of chopper line in Linac4 tunnel currently planned for ~end summer 2013

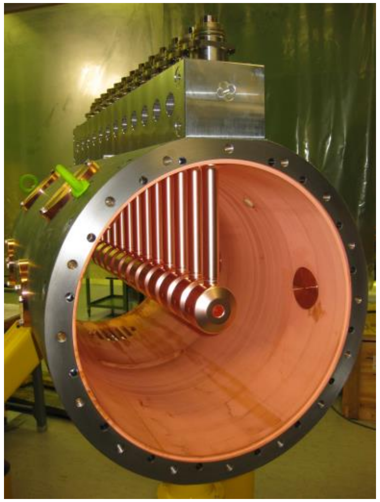
Chopper Line (2)

- **Chopper is main Linac4 BIS actor together with pre-chopper**: chopper pulses and sends beam to internal 3 MeV dump in case of false BEAM_PERMIT during beam pulse duration
- Provides in addition *USER_PERMIT* to source RF master BIC
- Correct dumping requires action of mainly 3 quadrupoles in chopper line → 3 *USER_PERMITs* of their AQN values

Drift Tube Linac (DTL)

- 3 tanks, 108 permanent magnet quadrupoles
- Construction of tanks progressing at CERN with contribution from ESS Bilbao
- First tank to be installed in Linac4 tunnel end of 2013 (→ 12 MeV)
  - Goal: Ready with commissioning up to 50 MeV after LS1

Prototype



Assembly of first tank

Cell-Coupled Drift Tube Linac (CCDTL)

- 7 modules of 3 DTL-type cavities (2 drift tubes each) connected by coupling cells
- Produced and assembled in Russia
- 14 PMQs between cavities, 7 EMQs between modules
- To be installed in Linac4 tunnel ~summer 2014

CCDTL module 2 during tests in Novosibirsk

PIMS (Pi-Mode Structure)

- 12 electron-beam welded 7-cell copper cavities operating in π-mode
- Production location: NCBJ Swierk (Poland) + contribution from FZ Jülich and CERN
- To be installed in Linac4 tunnel beginning 2015
- Last 2 modules used for longitudinal painting (fill PSB buckets as uniform as possible for optimum space-charge conditions in addition to transverse painting) = 2nd phase of PSB commissioning with Linac4

PIMS prototype built at CERN; 4/3/2010

Accelerating Structures and BIS

- Combined RF status of all klystrons as *USER_PERMIT* in Linac4 BIC
  - ‘Staging’ during different commissioning phases or maskable input

Additional Linac4 *USER_PERMITs* - BI

- **BLMs**: have to assure equipment safety (assuming sufficient coverage); not sensitive enough at 3 MeV – no beam loss monitor currently foreseen at this energy (also no neutron detector)
  - **High-loss** *USER_PERMIT*: hardware-based; have to define damage threshold; cycle independent
  - **Low-loss** *USER_PERMIT*: cycle dependent thresholds and allowed # of bad pulses (FESA class); operator reset
- **Watchdogs**: compare transmission between 2 BCTs (EDMS 1155020)
  - **High-loss** *USER_PERMIT*: as far as possible hardware-based; cycle independent, but destination dependent (stops all cycles to a certain destination in case of single occurrence of high losses)
  - **Low-loss** *USER_PERMIT*: cycle dependent; bad pulse counter in FESA class; operator reset

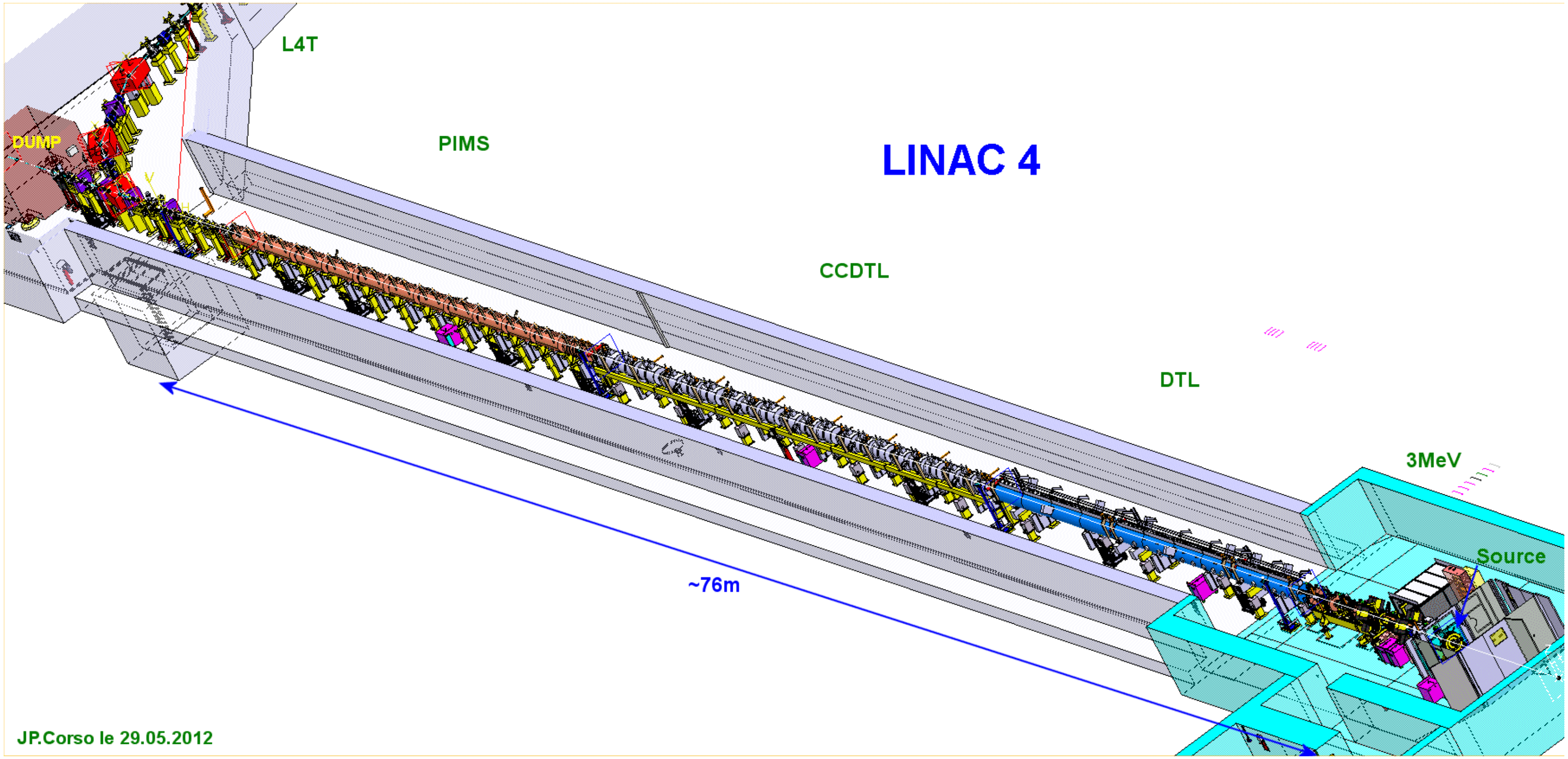
Additional Linac4 *USER_PERMITs*

- **Operator switch**: The operators in the CCC can inhibit the source RF
- **Vacuum valves**
- **External conditions**: conditions requiring an inhibit of the full pulse (see slide 5)
- Status of the various interlock zones (corresponding BIC beam permits) in combination with the information on the destination (AQN values of bending magnets)
- BLMs in the PS for destination PS (only destination to be supplied via timing system)

22

Transfer and Measurement Lines

Linac4, L4Z and L4T



New Transfer Line (L4T) + Linac4 Dump Line (L4Z)

- Current, position and bunch length measurement at Linac4 exit
- Hor. bending magnet:
  - Straight to Linac4 dump + transverse emittance measurement with 3 wire grids (L4T.MBH.0250)
  - Bend direction Linac2 transfer line (L4T.MBH.0250+L4T.MBH.0450+L4T.MBH.0650 powered in series; enter in Linac2 tunnel at LT.BHZ20)
- Beam transport and vertical level adaptation (2 vertical bends powered in series)
  - In addition debuncher and some beam diagnostics (profile, current, position and BLMs)
  - Beam stopper
- Installation of transfer line summer 2014
  - Has to be ready in case of Linac2 breakdown to provide 50 MeV protons to PSB

Linac2 Transfer Lines (LT+LTB), LBE and LBS

- Keep **LT, LTB** practically unchanged
  - Turn LT.BHZ20 and upgrade some magnet power converters
  - Upgrade of transformer electronics for precise transmission/watchdog measurements along all the lines
  - New pickups up to PSB
- At LTB.BHZ40: straight into PSB or split into **LBE+LBS** measurement lines (to be used for Linac4 transfer line and final commissioning at 160 MeV):
  - LBE: Upgrade of LBE for emittance measurement using 3 wire grids; installation of new dump
  - LBS: Upgrade for absolute energy and energy spread measurements at 160 MeV; new spectrometer magnet and dump

Remark: The above lines need to stay compatible with ion measurements from Linac3.

- **BI** line: change radically PSB injection (out of scope today…)

USER_PERMITs in Transfer Lines, LBE and LBS

- BLMs (high-loss, low-loss)
- Watchdog (high-loss, low-loss)
- Vacuum
- AQN of bending magnets
- Beam stopper in L4T

- In SIS (list not exhaustive): Debuncher, magnets with WICs (tbd if to be implemented in hardware), information on dump status

Summary

- The beam interlock system for rapid cycling machines is fundamentally different compared to machines like LHC
- Linac4 beams will differ wildly in intensity and pulse structure and will need to be sent to different destinations every 0.9/1.2 s
  - Destination information now handled through acquisition values of bending magnets
- Current BIS design should assure protection of Linac4 together with maintaining operational flexibility
  - Linac4 will profit from acquired experience with the BIS in SPS/LHC (hard- and software)

Spare Slides

Linac4 Design Parameters

Ion species	H^-
Output Energy	159.4 MeV
Bunch Frequency	352.2 MHz
Max. Rep. Rate	2 Hz
Max. Beam Pulse Length	1.2 ms
Max. Beam Duty Cycle	0.24 %
Chopper Beam-on Factor	65 %
Basic chopping scheme: 222 transmitted /133 empty buckets	
Source current	80 mA
RFQ output current	70 mA
Linac4 average pulse current	40 mA
N. particles per pulse	1.0×10^{14}
Transverse emittance	0.4 π mm mrad

Max. rep. rate for accelerating structures 50 Hz

H^- particles + higher injection energy (160/50 MeV, factor 2 in $\beta\gamma^2$) → same tune shift in PSB with twice the intensity.

Re-use 352 MHz LEP RF components: klystrons, waveguides, circulators.

Chopping at low energy to reduce beam loss at PSB (bunch-to-bucket transfer).

- Structures, klystrons and shielding dimensioned for 50 Hz (HP-SPL).
- Power supplies, electronics and infrastructure (water…) dimensioned for 2 Hz (LP-SPL), 1.2 ms pulse.

PSB Beam Production with Linac4

A few examples for illustration…

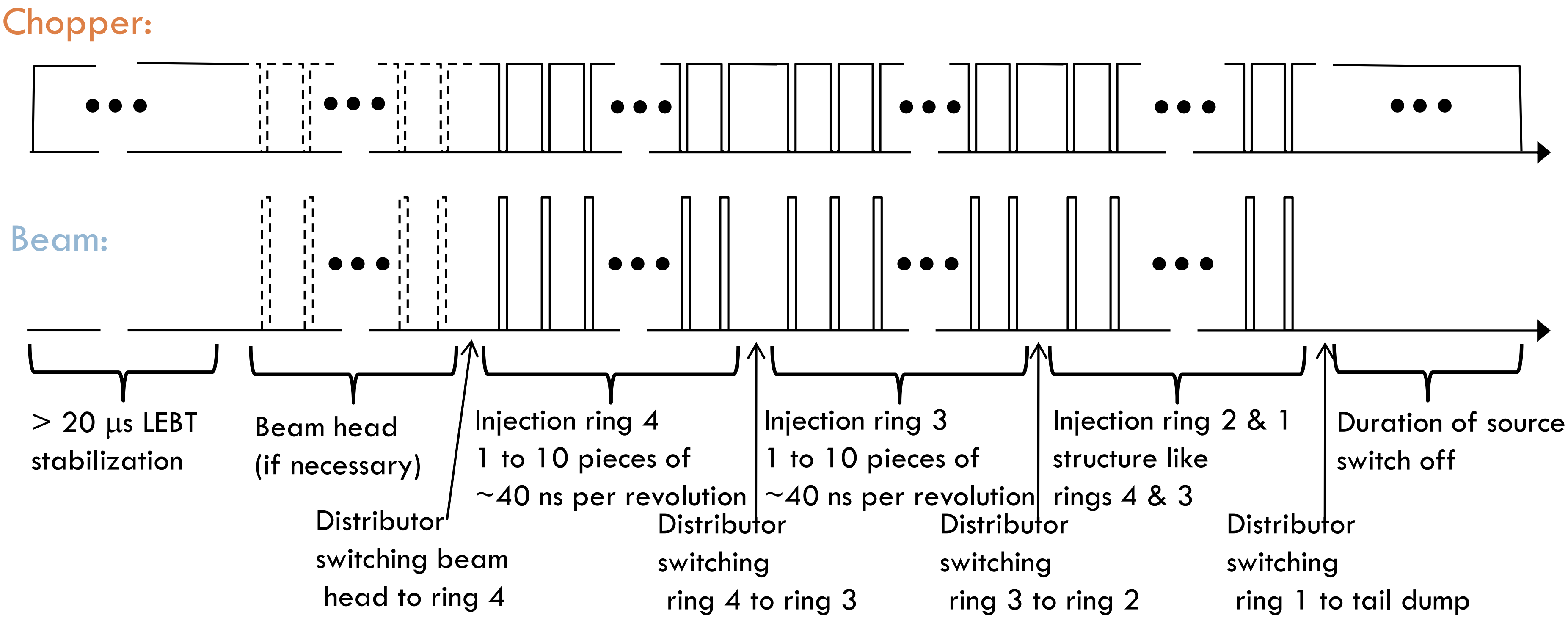
Very Low Intensity Beams (1/2)

- Simple calculation:
  - One 30 ns chopper gap (=min. chopper OFF time) lets 11 Linac4 bunches through
  - At 65 mA one would only need 6-27 Linac4 bunches to produce the LHCPILOT and LHCPROBE beam ($5\ 10^9$ p / $5\text{-}23\ 10^9$ p)

Linac4 Current	# Particles/Linac4 Bunch
65 mA	$1.15\ 10^9$
40 mA	$0.70\ 10^9$

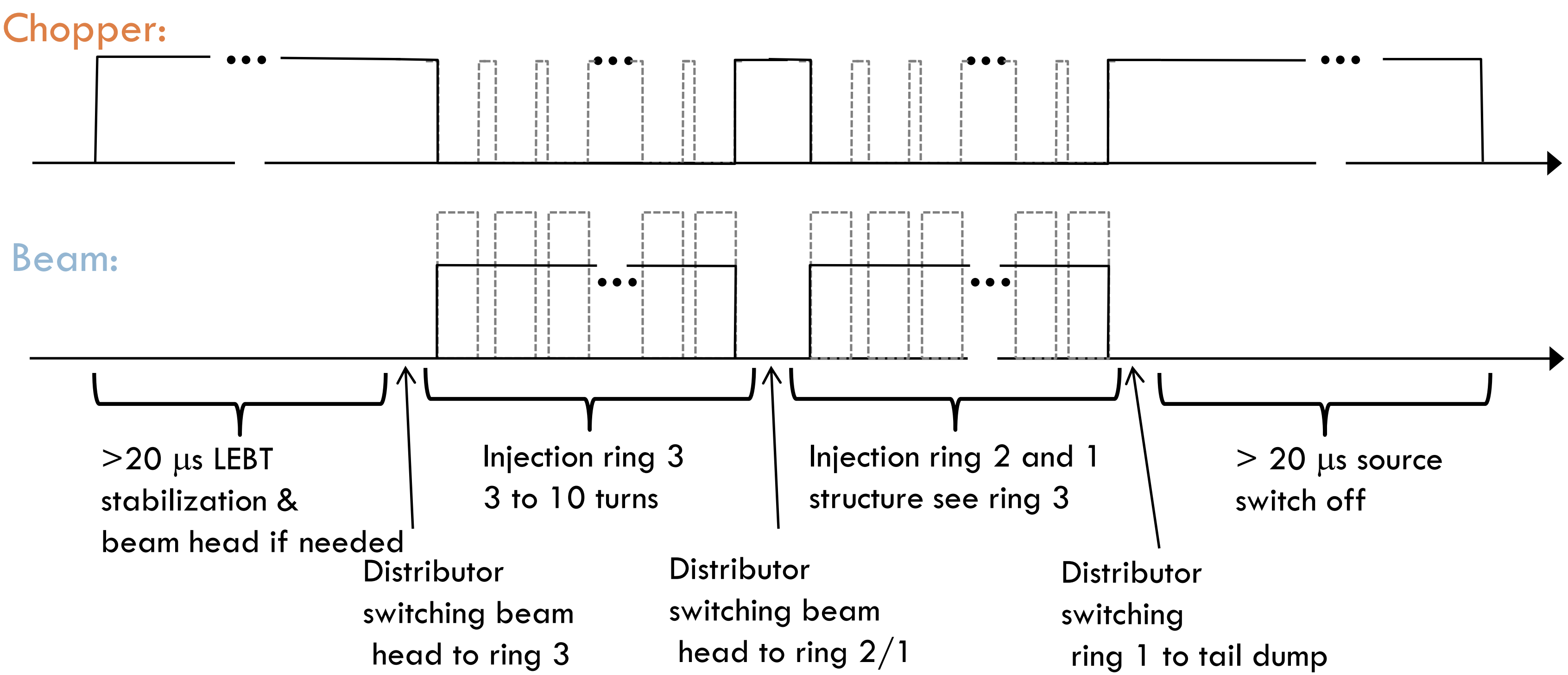
  - A single PSB turn (~1 µs at 160 MeV) without chopping at 65 mA yields already $4\ 10^{11}$ particles.
- At present: very low intensity obtained by heavy shaving (longitudinal, if not too small transverse emittances required – e.g. for LHCPILOT & LHC single bunch physics)
  - Some losses and activation
- Aim: Find schemes allowing to reduce losses using the chopper to inject less particles

Very Low Intensity Beams (2/2)



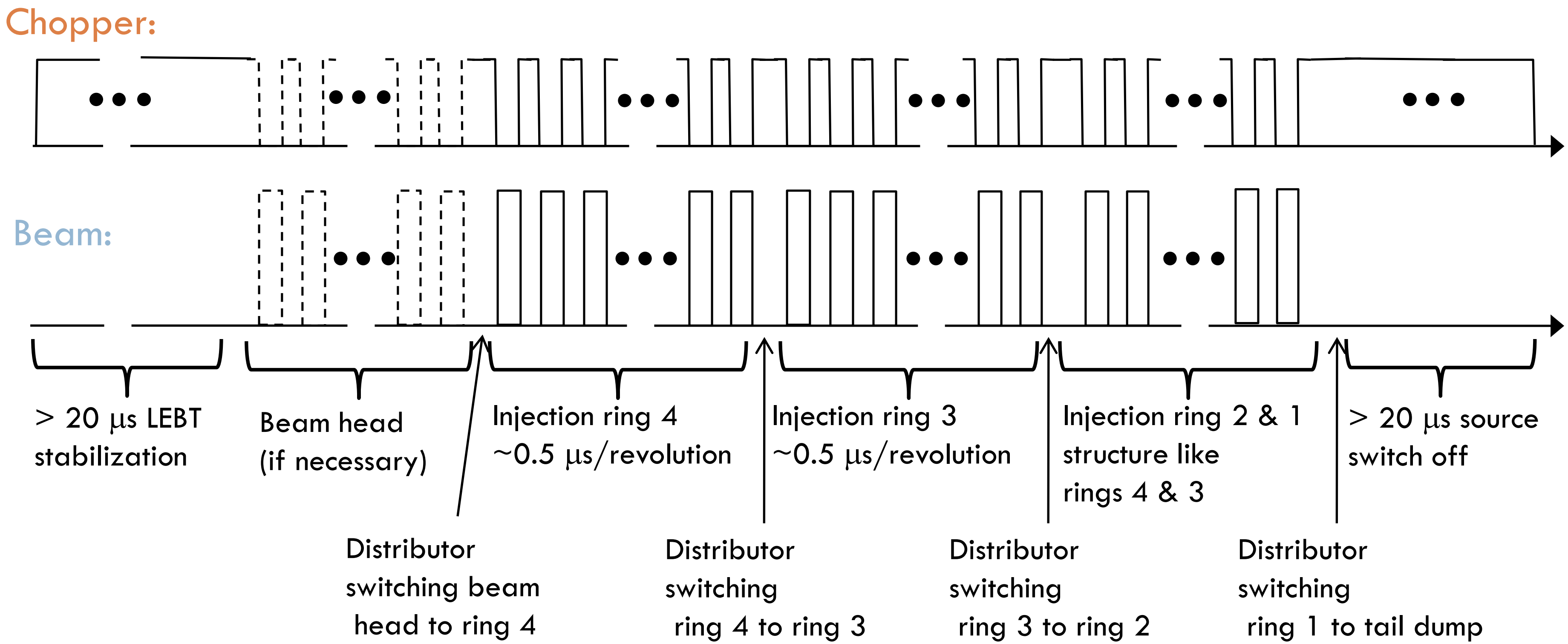
- Example to produce one low intensity bunch in each Booster Ring (in case some rings are not used, the Linac4 source pulse has to be shortened; trigger several distributor levels)
- Injection without RF on plateau and "slow" capture after filamentation (say ~10 ms)
- Several turns injected to obtain transverse emittances, longitudinal shaving (few particles lost) and blow-up to create longitudinal emittances.
- No synchronization between Linac4 and PSB RF and between PSB rings required

First intermediate (and high) intensity beams with "slow" capture



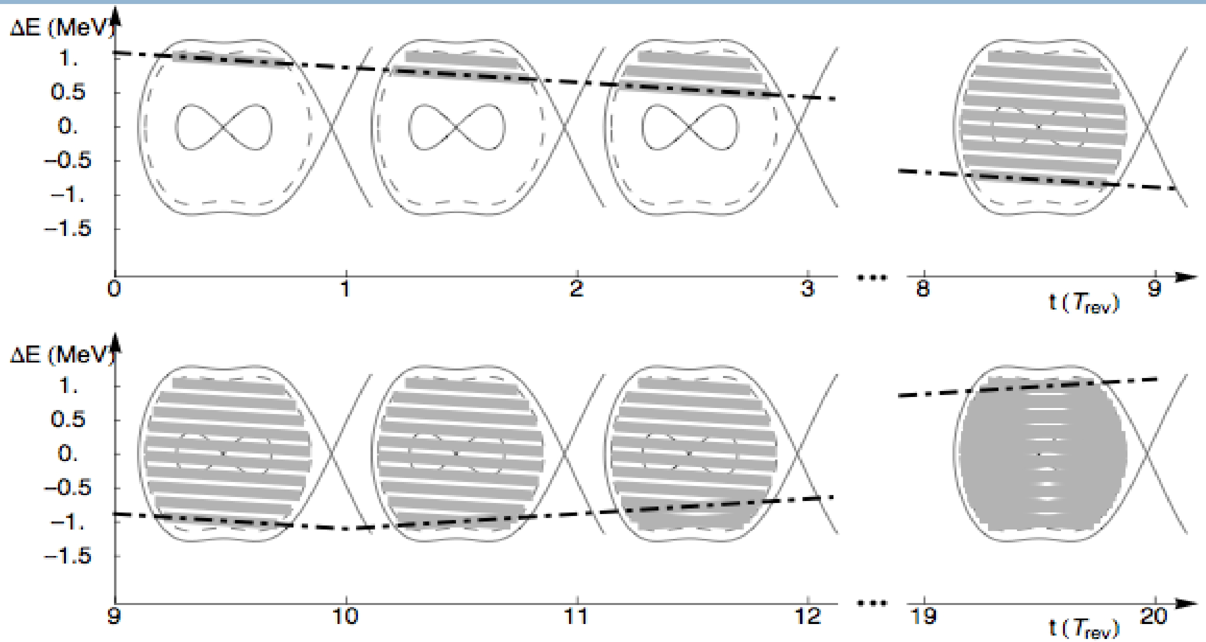
- Inject 3 to 10 turns, I_{av} < 40mA (solid: reduced peak current, dotted: chopping to reduce I_{av})
- Injection on plateau (~x2 less tune spread than now) followed by filamentation and slow capture
- Adjust working point
- Maximum achievable intensity (losses and activation) compatible with CNGS??
- No synchronization between Linac4 and PSB RF and between PSB rings required

Intermediate Intensities – Injection into Waiting Buckets without Longitudinal Painting



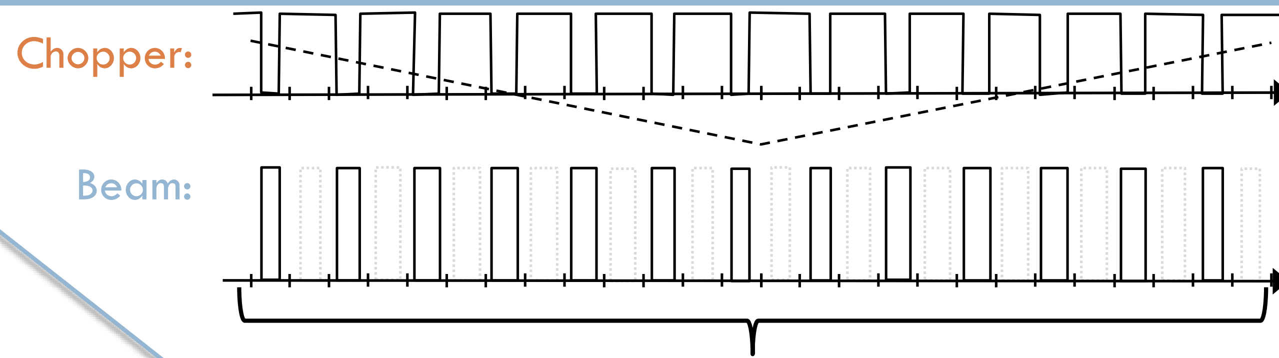
- Example to produce beam in each Booster Ring (if needed skip injection into unwanted rings)
- In case of a problem with one ring-specific elements → external PSB condition → need to change:
  - Pre-chopper timing (start pre-chopper earlier)
  - Use different chopper program 'on the fly'
  - Change distributor timings
  - Adapt PSB RF if injecting on a ramp

Longitudinal Painting for maximum Brightness (LHC) and Intensity (CNGS and ISOLDE) (1/4)



- Basic idea:
  - Saw-tooth shape energy offset (w.r.t. PSB injection energy) variations of Linac4 beam with 2 last PIMS modules
  - Switch beam on/off by chopper if it is inside/outside bucket (with margin)
  - Inject into waiting **accelerating** bucket!
- Issue: 40 turns minimum energy modulation period and 65 mA peak beam current
  - One energy modulation period yields more intensity than nominal LHC (see later)
  - Might require to chop additional holes into the 'on' structure to obtain uniformly filled bucket

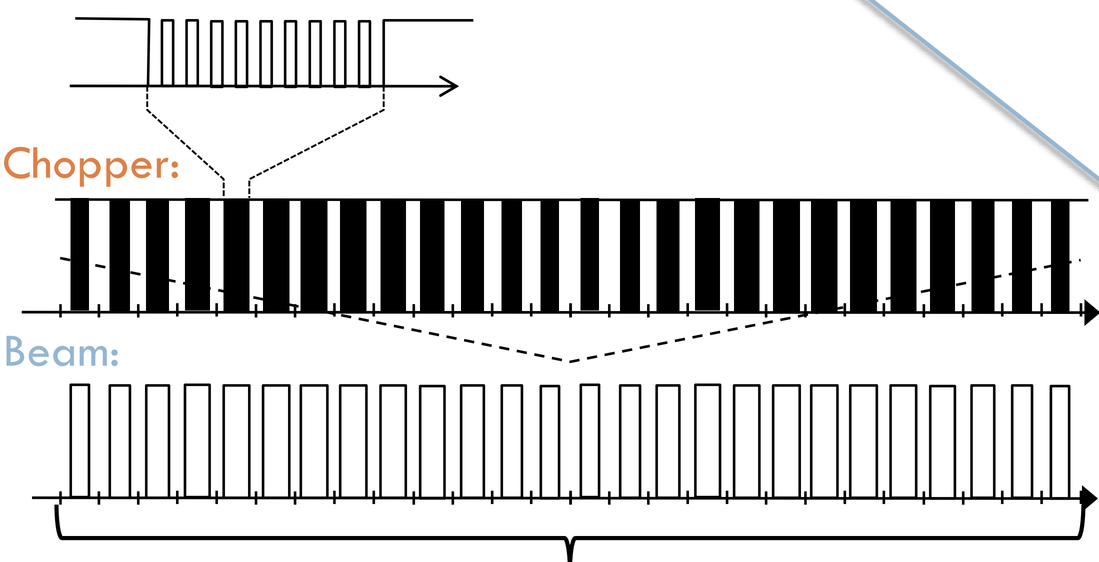
Longitudinal Painting for maximum Brightness (LHC) and Intensity (CNGS and ISOLDE) (4/4)



Injection into one ring with one energy modulation period (lasting 26 turns in this example)

- Injection every second turn to halve intensity
- Nominal (for single batch PS transfer) LHC intensity after one energy modulation period with 65 mA peak beam current

- Reduce "average" current during beam on by chopping additional short gaps



one energy modulation period lasting 26 turns in this example