CERN Lab Talk

Current and Future Projects
Recent LLRF achievements and challenges

Wolfgang Hofle

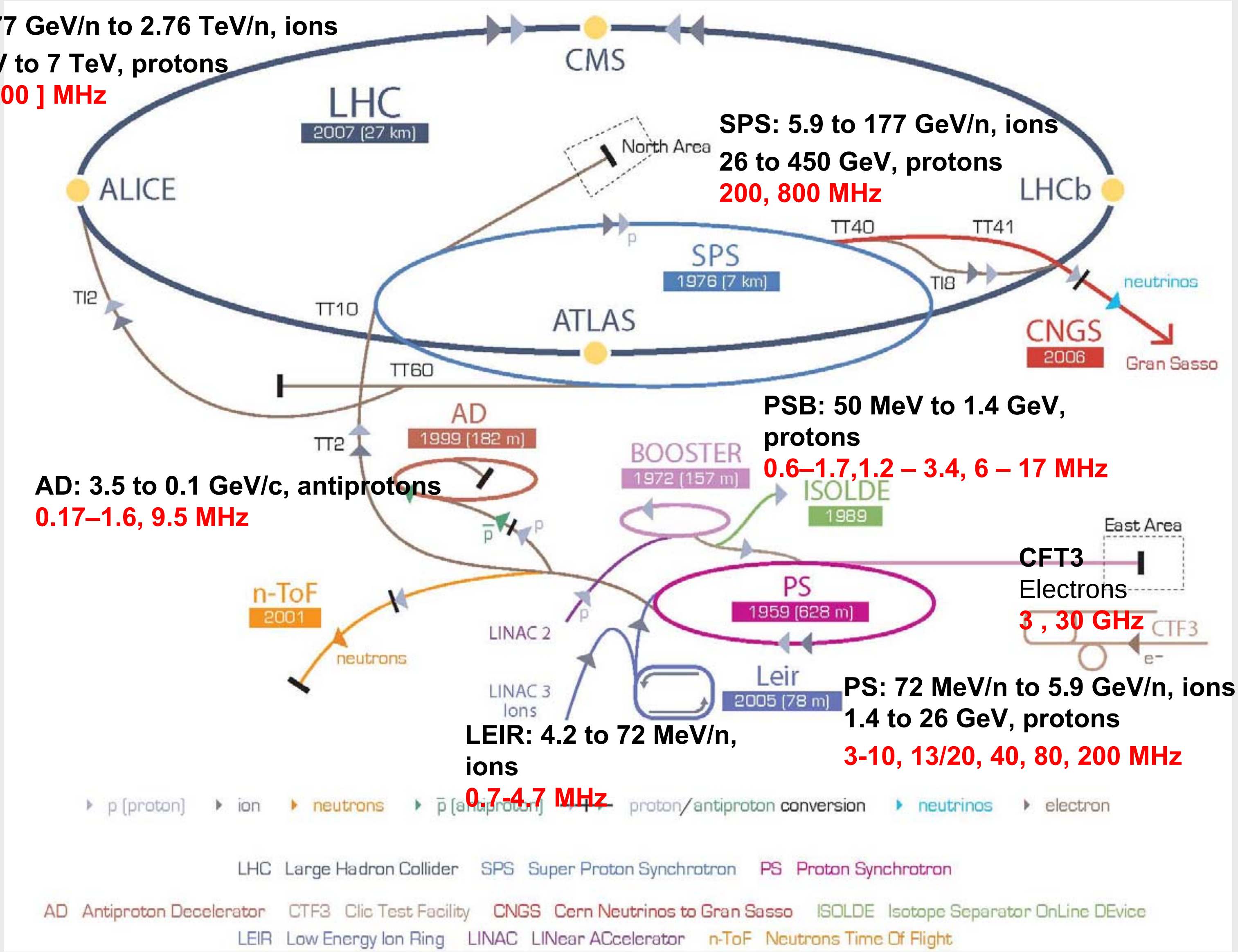
CERN AB/RF/FB

LLRF: AB-RF-FB and AB-RF-CS Sections
Special thanks to M.E. Angoletta, P. Baudrenghien, J. Molendijk,
V. Rossi, D. Valuch

Outline

- Overview of CERN accelerators and the LHC Injector chain
- LHC Project status and plans for commissioning
- Transverse feedbacks
- LHC Ions Injector chain: Recent Progress and LLRF issues
- Upgrade plans for the LHC injector chain
- Summary and what's been omitted

Current CERN Accelerator Complex



LHC: 177 GeV/n to 2.76 TeV/n, ions
450 GeV to 7 TeV, protons
400, [200] MHz

SPS: 5.9 to 177 GeV/n, ions
26 to 450 GeV, protons
200, 800 MHz

PSB: 50 MeV to 1.4 GeV, protons
0.6–1.7,1.2 – 3.4, 6 – 17 MHz

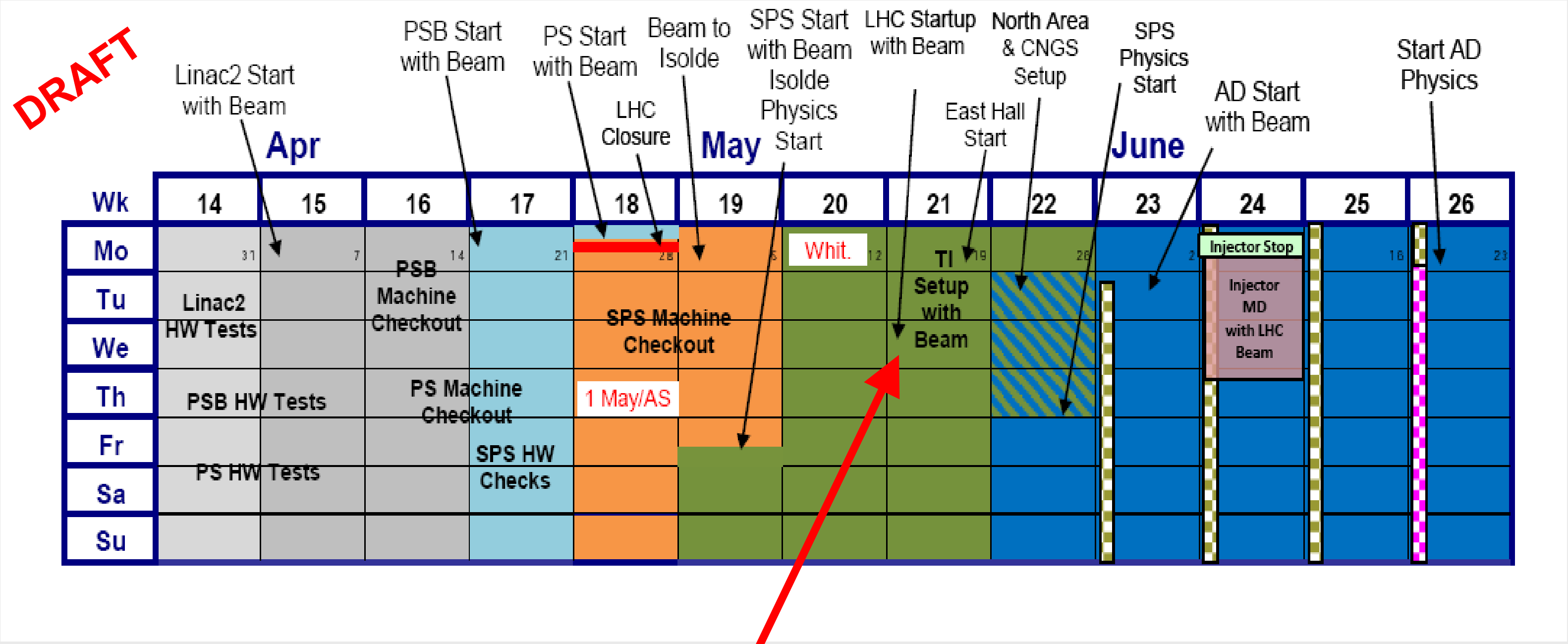
AD: 3.5 to 0.1 GeV/c, antiprotons
0.17–1.6, 9.5 MHz

CFT3
Electrons
3 , 30 GHz

PS: 72 MeV/n to 5.9 GeV/n, ions
1.4 to 26 GeV, protons
3-10, 13/20, 40, 80, 200 MHz

LEIR: 4.2 to 72 MeV/n, ions
0.7-4.7 MHz

LHC Project Status and plans for commissioning



LHC start-up with beam May 2008

Injectors will start-up spring 2008, LHC beams lead start-up

Start-up of LHC with beam scheduled for 21st May 2008

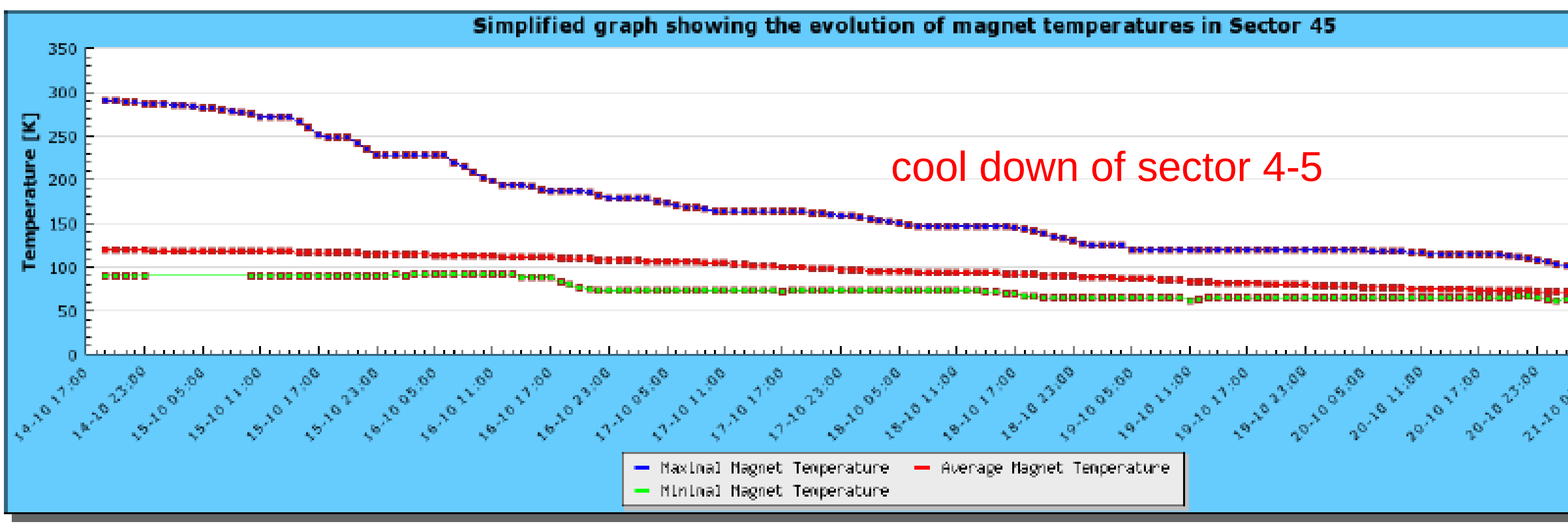
Commissioning of LHC LLRF and transverse dampers with beam 2008

Cavities + RF system
& Transverse Dampers
are all in point 4

Sector 45
The left part of the sector (from IP4 to 17L5) is floating around 90K while the rest is being cooled down from room temperature. As soon as this part reaches 80K (foreseen for the end of week 42) the sector will be cooled down all together to 1.9K. Due to the particular conditions, the access to the left part of the sector is limited while the access to point 5 is forbidden. As soon as the second phase of the cool down starts the access will be restricted but possible in all the sector.

Sector 56
After the successful pressure test, carried on at the end of w.38, the last days of last

Cryo main page - Sector 45



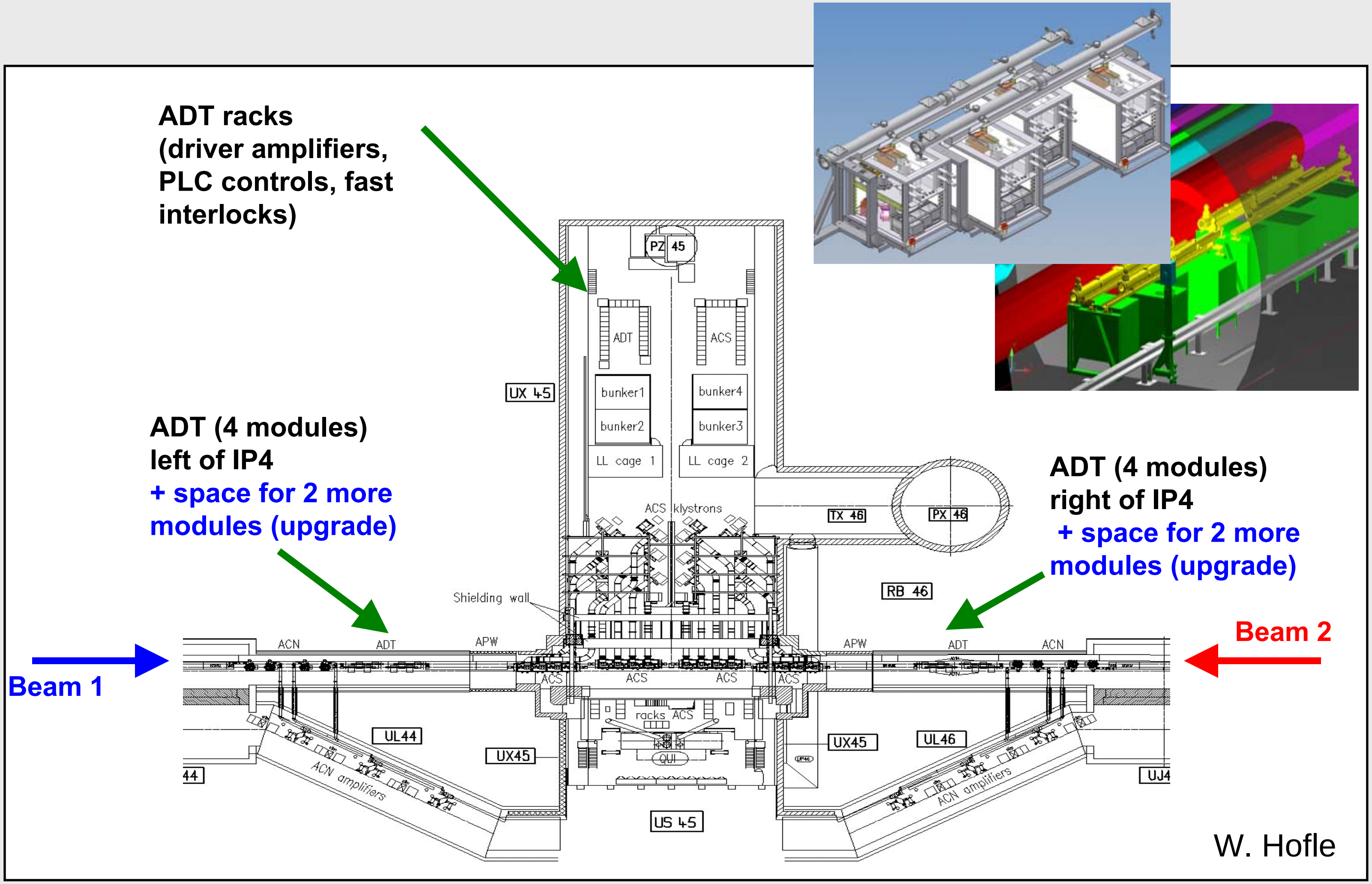
LHC Status and plans

- LHC has 8 sectors to cool down and commission (~27 km)
- Sector 7-8 cool-down and powering tests for 450 GeV done, now warmed up again
- Sector 4-5 cool down started, expected at LHe in November 07
- RF Cavity cool down to start in November 2007
- RF getting ready for cavity conditioning, see talk by J. Molendijk (Monday pm)
- LHC Lowlevel RF to be presented by P. Baudrenghien (Tuesday am)
- Staged commissioning with varying bunch patterns

Machine parameters		450GeV		Stage A		Stage B		Stage C			Stage D	
		Target		Target	Limit	Target	Limit	Target	Limit		Target	Limit
spacing	ns	2021	Commission hardware for high energy operation	2021	566	75	75	25	25	Installation of phase II collimators and full beam dump diluters	25	25
bunch length	m	0.1124		0.0755	0.0755	0.0755	0.0755	0.0755	0.0755		0.0755	0.0755
crossing angle	urad	0		0	0	250	250	285	285		285	285
bunch intensity		4.00E+10		4.00E+10	9.00E+10	4.00E+10	9.00E+10	5.00E+10	5.00E+10		9.00E+10	1.15E+11
bunches		43		43	156	936	936	2808	2808		2808	2808
energy	eV	4.50E+11		7.00E+12	7.00E+12	7.00E+12	7.00E+12	7.00E+12	7.00E+12		7.00E+12	7.00E+12
F		1.00		1.00	1.00	0.96	0.92	0.90	0.84		0.90	0.84
normalised emittance	cm	3.75E-04		3.75E-04	3.75E-04	3.75E-04	3.75E-04	3.75E-04	3.75E-04		3.75E-04	3.75E-04
beta*	cm	1100		200	200	200	100	100	55		100	55
luminosity	/cm2s	7.16E+28		6.12E+30	1.12E+32	1.28E+32	1.24E+33	1.13E+33	1.91E+33		3.65E+33	1.01E+34
total inel cross section	cm2	6.00E-26		6.00E-26	6.00E-26	6.00E-26	6.00E-26	6.00E-26	6.00E-26		6.00E-26	6.00E-26
event rate per cross		0.01		0.76	3.85	0.73	7.09	2.14	3.63		6.94	19.18
protons per beam		1.72E+12		1.72E+12	1.40E+13	3.74E+13	8.42E+13	1.40E+14	1.40E+14		2.53E+14	3.23E+14
current per beam	mA	3.09E+00		3.09E+00	2.53E+01	6.74E+01	1.52E+02	2.53E+02	2.53E+02		4.55E+02	5.81E+02
energy per beam	Joules	1.24E+05		1.93E+06	1.57E+07	4.19E+07	9.43E+07	1.57E+08	1.57E+08		2.83E+08	3.62E+08
beam size	um	293.3		31.7	31.7	31.7	22.4	22.4	16.6		22.4	16.6

http://lhccwg.web.cern.ch/lhccwg/

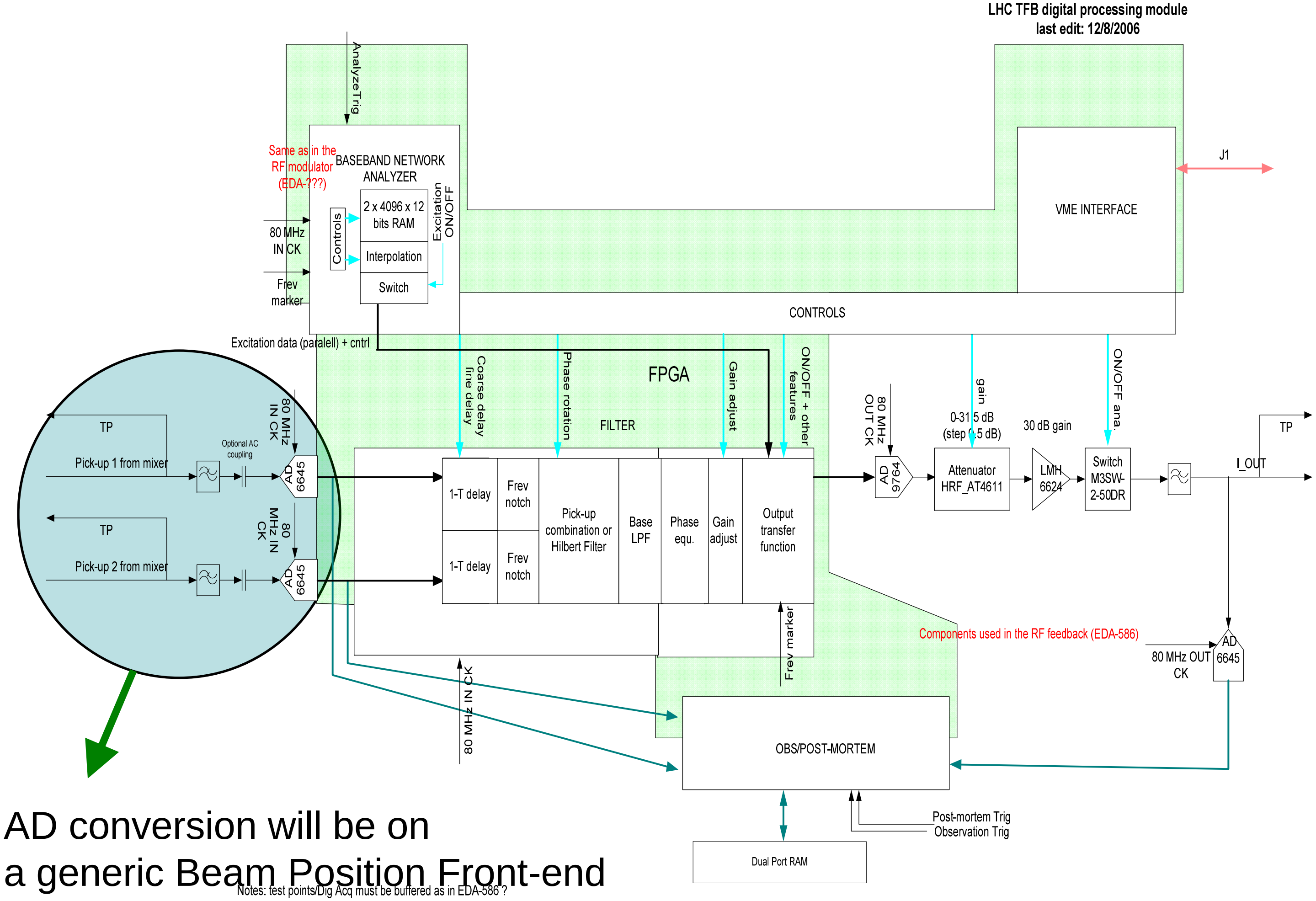
Transverse Feedbacks


ADT racks
(driver amplifiers,
PLC controls, fast
interlocks)
ADT (4 modules)
left of IP4
+ space for 2 more
modules (upgrade)
ADT (4 modules)
right of IP4
+ space for 2 more
modules (upgrade)
Beam 1
Beam 2
PZ 45
ADT
ACS
UX 45
bunker1
bunker2
bunker4
bunker3
LL cage 1
LL cage 2
ACS klystrons
TX 46
PX 46
RB 46
Shielding wall
ACN
ADT
APW
APW
ADT
ACN
ACS
ACS
ACS
ACS
racks ACS
QUI
UL44
UX45
UX45
UL46
44
UJ4
ACN amplifiers
ACN amplifiers
US 45
W. Hofle

Beam parameters and requirements for nominal intensity:

Injection beam momentum	450 GeV/c
Static injection errors	2 mm (at β_{max}=183 m)
ripple (up to 1 MHz)	2 mm (at β_{max}=183 m)
resistive wall growth time	18.5 ms
assumed de-coherence time	68 ms
tolerable emittance growth	2.5 %
Overall damping time	4.1 ms (46 turns)
bunch spacing	25 ns
minimum gap between batches	995 ns
lowest betatron frequency	> 2 kHz
highest frequency to damp	20 MHz
choice:	“electrostatic kickers” (“base-band”)
aperture	52 mm
kickers per beam and plane	4
length per kicker	1.5 m
nominal voltage up to 1 MHz at β=100m	+/- 7.5 kV
kick per turn at 450 GeV/c	2 μrad

LHC TFB Signal processing based on LHC 1TF FB board (see Poster by V. Rossi)



AD conversion will be on
a generic Beam Position Front-end
(see Poster by D. Valuch)

Currently *installed* transverse feedback systems in CERN Synchrotrons

Accelerator	Digital / analogue processing	Power / kicker / bandwidth	Usage in operation
PS Booster (protons) 50 MeV – 1.4 GeV kin. E.	multi turn injection from Linac 2 analogue beam offset signal suppression, analogue delay (cables & switches)	100 W, 50 Ω stripline Limited to 13 MHz in operation But built for 100 MHz bandwidth, baseband	H-plane: **used and required** V-plane: beam stable w/o FB
AD (anti-proton decelerator) 3.57 GeV – 0.1 GeV	Copy of booster system	100 W, 50 Ω stripline 100 MHz bandwidth baseband	used only for excitation purposes
SPS (protons, ions) (14 – 450) GeV/c protons FT (26 – 450) GeV/c LHC beam	digital notch filter and 1T-delay (Altera FPGA, 80 MHz clock) commissioned in 2000/2001	tetrode amplifiers with two 30 kW tetrodes in push-pull directly coupled to a kicker (base band); feedback bandwidth ~10 kHz to 20 MHz	H-plane: used in operation V-plane: used in operation **used and required for operation** above $5x10^{12}$ protons (max ~$5.5x10^{13}$ ppp accelerated)

Current transverse feedback system *projects* at CERN

Accelerator	Digital / analogue processing	Power / kicker / bandwidth	Planned commissioning and usage
LEIR (ions: Pb^{54+}) 4.2 MeV/u – 72 MeV/u	copy of PS Booster System New: remote control of pick-up vector sum	100 W, 50 Ω stripline	**2007** Commissioned
PS (protons, ions) 1.4 GeV – 25 GeV (kinetic E)	synergy with LHC Damper for The low level digital processing	2 kW solid state power amplifier; 112 Ω stripline (0.9 m length), planned with ~30 MHz bandwidth in baseband, lower cut-off ~50 kHz	**2008** injection damping and feedback will be beneficial in particular for high intensity CNGS beams and LHC beams. Currently horizontal instabilities are cured by introducing coupling to the vertical plane which constrains the tunes
LHC (protons, ions) protons: 450 GeV/c – 7 TeV/c	digital notch filter and 1T-delay, built-in diagnostics 14 bit DAC Altera FPGA, 40/80 MHz clock new development in progress	tetrode amplifiers with two 30 kW tetrodes in push-pull directly coupled to kicker (base band) similar to SPS system 3 kHz -> 20 MHz	**2008** injection damping feedback loop closed during ramp switch off during physics?

Progress with Ions for LHC

I-LHC Project (ions for LHC)

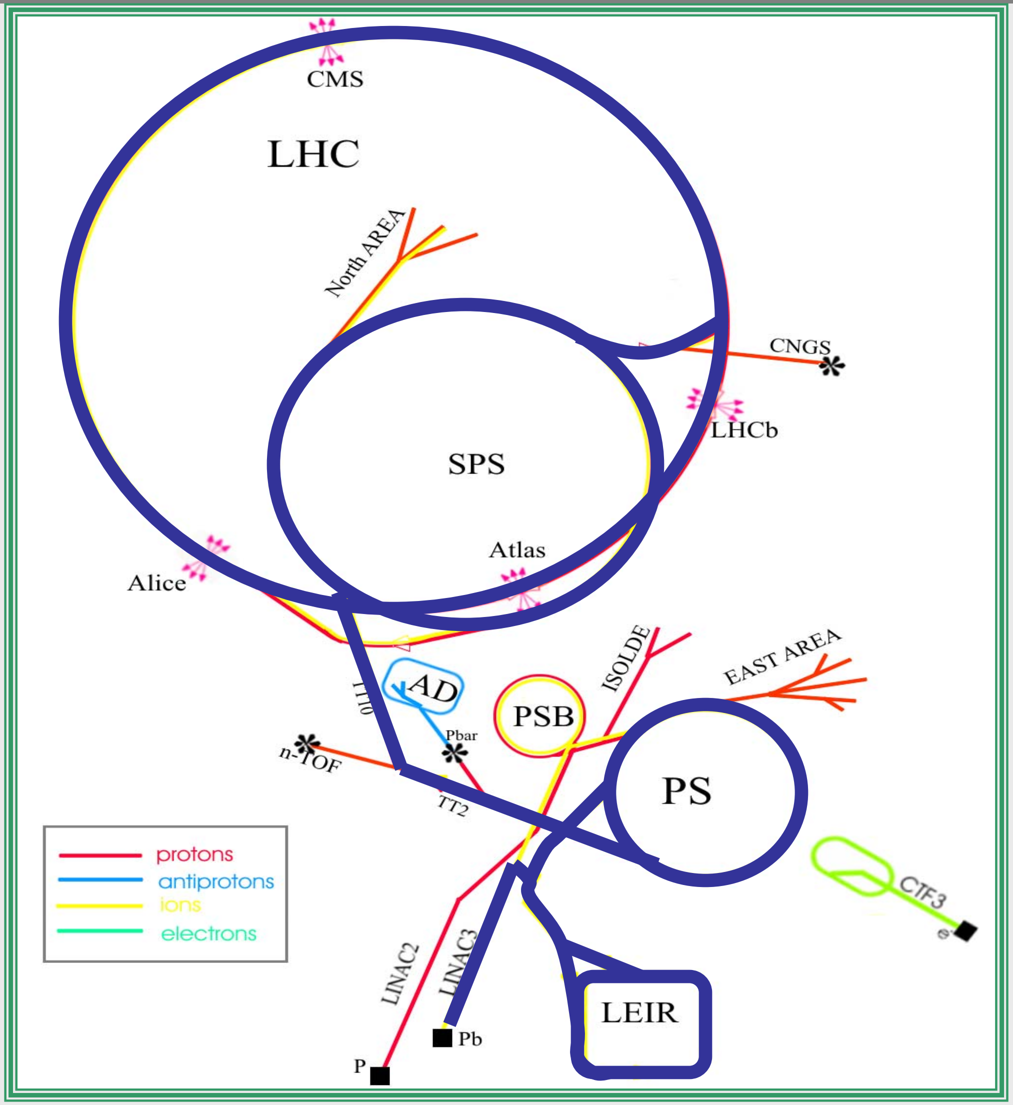
Plan: LHC to collide Pb^{82+} ions 2009

Later also lighter ions

LEIR commissioned 2005
new fully digital beam control system
collaboration with BNL

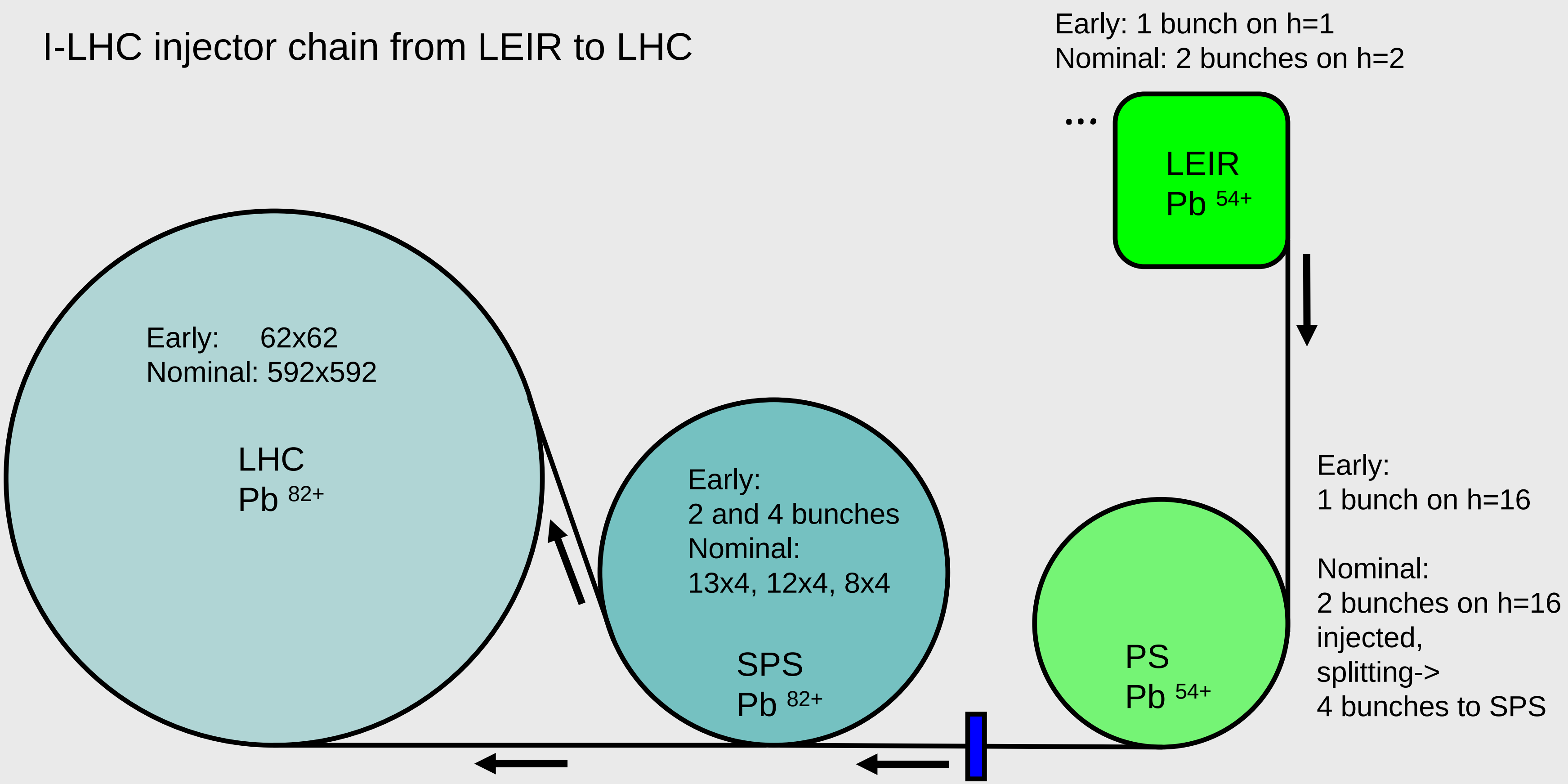
2006: Pb commissioning started in PS
dedicated LLRF system based on PS
LLRF for LHC protons (MDDS,
Multi-harmonic sources, tagged clock

2007: Acceleration of Pb ions in SPS
with new MDDS and SDDS (based
on LHC LLRF developments)
Fixed frequency acceleration



Ions for LHC – bold blue line (Linac3-LEIR-PS-TT2-TT10-SPS-LHC)

I-LHC injector chain from LEIR to LHC



I-LHC bunch trains from LEIR to LHC

891 = 8x(4b+1.25e)+7.75e + 2x[13x(4b+1.25e)+7.75e] + 3x{12x(4b+1.25e)+7.75e+2x[13x(4b+1.25e)+7.75e]} + 21e

8x4	13x4	13x4	12x4	13x4	13x4	12x4	13x4	13x4	12x4	13x4	13x4

LHC

LHC harmonic number (~400.8 MHz) h = 35640 = 10x4x891
592 bunches in 891 bunch places
gaps between batches injected from SPS: 1000 ns (9 missing bunches) abort gap: 30 missing bunches (3.1 ms)

SPS

SPS batches: 13x4, 12x4, 8x4
gaps between batches injected from PS: 225 ns (1.25 missing bunches)

PS

PS: 4 bunches: spacing ~100 ns

LEIR

LEIR: 2 bunches

Early scheme LHC (62x62): 2444 4444 4444 4444
Bunch spacing 1.350 ms (source: R. Bailey, LHC MAC June 05)

magnetic alloy-based (Finemet®), wide-band, non-tunable cavity

Dual harmonic operation *on a single cavity* (*h*, 2*h*)

Cavity servo-loop to be tuned on *h* & 2*h*

Real-time control of gap relay to short-circuit cavity

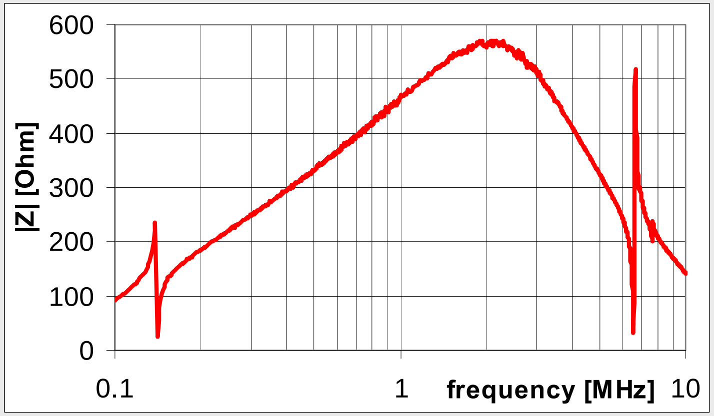
High cavity voltage dynamic range (~60 dB)

Early operation: $h = 1 \rightarrow f_{RF,MIN} = 0.36$ MHz
Nominal operation: $h = 2$

f_{RF} 0.7 – 2.8 MHz for Pb54+
f_{RF} 0.7 – 5 MHz for lighter ions

Beam control features:

- Frequency program.
- Phase/radial/synchro loops (DSP)
- Radial steering, frequency offset etc.
- Bunching after injection(s) & acceleration on same cycle.
- RF trains generation…



LEIR cavity impedance Z

M.-E. Angoletta

LEIR Digital RF Hardware

Daughter cards development continues:

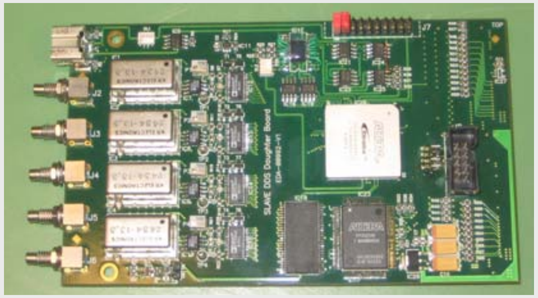
4 channel 14 bit ADC AD 9245BCP-80 (80 MHz max)

NEW:
2 MB/10 ns (instead of 500k/12ns) SRAM (1 M x 16 bits)

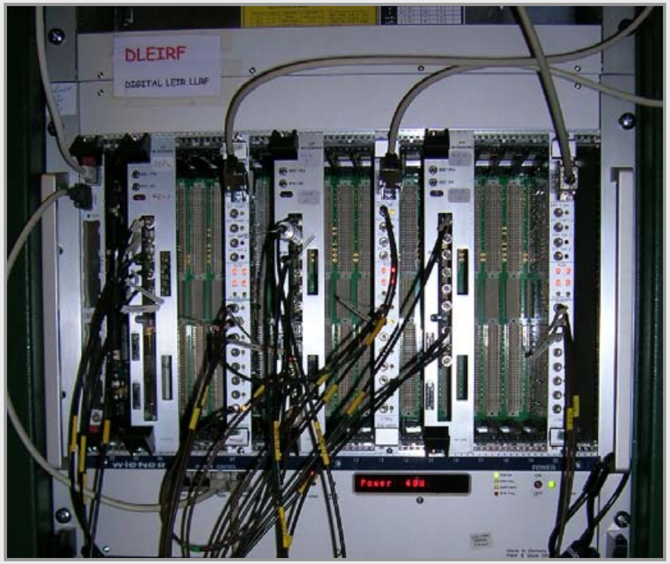
Altera Stratix EP1S20F484C5 (instead of EP1S10)

DDC digital down converter daughter card

SDDS Slave DDS daughter card



4 channel 14 bit DAC AD 9754BCP-80 (125 MHz max)
NEW:
2 MB/10 ns (instead of 500k/12ns) SRAM (1 M x 16 bits)
Altera Stratix EP1S20F484C5 (instead of EP1S10)

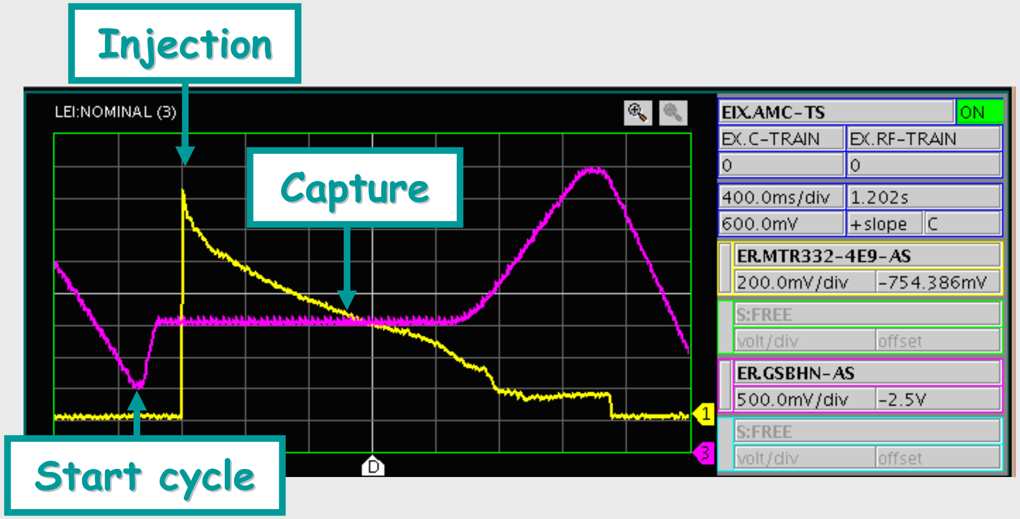


LEIR digital BC system crate & hardware

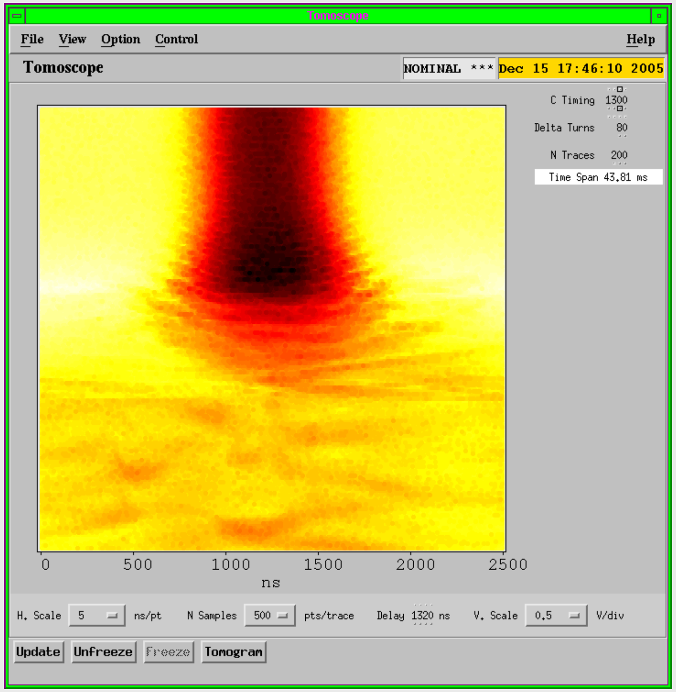
DSP carrier board with daugther cards

MDDS with AD9858 1GHz clock DDS

A. Blas



Start-up of LEIR LLRF with O^{4+}



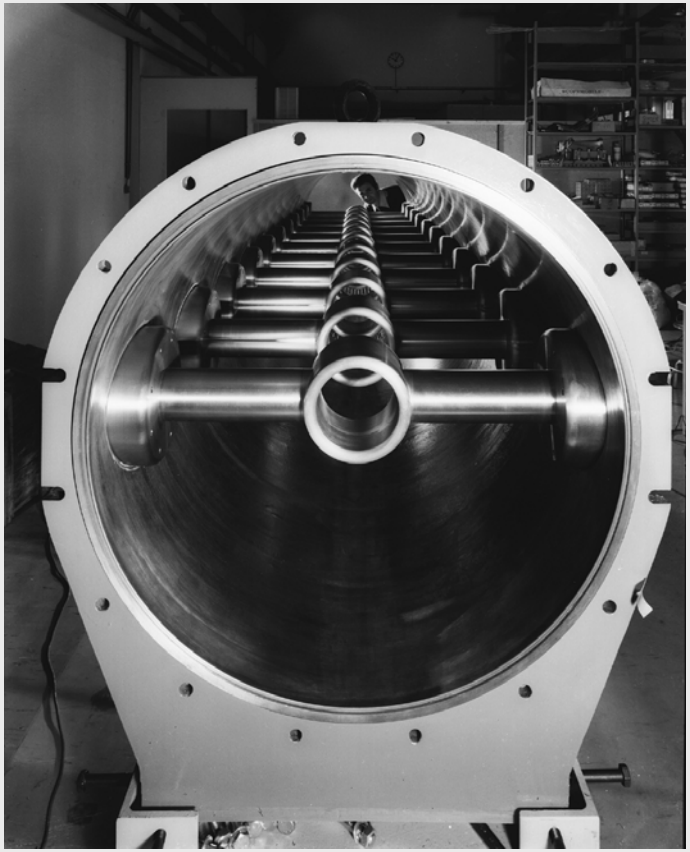
Beam capture - tomoscope "Waterfall" plot.

2005 Start of LEIR Beam commissioning, Digital LLRF
2006 LEIR providing early beam to PS
2007 LEIR operationally running with early beam for SPS commissioning; running for PS commissioning for nominal beam; work on LEIR software integration and cavity servo loops continues

M.-E. Angoletta

Pb Ions are heavy – and slow

SPS LLRF Challenges: Ions for LHC



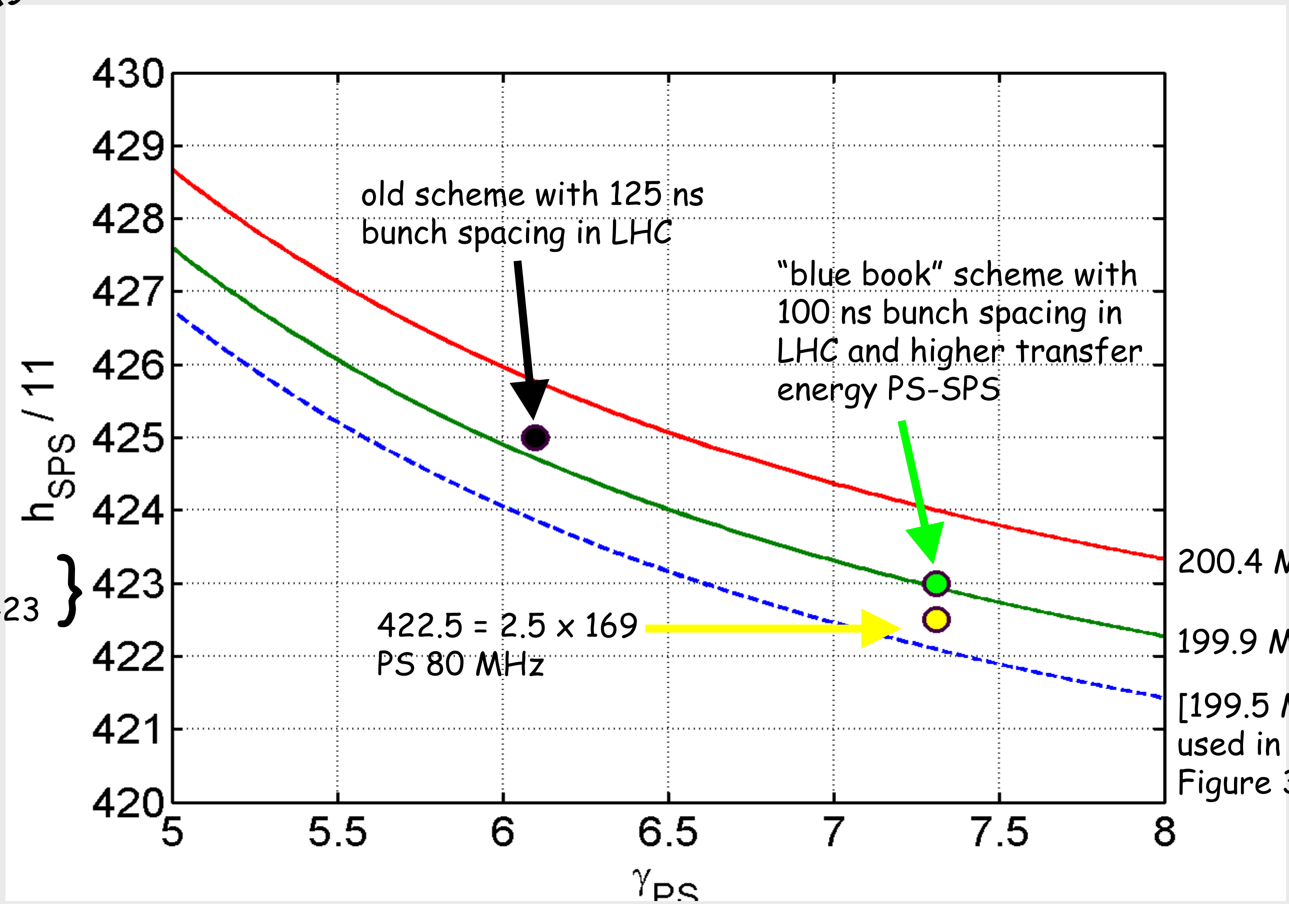
SPS Traveling wave cavity system

Center frequency 200.22 MHz

Bandwidth +/- 500 kHz

Frequency swing too large for unique h in SPS during acceleration !

PS-SPS: choice of harmonic numbers and limits from SPS 200 MHz TWC system



200.4 MHz (450 GeV/c)

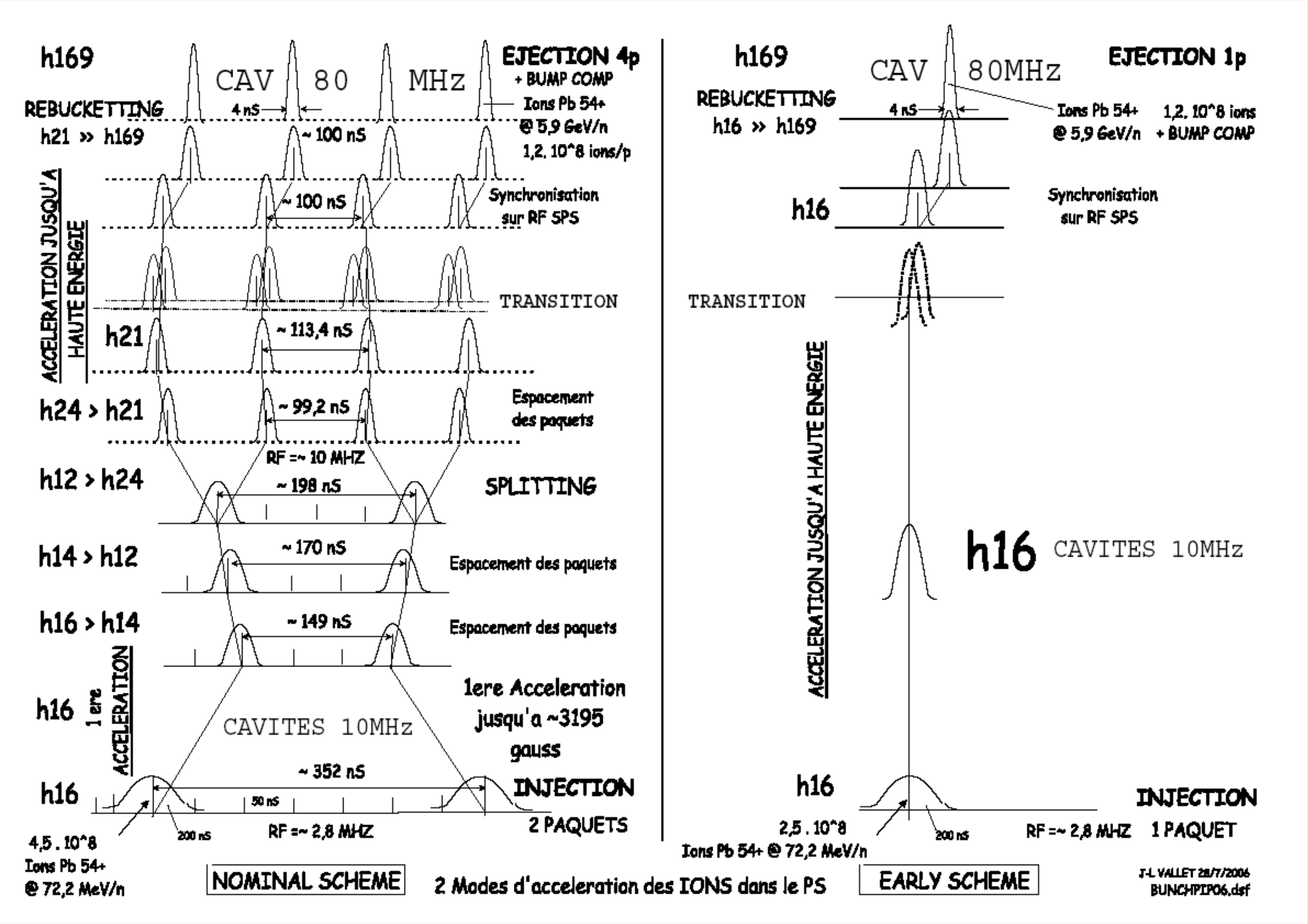
199.9 MHz (14 GeV/c)

[199.5 MHz (10 GeV/c) used in blue book, Figure 37.7]

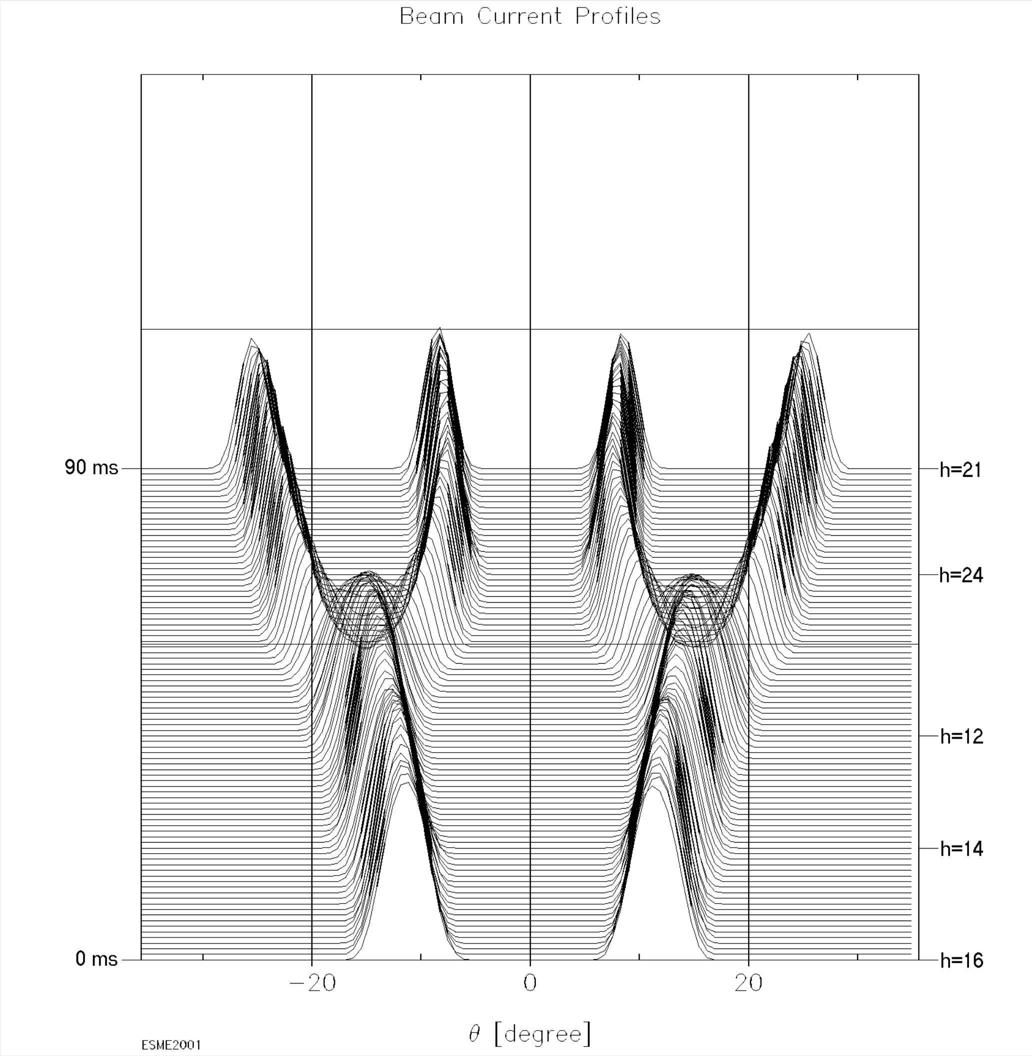
423 = 9 x 47

4653 = 11 x 423

Scheme for accelerating ions for LHC in the PS

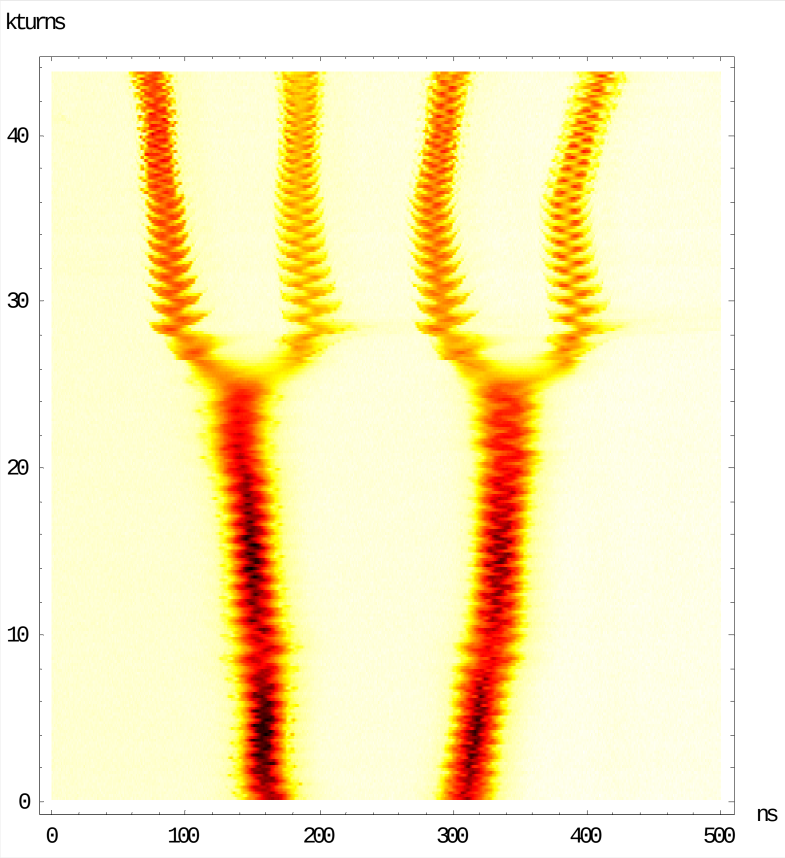


PS Ions for LHC LLRF: J.-L. Vallet / M. Schokker

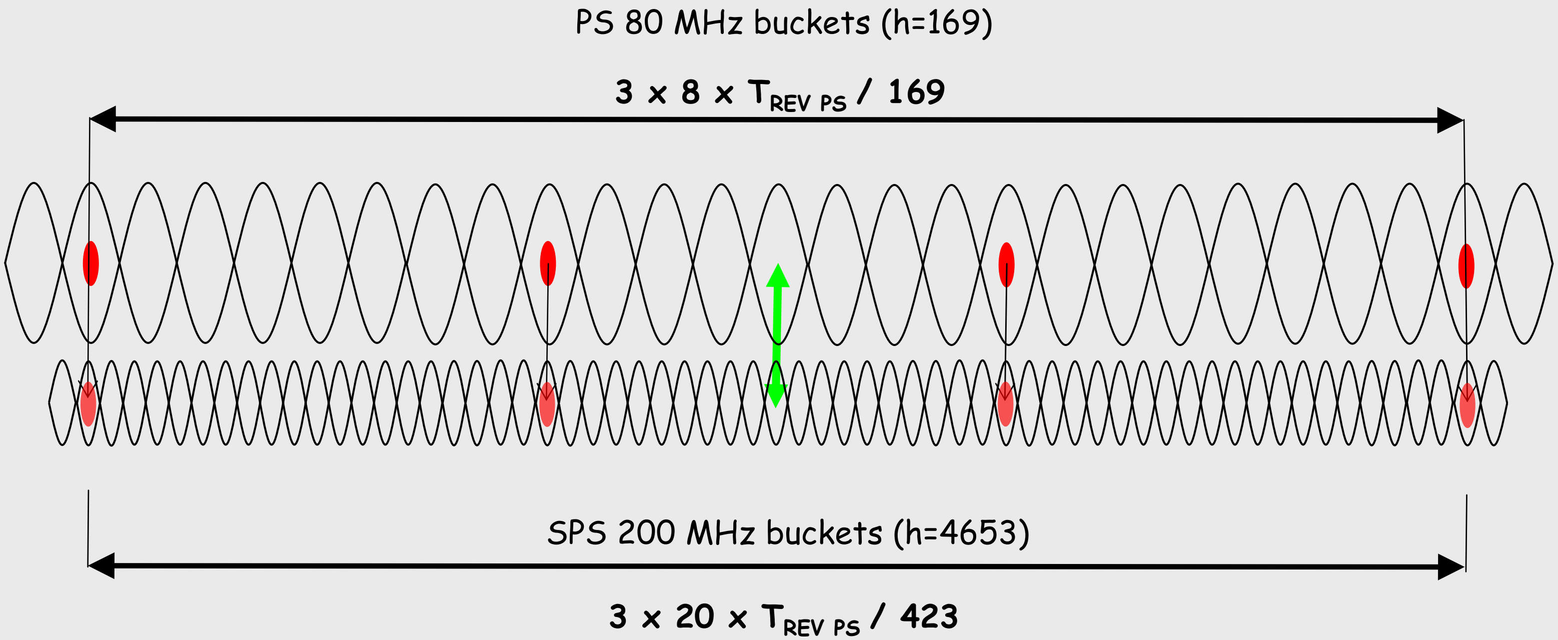


Simulation

Measurement

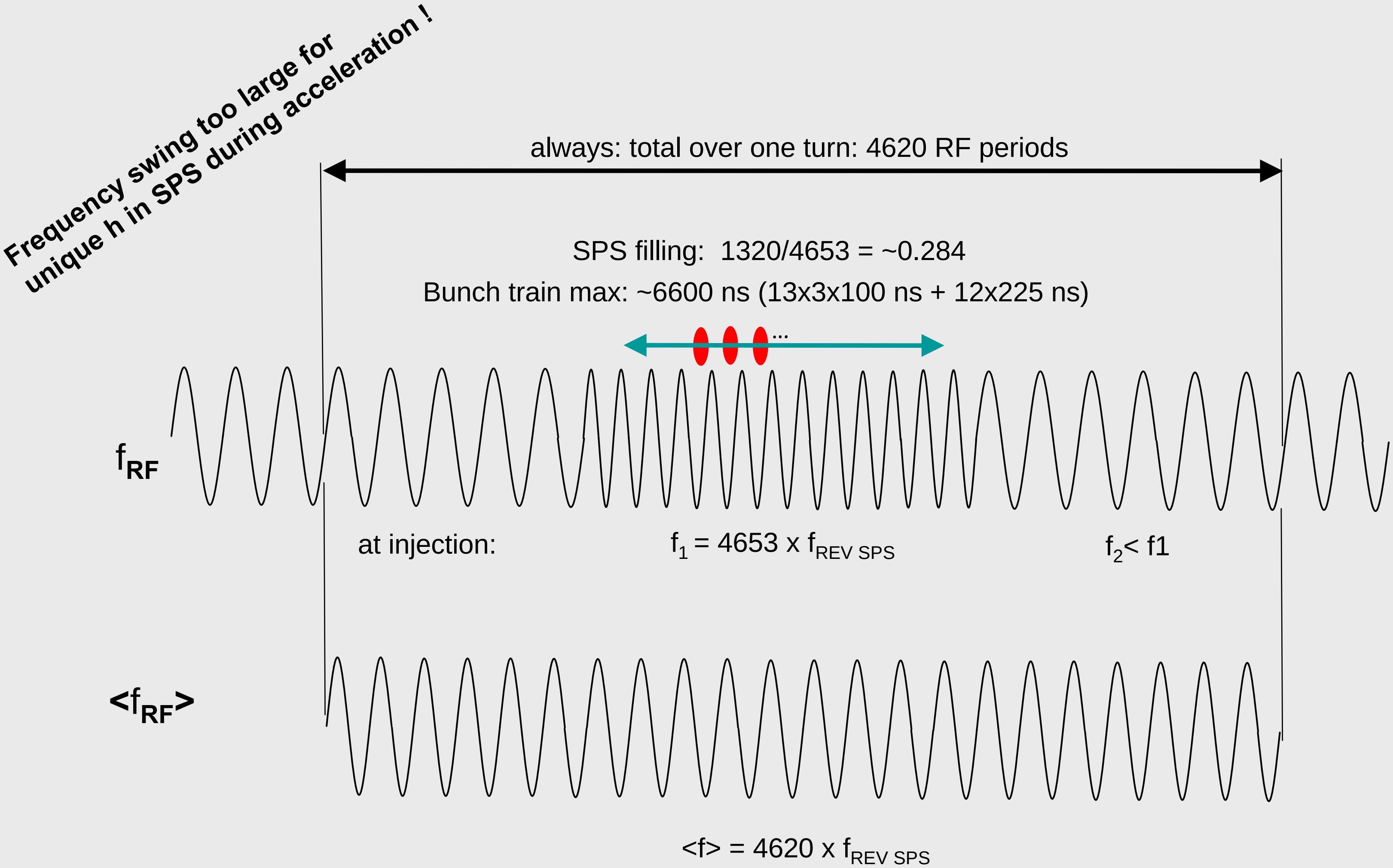


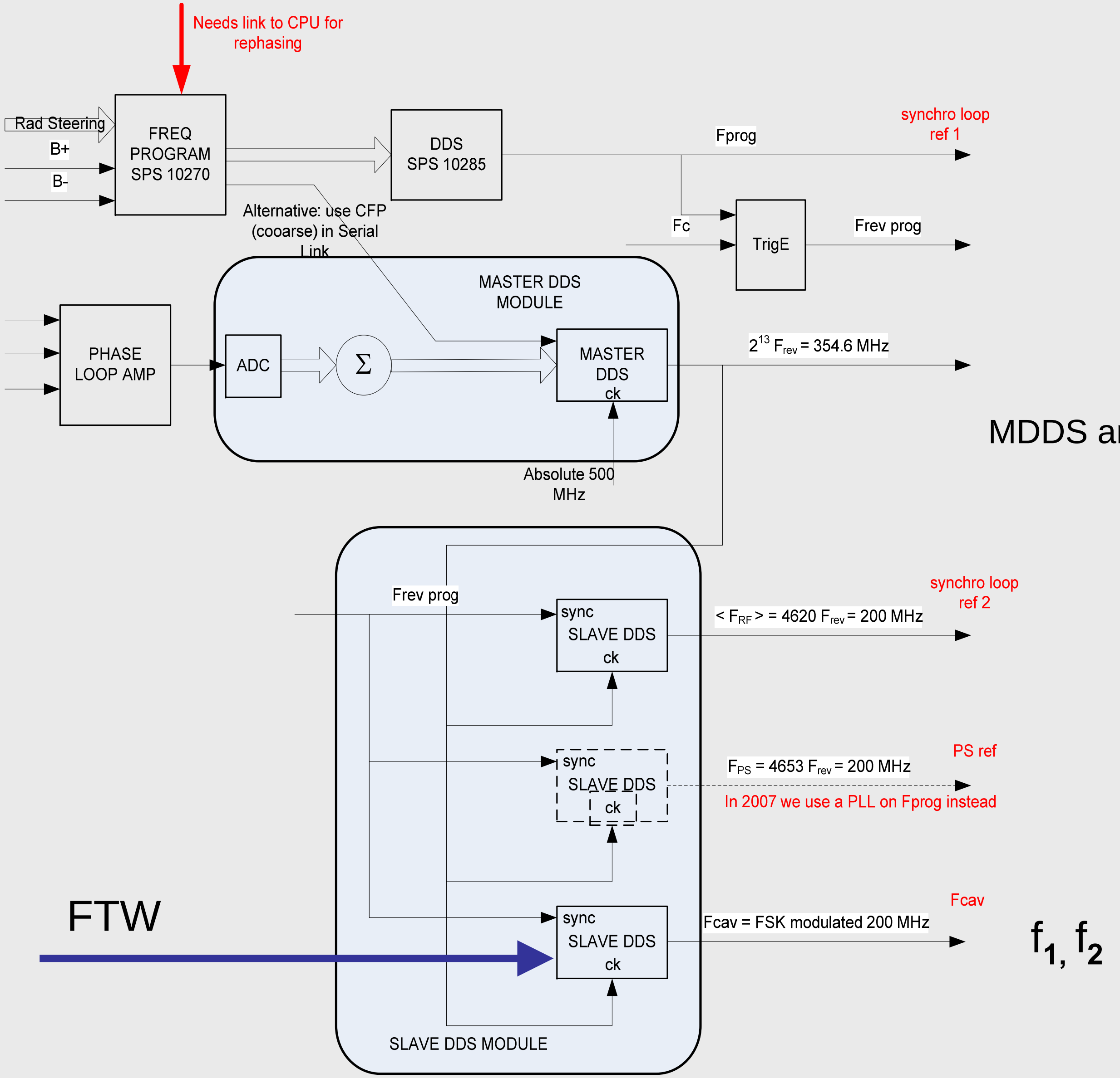
S. Hancock



Phase error for outermost bunches: $\frac{1}{2}\times 2\pi \times 423\times\left[\frac{3\times 8}{169}-\frac{3\times 20}{423}\right]=12.78^{0}$

Fixed frequency (constant harmonic number) acceleration in SPS for LHC ions





MDDS and SDDS with AD9959

1) Injection: $f_1 = 4653 \times f_{REV} \sim 199.98$ MHz f2=

2) After injection: compress batch by moving f_1 to 200.22 MHz (TWC center frequency)

3) Switch to radial loop and accelerate keeping f_1=200.22 MHz *constant*. f_2 will increase during acceleration; $\langle f_{RF} \rangle = 4620 \times f_{REV}$; f_{RF} is modulated but features always exactly 4620 periods per turn in a phase continuous way

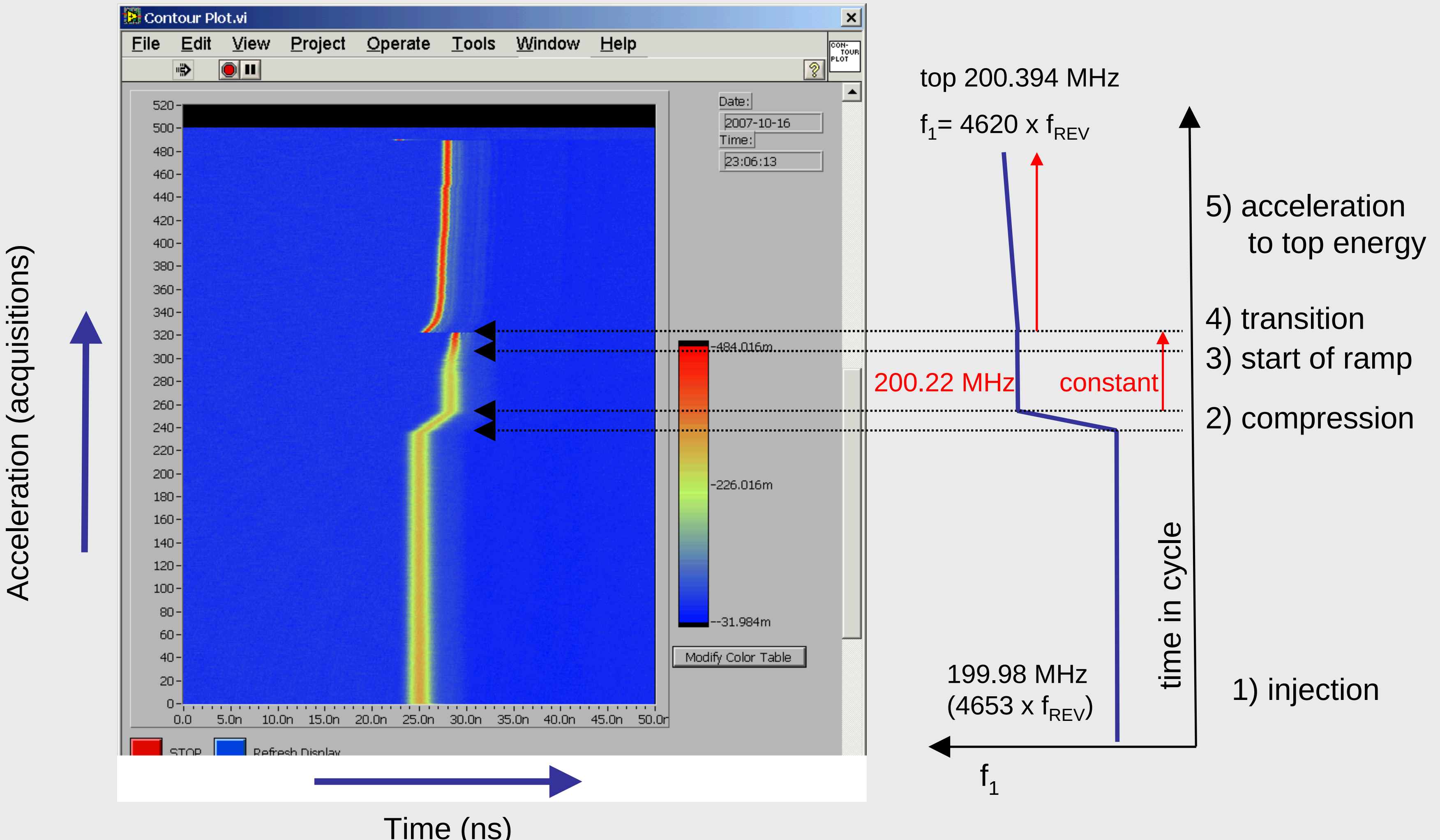
4) When $f_1=f_2$ (@transition) continue acceleration without FSK modulation $f_{RF}=f_1=f_2=\langle f_{RF} \rangle = 4620\ f_{REV}$ will increase

5) Lock on LHC RF frequency with synchro loop at top energy

Postponed to 2009

6) Rephasing with LHC common frequency f_c (maximum 1/14 of SPS circumference) will take <500 ms

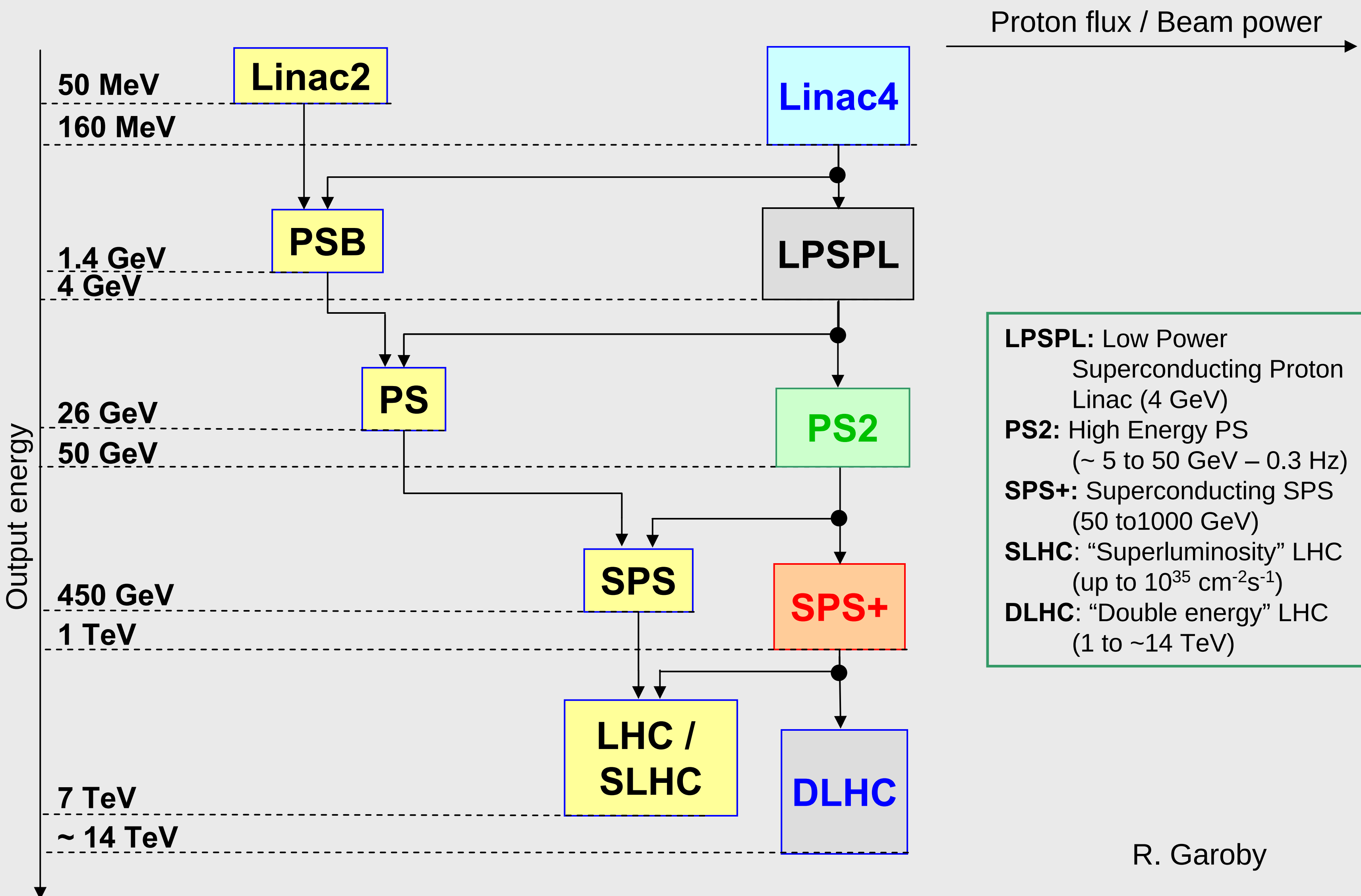
7) Fine synchronization @ 200 MHz and extraction


Contour Plot.vi
File Edit View Project Operate Tools Window Help
Date:
2007-10-16
Time:
23:06:13
484.016m
226.016m
-31.984m
Modify Color Table
STOP
Refresh Display
Acceleration (acquisitions)
Time (ns)
top 200.394 MHz
f_1= 4620 x f_{REV}
200.22 MHz
constant
199.98 MHz
(4653 x f_{REV})
f_1
time in cycle
5) acceleration to top energy
4) transition
3) start of ramp
2) compression
1) injection

T. Bohl

Future upgrades to the proton injectors

Future Upgrades to CERN Accelerator Complex [5]



LPSPL: Low Power Superconducting Proton Linac (4 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
SLHC: "Superluminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: "Double energy" LHC (1 to ~14 TeV)

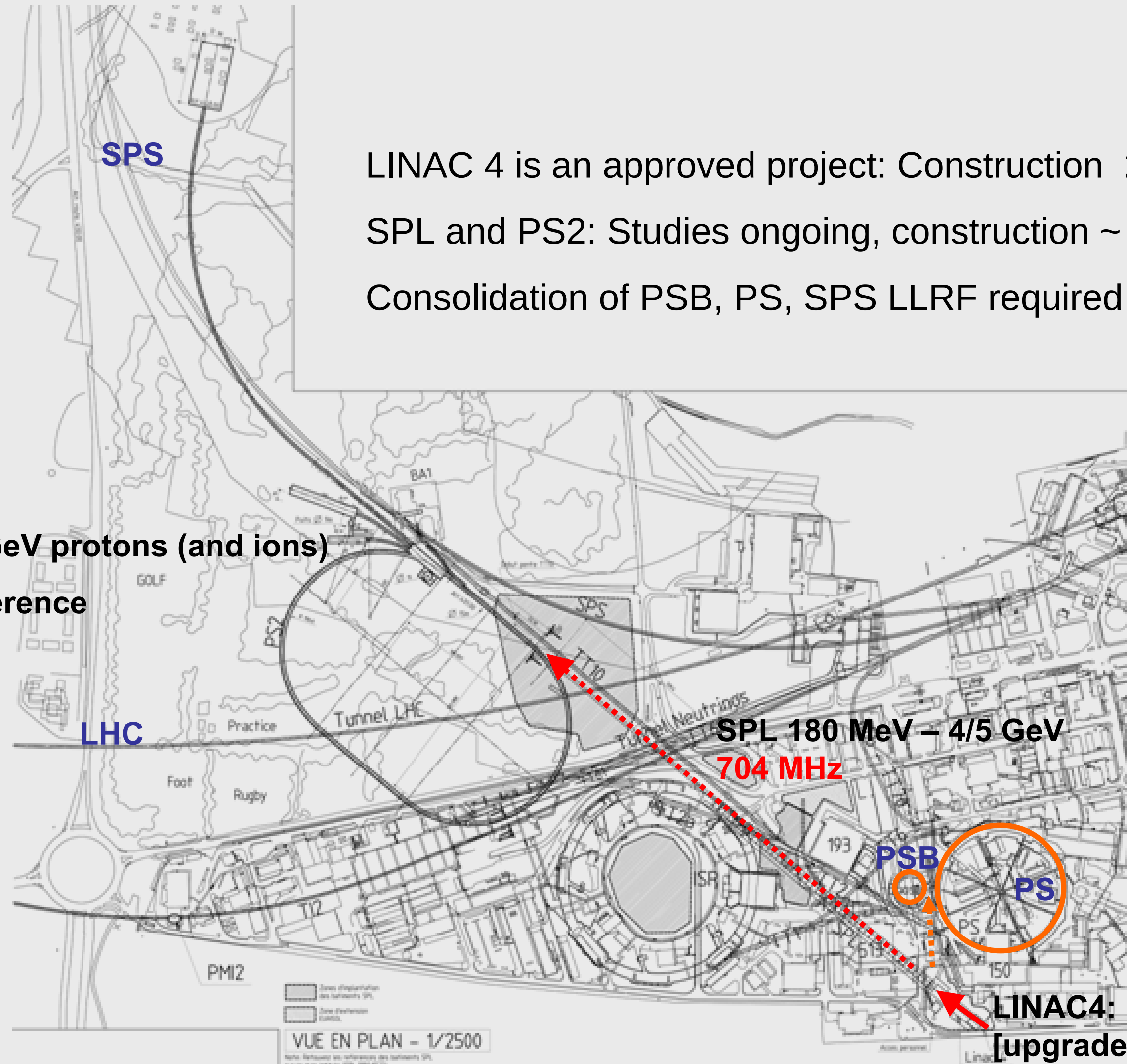
R. Garoby

Future Upgrades to CERN Accelerator Complex [5]

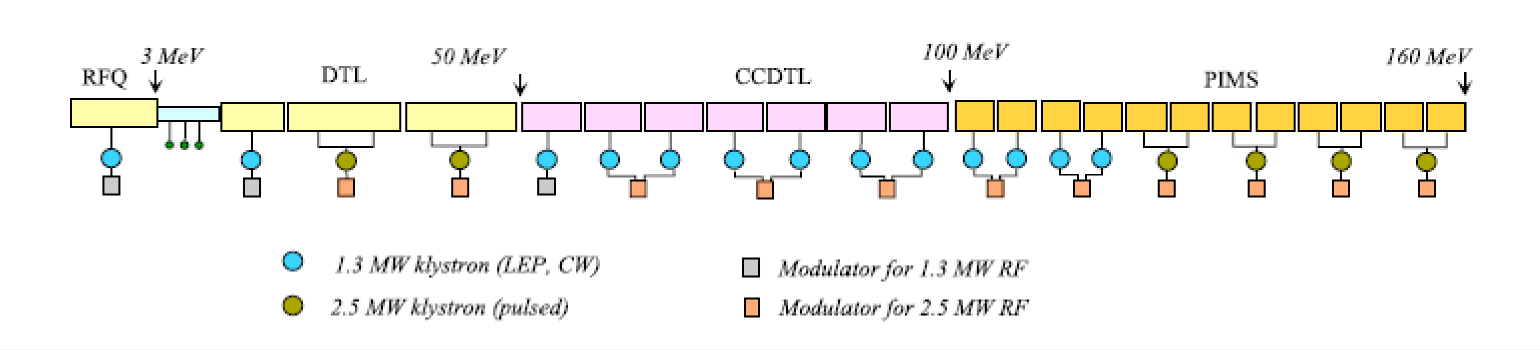
LINAC 4 is an approved project: Construction 2008-2011

SPL and PS2: Studies ongoing, construction ~ 2012-2016

Consolidation of PSB, PS, SPS LLRF required



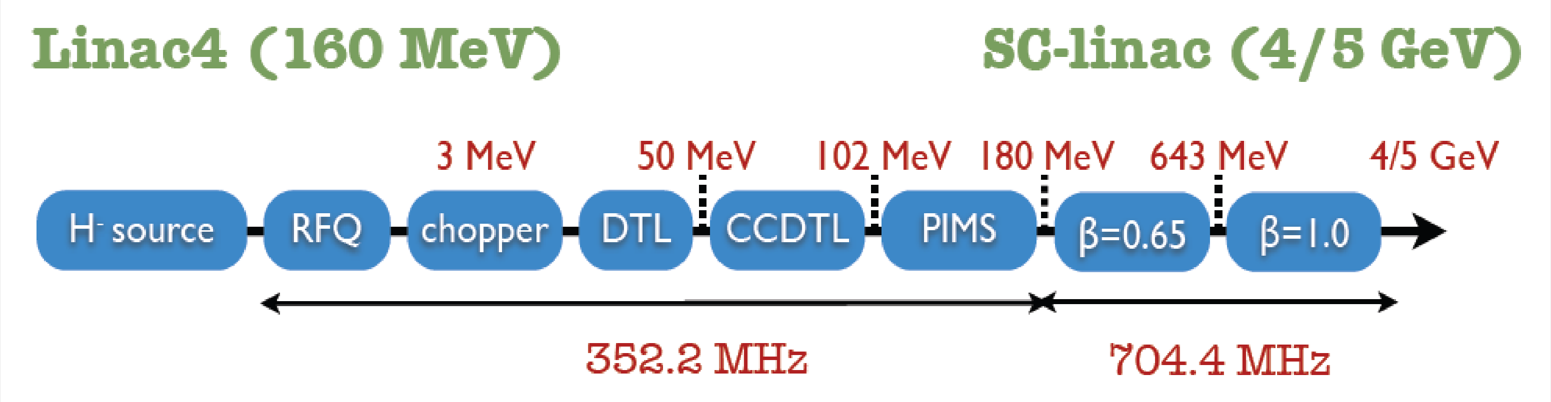
Linac4 updated design



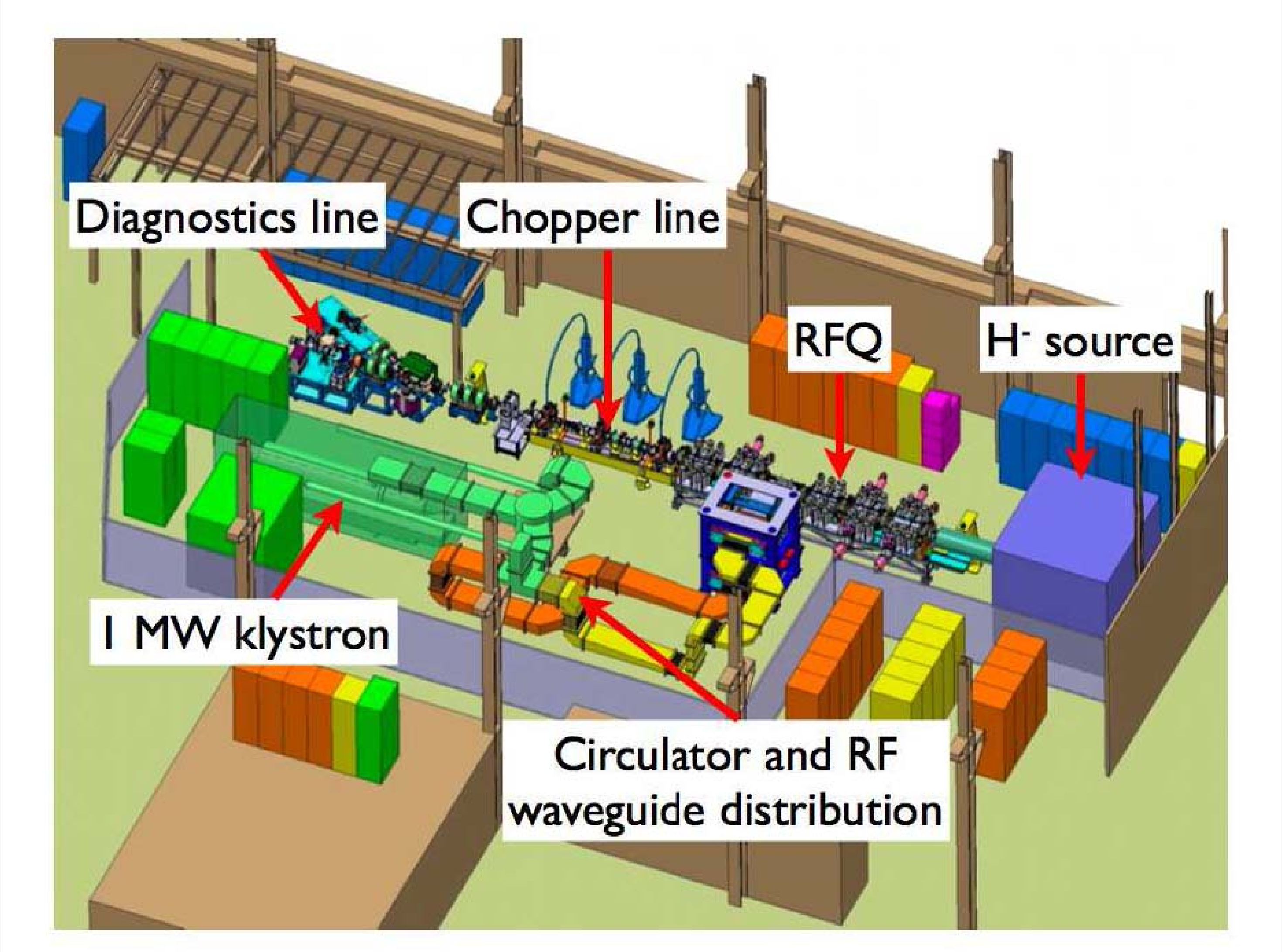
1x10^{14} H- / per pulse, 2 Hz repetition rate

F. Gerigk et. al. [7]

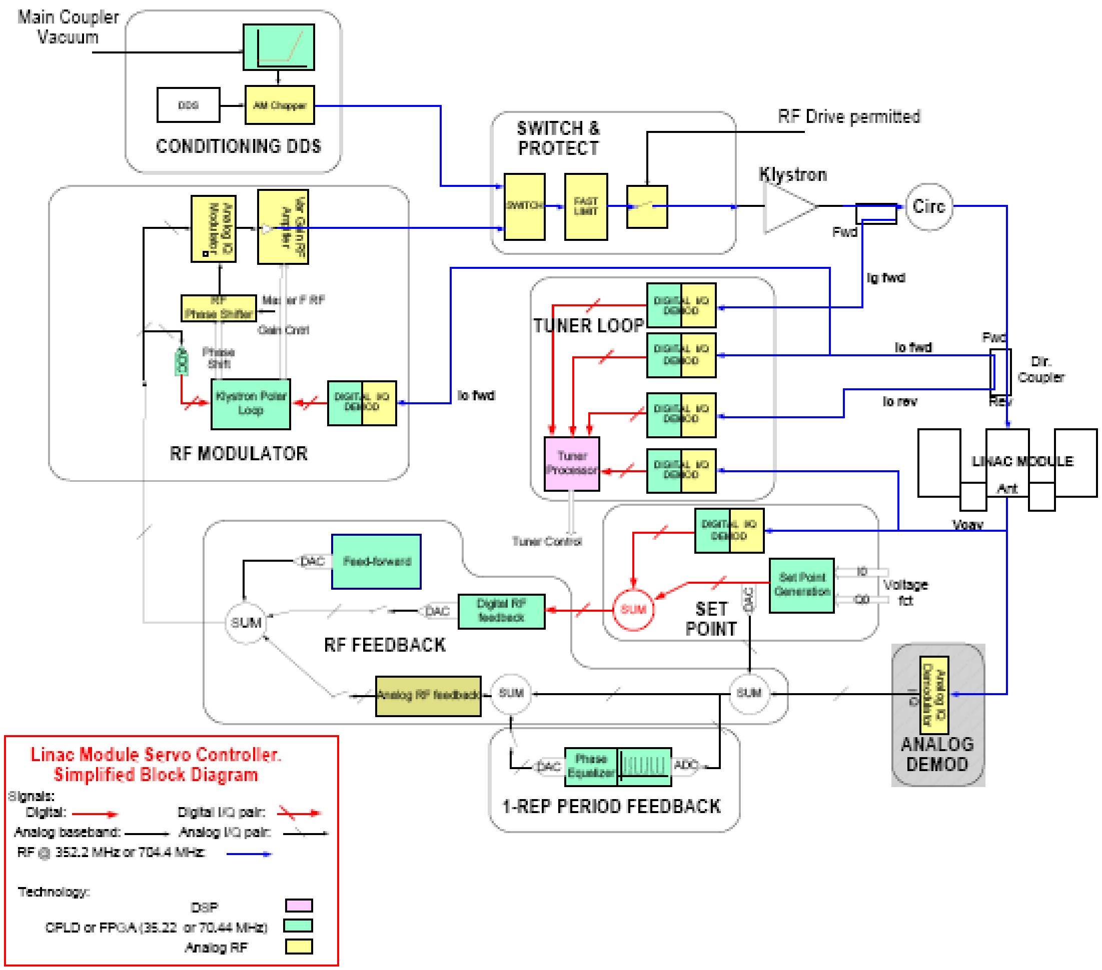
Future extension for SPL; for PS2: 1.5x10^{14} H- / per pulse (1.2 ms)



Front end for LINAC4 (3 MeV test stand)



C. Rossi [8]



LL Hardware:
similar to LHC but
at 352.2 MHz

- tuner loop
- FB (dig. only)
- Feed-forward or
  1-shot delay FB

Implementation:
same VME crate as
LHC, 1 crate/Klystron

Challenge:
phase stability
of RF distribution
re-use LEP fibers
(temp. stabilized)

P. Baudrenghien [8]

Summary

LHC en route for commissioning with beam in 2008

LHC TFB LL is based on LHC LLRF developments, migration to TFBs in other accelerators foreseen

Important progress with acceleration of ions in injectors

- New digital LLRF for LEIR successfully commissioned
- PS acceleration of Pb ions with newly configured beam control, PS RF gymnastics for ions
- SPS: Deployment of LHC based LLRF hardware for acceleration of ions successful

Upgrade of injector chain: LINAC4 project has been approved, proposal for LLRF based on LHC LLRF

For future LLRF systems:

Continue trend towards generic solutions for groups of accelerators

Not covered by presentation, but equally important

High intensity protons for CNGS

Linac2 and Linac3

AD

CLIC and CTF3 (see CLIC Workshop October 2007 [9])

References

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