Status and planning of PS & PSB B-train system upgrade

Rachel Avramidou, Anthony Beaumont, Marco Buzio, Regis Chritin, Martino Colciago, David Giloteaux, Marco Roda
TE/MSC/MM

1. Component R&D
   Integrators, synthetic B-train, White Rabbit distribution, FMR/EPR field markers, operational interface, test setups
2. PS system
   status, planning and deliverable
3. PSBU system
   status, planning and deliverable
4. Budget

Component R&D

FMC Integrator

- 100T FMC card hardware frozen
  components for 26 units ordered
  - upgrade to 64 bit Linux drivers ongoing

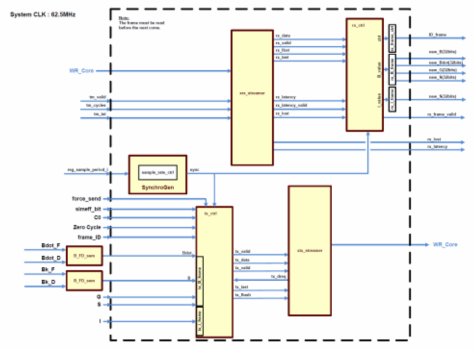
- Prototype FPGA code with basic functionality
  can be updated via the network with minimal disruption
  (a few hours estimated; all testing done offline beforehand)

- Planned improvements:
  - rewrite the prototype VHDL code in collaboration with BE/CO
  (remove timing constraints leading to occasional glitches)
  - upgrade to White Rabbit core WRPC Version 3

- Advanced functions to be implemented:
  a) on-the-fly correction of drift and gain with two markers at different levels + estimation of voltage offset and gain error
  b) use a standard DC field measurements (e.g. from NMR teslameter or Hall probe) as a variable-level field marker (necessary to correct drift on long plateaux, as in ELENA)
  c) field-dependent gating of marker triggers to reject spurious resonances
  d) field-, current- and history-dependent calibration parameters such as the magnetic length (to model saturation and hysteresis effects)

Kontron KISS: Open Modular Computing Specification industrial PC bus standard.

SPEC (Simple PCIe FMC carrier) + FMC
(FPGA mezzanine cards) for modular custom electronics.



VHDL streamers in the Spartan 6 Xilinx FPGA

Measurement resolution

The magnetic field resolution ΔB (unlike the old system) is a function of many parameters and changes continuously during a cycle

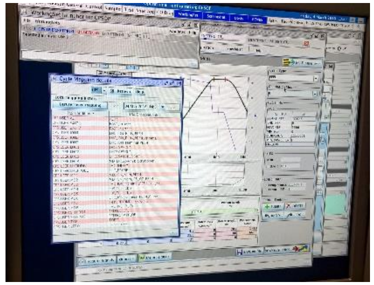
Limiting factors:

- discrete serial distribution: $\Delta B = 10$ nT (LSB of a 32-bit value)
- theoretical resolution of the integrator:
  function of the attached coil, $\Delta B = \frac{2^{-n} V_{in}}{A_c f_s} < 1$ nT typically
- WR frame processing and distribution:
  $\Delta B \geq f_{WR} \frac{dB}{dt} \approx 3\ \mu$T (0.03 G) for the PS, 6 μT for PSB
  NB: today $f_{WR} = 250$ kHz, theoretically 1 MHz is possible but untested yet
- measurement noise: must be measured on the final setup, expected to be in the range 1 to 50 μT

(NB: similar target for all machines, since the coil is always specified to get a few V output. Major differences may come from marker reproducibility)

Synthetic B-train today

B_{up}/B_{down} distributed on same channel as the measured B-train
three different functions carried out with the same facility

LSA →  → GM/FESA2 classes → Btrain FEC → dB/dt or Bup/Bdown signals

Cycle reference

1. Reference B(t) or dB/dt
   to be used to check the RF system
2. Reference B(t) or dB/dt
   kicking in in case of power converter fault

No magnetic field
No beam

Aim: conformity to reference

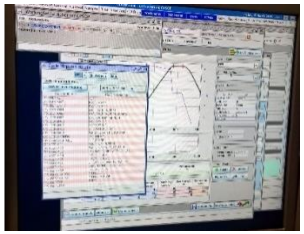
3. Estimated B(t) or dB/dt
   used in special cases as a replacement for the measurement

Normal operation
Aim: accuracy

New FMC-based field synthesizer/simulator

LSA

Cycle database



B(t) vectors

SIMULATED B-train

no current in the magnets

image of reference field

machine restart, RF cavity tuning

$B_i = B(t_i)$ samples calculated in RT

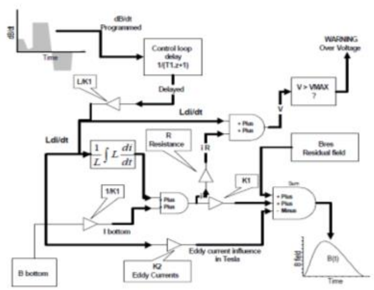
$I_1(t)$

$I_2(t)$

$I_3(t)$

…

Excitation current measurements



$$B = B_0 + k_1 I_m - k_2 L \frac{dI_m}{dt}$$

Mathematical magnetic model

SYNTHETIC B-train

replaces the measurement

reference

New requirement since 2015

dedicated PJAS expected 09/2016

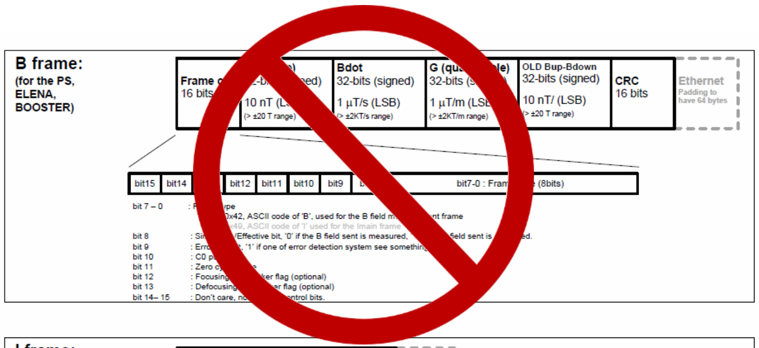
marco.buzio@cern.ch

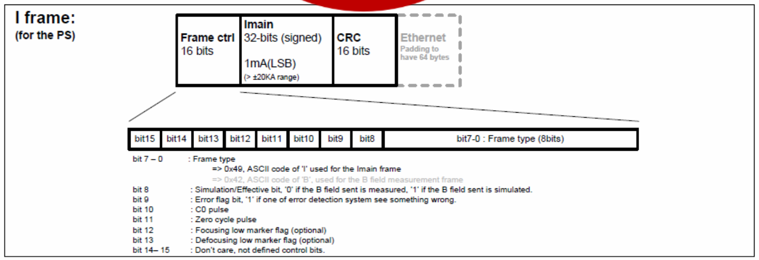
- Successful tests of transmission at the PS to RF and tx/rx from POPS
- Measured performance: latency 10 μs @ 250 kHz (RF), 5.6 μs @ 1 kHz (POPS), jitter 2 $\mu s \rightarrow$ field error $< 30\ \mu T$ on acceleration ramp
- Regular meetings, strong support being received by BE/CO
- Currently being upgraded to production version FESA core 3 (expected to be stable)
- NB: serial distribution of values, not increments → no need for initial pulse burst
- Major upgrade of Ethernet frame being implemented:

1) **Incorporate permanently B_{up}/B_{down}**
   Useful across 5 machines from here well after start run 3

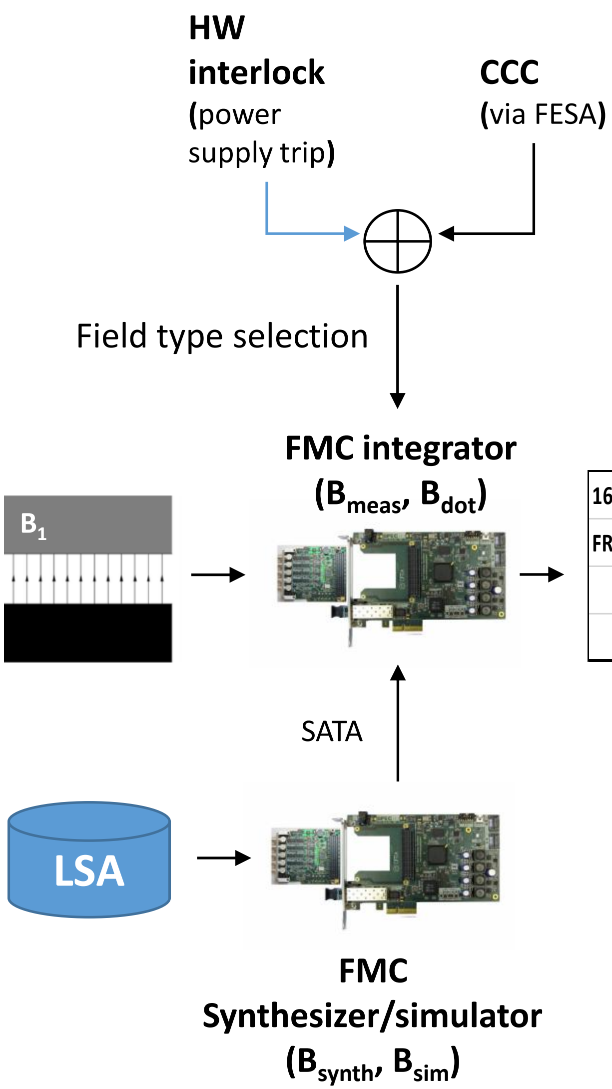
2) **Drop field multipoles slots**
   - included in the original specification (2011) as placeholders for possible future extensions
   - not needed in real time
   - even assuming multipole power converter as future users (remembe B_2 feedback to quad PC used at SPS in the past)
   they would use a separate WR connection
   - not easy to merge into the B frame anyway (any integrator is dedicated to one field component only)

3) **Introduce synthetic B-train**
   Not originally foreseen





White Rabbit distribution – production Ethernet B-frame



The meaning of the slots is fixed for all operating modes and machines (tradeoff between 15% wasted space vs. implementation simplicity)

active field slots
meaning changes according to selected field type and order

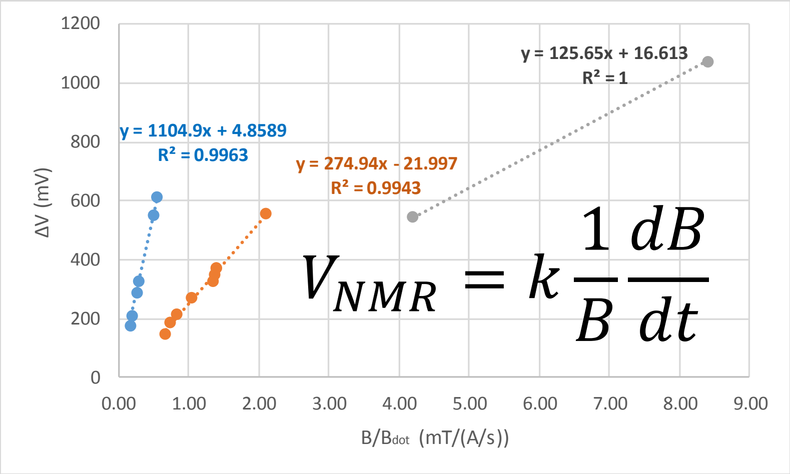
diagnostic field slots
make possible high resolution, error checking in real time

16 bit	32-bit signed integer	32-bit signed integer	32-bit signed integer	32-bit signed integer	32-bit signed integer	32-bit signed integer	16 bit
FRAME CTRL	Active B_n	Active dB_n/dt	Old B_{UP}/B_{DOWN}	$B_{n,measured}$	$B_{n,synthetic}$	$B_{n,simulated}$	CRC
	10 nT (LSB)	1 µT/s (LSB)	10 nT (LSB)	10 nT (LSB)	10 nT (LSB)	10 nT (LSB)	
	range ± 21.5 T	range ±2145 T/s	range ± 21.5 T	range ± 21.5 T	range ± 21.5 T	range ± 21.5 T	

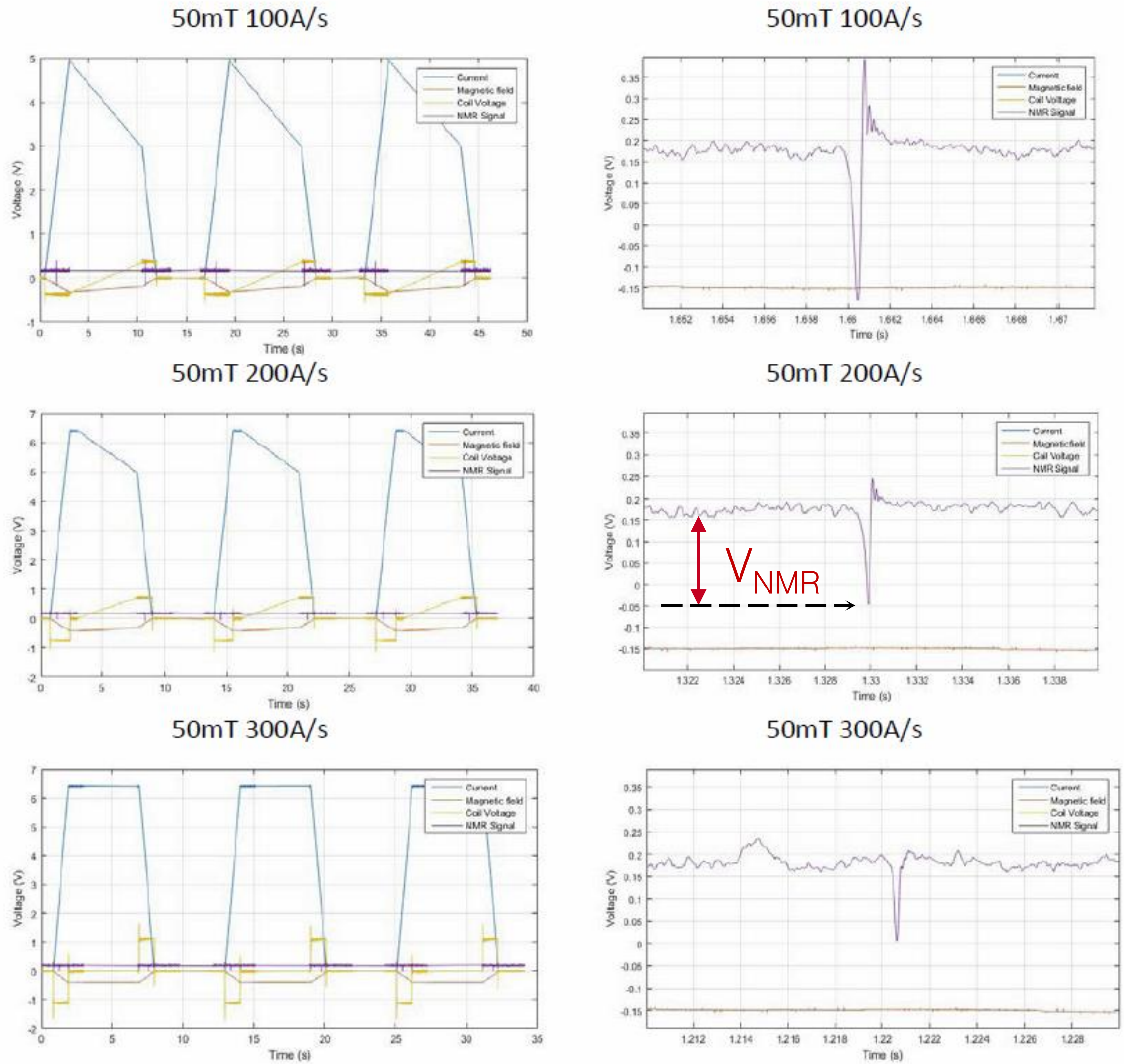
CONTROL frame (common to B and I frames):

- **Frame type** 1 bit "Bn" or "In"
- **n** 3 bits order of the field multipole (n=1 dipole, n=2 quadrupole … n=6 dodecapole) *or* index of the power converter (n=1 POPS, n=2 F8L ….)
- **Field type** 2 bits measured || synthetic || simulated

- Hall-probe array being tested for absolute multipole measurement
- NMR marker for ELENA being optimized (along with FMC peak detector)
- Peak detection threshold must be parameterized to allow for flexibility in setting the marking point



$$V_{NMR} = k\frac{1}{B}\frac{dB}{dt}$$

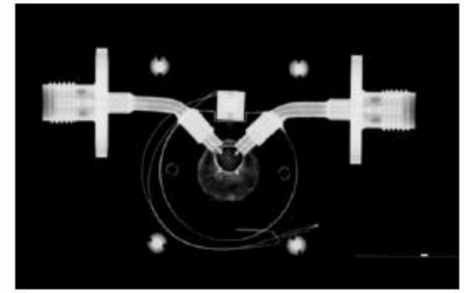


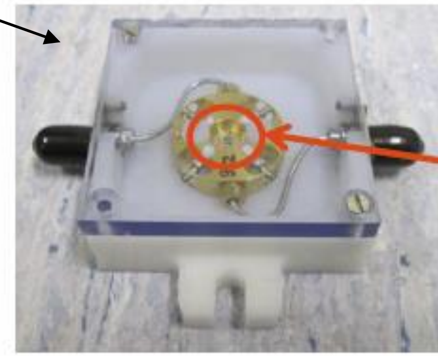
FMR field markers

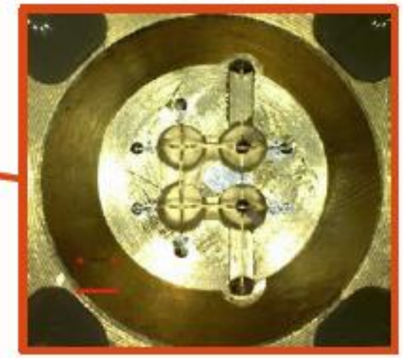
- <u>Currently installed</u>: commercial Omniyig single-crystal YIG (50 to 400 mT)

Prototypes under study:

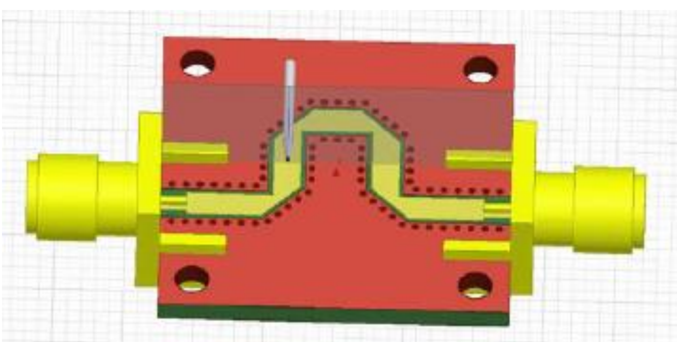
- Rhode & Schwarz YIG for medium-high field application (100 to 700 mT)
- Custom-made PCB-based resonators developed in partnership with EPFL with either FMR or EPR samples
  (aim: master this critical technology, produce large numbers relatively inexpensively. Integrated microelectronics for high frequency will be developed by EPFL).



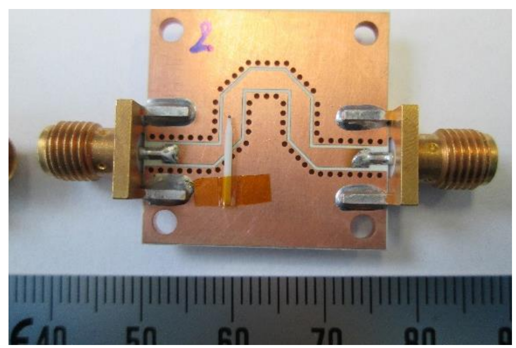




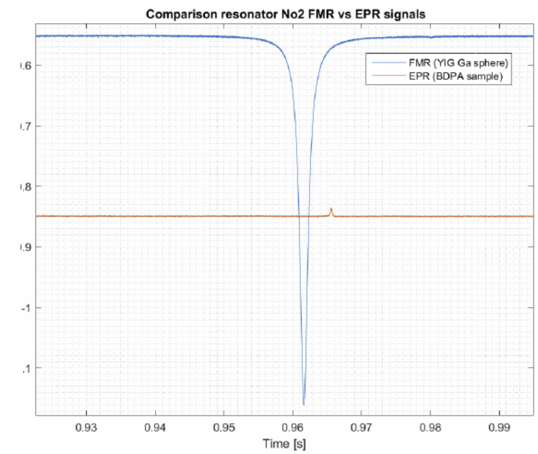
Courtesy Gerd Hechtfischer (R&S), Fritz Caspers



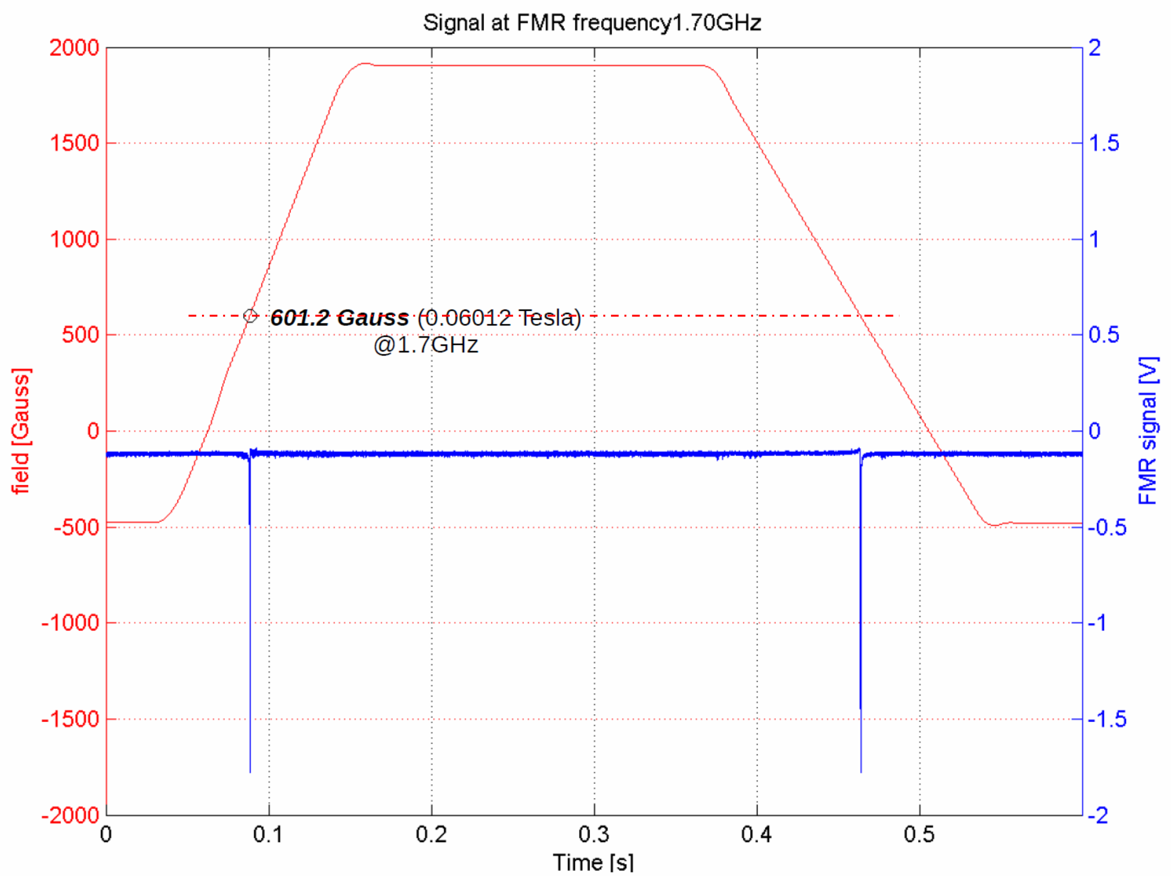
transmission /reflection/resonator configurations being designed with Ansys HFSS



first batch of prototypes being tested with FMR and EPR samples (EPR gives weaker signals, potentially with superior S/N ratio)



- Possibility to mark the field also on the down-ramp
- Continuous correction of drift, in preparation for next cycle even if beam not present (2 × improvement expected)



Field markers - operational flexibility

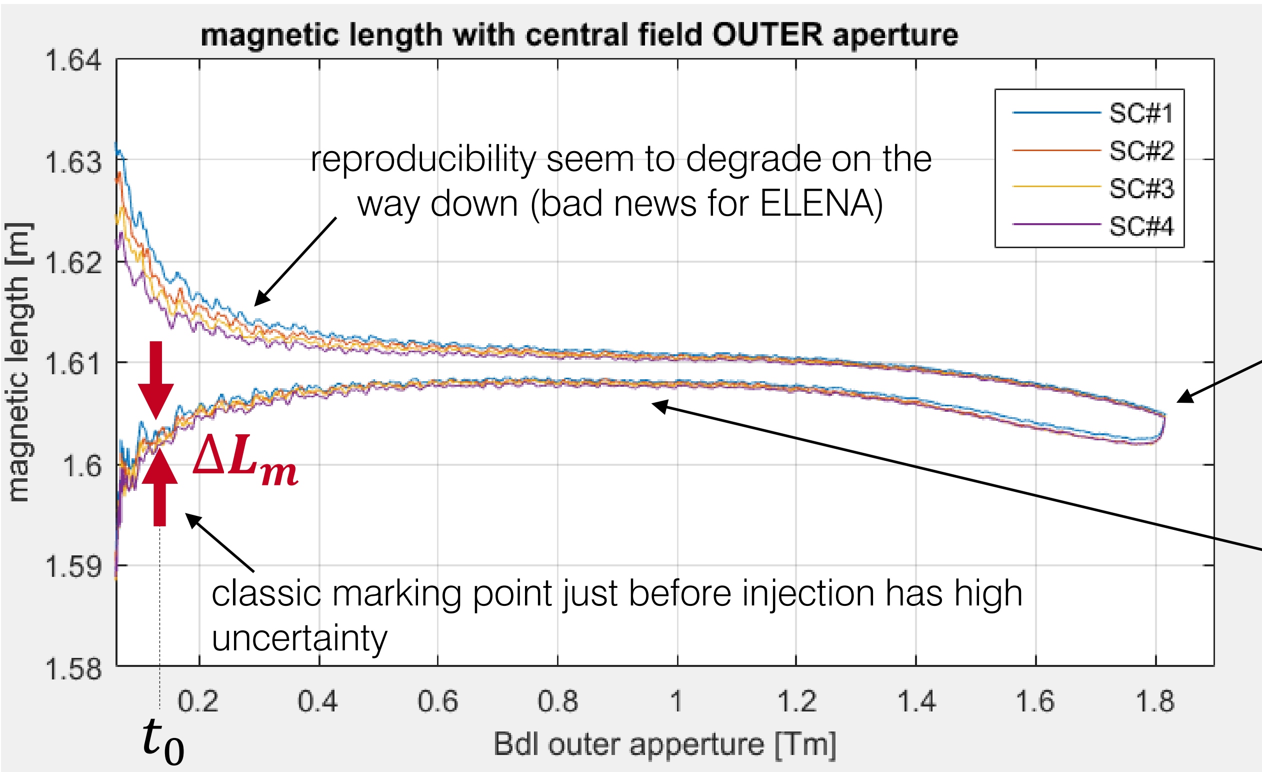
- PPM setting of $B_0 = B(f_0)$ mode possible in principle via FESA classes (to be tested)
- BUT: markers will be optimized for a specific field/frequency and the marking point will be optimized. Also the calibration curve is non linear and repeatability changes vs f.
  Why not define alternative diagnostics ? (now would be the right time to ask !)

$$B(t) - B_{meas}(t) = \frac{1}{A_c}\int_{t_0}^{t} V_o(\tau)d\tau + B(t_o)\frac{\Delta L_m}{L_m}$$

B-train measurement error

Fluctuating coil offset (drift error)

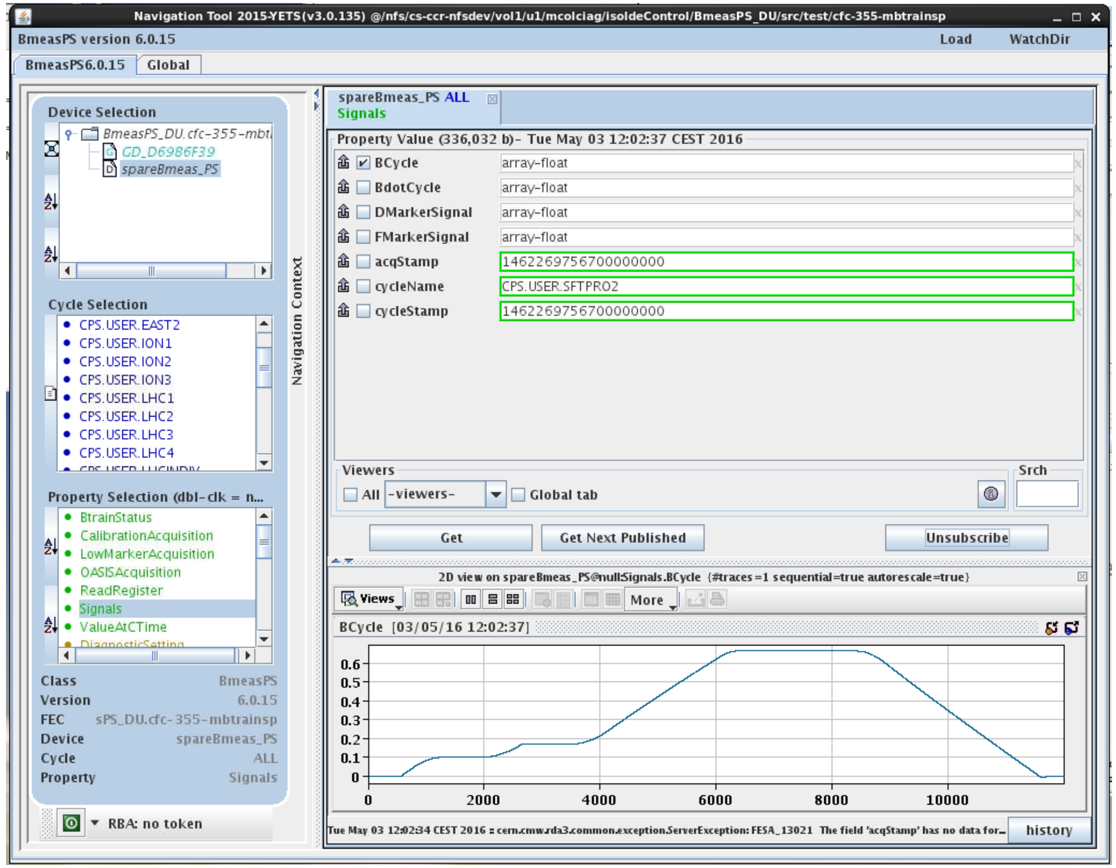
Error due to the reproducibility of the magnetic length



Zero uncertainty at the end of the flat-top (least useful place for accelerators !)

Optimal marking point might well be in the centre of the linear range of the magnet

- Prototype class BmeasPS v. 5.0 deployed in PS OP system
  (quick-and-dirty class hacking together all functionality, hardcoded configuration and defaults)
- C++ code being refactored to increase modularity and allow uniform implementation in all machines
  Functionality of FMC cards, NMR interface and frequency generator split across standard C++ classes
  New FESA classes being tested in the PS SPARE system (BmeasPS v. 7.0) and in the bldg. 30 test station (Bmeas v. 0.1, to be deployed in ELENA)
- NMR code shared with other applications (ISOLDE, FFMM)
- Frequency generator compatible with multiple models



- Limitation being explored: amount of data that can be transferred from each FEC to the CCC at the end of each cycle (upcoming issue: very long ELENA cycles)
- Review planned with FESA team as soon as full spec completed

Operation Interface

- Configuration done at present via FESA Navigator

- CCC Java application: no competence/mandate

- Configuration parameters
  - switch OP/SPARE
  - switch MEASURED/SYNTHETIC/SIMULATED/OLD (B_{up}/B_{down})
  - integrator calibration coefficients: magnetic length, weighting factors, coil areas …
  - marker detector calibration coefficients: detection mode, voltage threshold, repetition delay …
  - internal configuration: decimation factors and data rates for DMA data transfer; internal ADC recalibration, …
  - marker field level (RF excitation frequency)
  - WR output data rate

- Diagnostic parameters
  - decimated signals (downsampled to 10 kHz) via FESA: B, Bdot, raw sensor output (marker, measuring coil)
  - high-speed signals provided in analog form to OASIS
  - auxiliary sensors (coil array, Hall probes, additional FMR markers)
  - continuous comparison between operational and spare chains, old and new measurement (where applicable), and between measured/synthetic/simulated magnetic fields → alarm levels to be raised (integrated in LASER ?)
  - internal diagnostics: drift and gain error (evaluated upon each marker arrival)
  - continuous evaluation of measurement uncertainty

Yet to be discussed: VISTAR as an additional White Rabbit user

General principle: all that can be done offline (i.e. not eating up beam time), should be

- Bldg. 30 (moved to 311 in 2018)
  main MSC/MM electronics lab, used for development activities and (upcoming)
  remote diagnostics

- Bldg. 375 (ISR8)
  main MSC/MM magnet test lab
  hosting two field marker test station (ELENA + 10 T/s dipole)

- Bldg. 867
  - unique test station in the HEP community equipped with 2 × 6kA power supplies (only station where the PS MU can be tested in with all combinations of main excitation + F8L + 4×PFW excitation circuits)
  - proposed test station for the PS, PSB (SPS) B-trains
  - some refurbishment needed (esp. power supply control)
  Objectives:
  - <u>validate the full PS B-train before replacement in LS2</u>
  - <u>full matrix current/harmonics at multiple working points</u>
  - <u>develop and test new integral coil fluxmeter</u>
  - <u>measure calibration parameters</u> (coil surfaces, magnetic length …) in all relevant cycle combinations


10 T/s dipole test bench in I8


B-train development rack bldg. 30

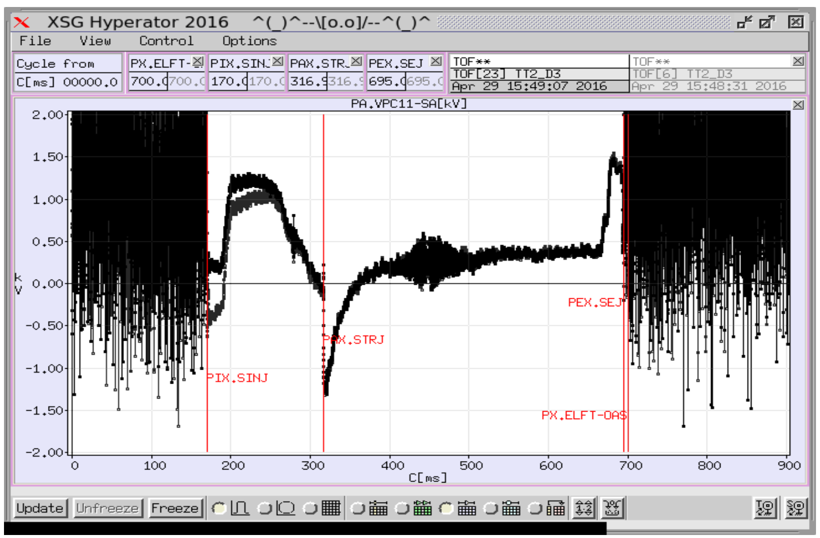
PS U17 under test in bldg., 867 (2005)

PS B-train Status and Planning

Status of PS B-train

- Prototype system deployed progressively since 2014, currently measuring in parallel with the old system and calibrated to be as close as possible to it (on selected cycles)
- Sensing coils: spare ~300 mm coils in F3/D3 blocks
- Omniyig FMR field markers: (f=1.38 GHz, B=495 G): 2× in D, 1× in F

- Nov 2015
  new measurement fed back to RF, protons and ions accelerated for different users including LHC, EAST, nTOF, AD, STFPRO …
- Dec 2015
  new measurement fed back to POPS, field regulation only (no beam) on cycles LHC and STPRO
- May 2016
  protons accelerated with old B_{up}/Bdown distributed via WR (RF only, with new frequency program)



MRP during a nTOF cycle

Difference old/new B measurement, typically < 1 G

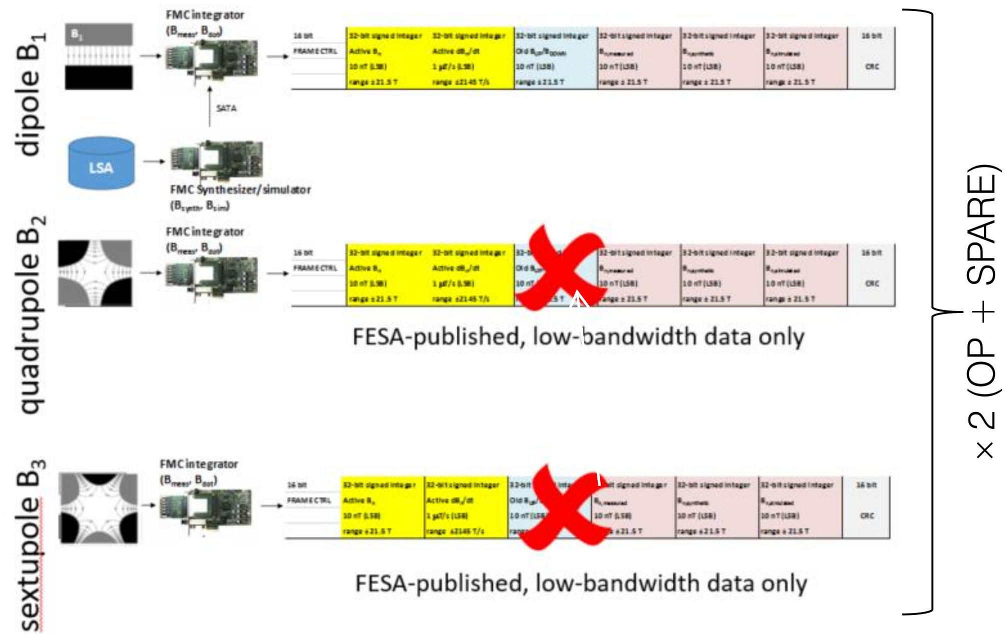
Courtesy D. Perrellet

PS B-train deliverable

- One integrator ch. per field component
  Multipoles obtained from analogue linear combination of coil signals
  WR transmission needed for quad and above ?

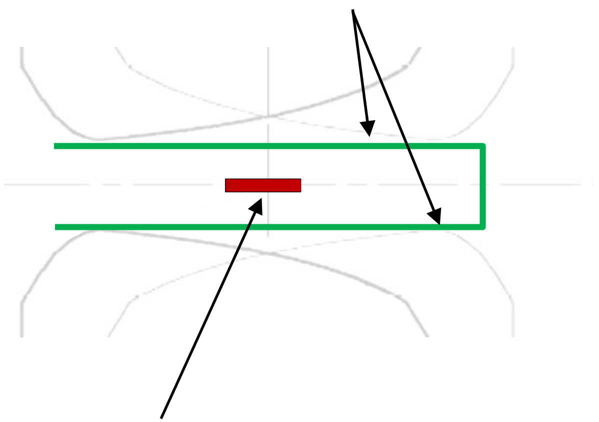
- One integrator card per field component
  The weighted average of F and D contributions is computed in the VHDL code

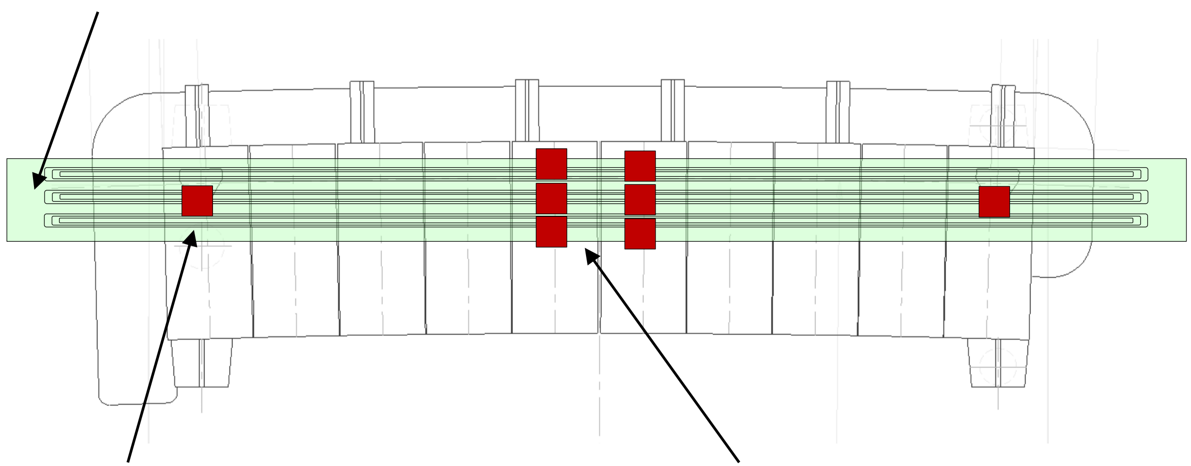
- Full set of new field sensors



PCB measuring coil arrays at the top and bottom allow
the measurement of normal and skew harmonics referred to the central axis

full integral coils allow the precise measurement of all nonlinear and dynamic effects





box structure open on one side allows field markers
to be installed precisely on the reference axis

field markers at multiple longitudinal positions
minimize the uncertainty linked to magnetic length fluctuations

field markers at multiple radial positions
to reference multipolar field components B_2, B_3 …

Planning of PS B-train

- 2016: mixed operation with old and new system
  Revert periodically back to B_{up}/B_{down} distribution to carry out system tests and upgrades
  (schedule agreed in coordination with BE/OP, BE/RF, BE/BI, TE/EPC)
  Pending tests:
  - MD in mid-June to test WR distribution of the new field measurement to POPS in PPM mode
  (critical to enable running tests in the shadow of normal operation)
  - beam tests with "problem" cycles (e.g. F8L degaussing, double CNGS cycles …) w/o radial correction loop

- YETS 2016/2017
  - Upgrade of FMC VHDL (integrator and marker cards), FESA Bmeas class, FMR sensors
  - system calibration

- 2017: default operation with new system
  - accumulation of statistics over full range of users
  - Mid-2017: maintenance of existing measured-train FEC not required anymore
  (NB still needed for synthetic B-train FEC)

- YETS 2017/2018m
  - Final upgrade of FMC VHDL and FESA classes, high field FMR
  - new synthetic B-train

- 2018: operation with new system by default
  - accumulation of statistics over full range of users

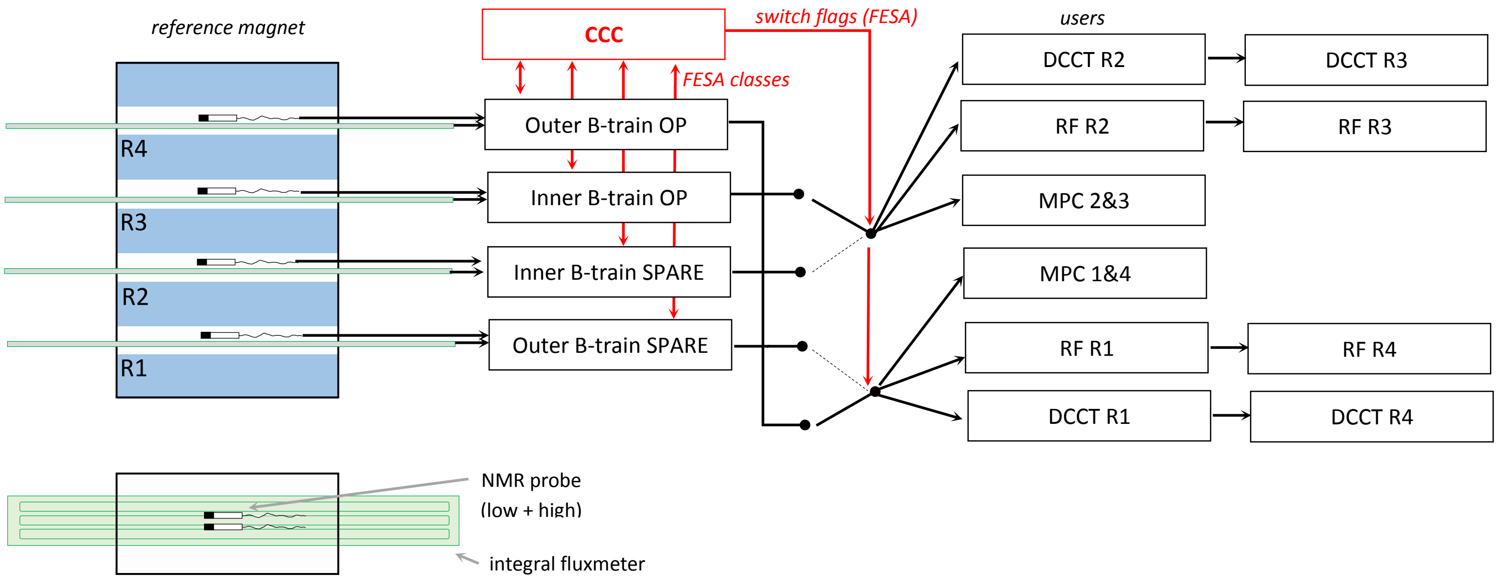
- LS2: completion of the upgrade
  - installation of integral coils, removal of old system
  (to ensure possible operation with MPS, ensure its compatibility with WR *or* add WR to B_{up}/B_{down} adapter)

Booster B-train Status and Planning

marco.buzio@cern.ch

PSBU B-train status and deliverable

- Deliverable: no changes wrt Nov 2015 meeting
- Installation in bldg. 245: care must be taken in the routing of current feeds directly above the reference magnet (in particular: keep feed/return as close as possible, no loops)
- Offline tests and definition of the PCB ongoing



Planning of PSBU B-train

- 2016
  - offline tests: dynamics, hysteresis and saturation effects, including cross-talk between rings (see A. Beaumonts' talk)
  - procurements of electronics (FMC already here), FEC and PCB fluxmeter

- YETS 2016/2017
  - installation of electronics (1 ch. only) in bldg. 361
  - sensors: install additional coil/marker in free gaps (1 & 4), split available signals

- 2017-2018
  - run the new B-train in parallel with old with new electronics and new/split sensors (feedback to new LLRF already possible)
  - installation of full new systems electronics in bldg. 245
  - test with new reference magnet as soon as POPS-B available

- LS2
  - switch to new system

Budget

Material cost breakdown

		Chains	Units	Chains	Units	Chains	Units	Chains	Units	Chains	Units	Chains	Units	Chains	Units
FMC	Integrator	2	1	2	5	2	1	0		1	1				
(proto + series + spares)	Marker	2	2	2	4	2	1	0		1	1				
	Synthetic	2	1	2	2	2	1	0	2	1	1				
	Other	2	1	2	1	2	1	0		1	1				

	Unit Cost	LEIR		PS		SPS		AD		Testbed		PSB		ELENA	
	kCHF	units	kCHF	units	kCHF	units	kCHF	units	kCHF	units	kCHF	units	kCHF	units	kCHF
Rack	2	2	4	2	4		0		0		0		0		0
Crate			0		0		0		0		0		0		0
Patch panel	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Cabling	10	1	10	1	10	1	10	1	10	1	10		0		0
			0		0		0		0		0		0		0
Front End Computer	2	2	4	2	4	2	4	1	2	2	4	4	8	2	4
FMC	2	*10*	20	*24*	48	*8*	16	*0*	0	*4*	8	*0*	0	*0*	0
CTRi	1	2	2		0		0		0		0		0		0
Btrain chassis	2	2	4		0	2	4		0		0		0		0
			0		0		0		0		0		0		0
WR cabling	20	1	20	0	0	1	20	1	20	1	20		0		0
WR switch	5	1	5	1	5	1	5	1	5	1	5		0		0
WR patch panel	5	1	5	1	5	1	5	1	5	1	5		0		0
			0		0		0		0		0		0		0
OASIS	40		0	1	40		0		0	1	40		0		0
Spy DAQ	20	1	20	1	20	1	20	1	20	1	20		0		0
Scope	5	1	5	1	5	1	5	1	5	1	5		0		0
			0		0		0		0		0		0		0
			0		0		0		0		0		0		0
			0		0		0		0		0		0		0
Reference magnet			0		200		0		0		0		0		0
			0		0		0		0		0		0		0
Hall probes	3	4	12	5	15		0		0		0		0		0
FMR marker	10	4	40	8	80		0		0	4	40	8	80		0
NMR marker	30		0		0	2	60		0		0	4	120	4	120
Frequency synth.	3	4	12	8	24		0		0	4	12	8	24		0
PCB coils			*10*		*200*		0		0		0		50		0
Supports			20		50		0		0		0		0		0
Drawings			10		30		0		0		0		0		0
			205		**742**		**151**		**69**		**171**		**284**		**126**

Spending profile

- Estimate presented to the Consolidation Day (Feb 2016)
- SPS not included (no definite demand yet)
- Staff already earmarked to cover project continuity

General code for magnetic measurements → 99336

FELL/DOCT/TS PJAS, FSU → Personnel

Budgets already allocated → ELENA, PSB

B.C.	Machine	2016	2017	2018	2019	2020		TOTAL
99336	**PS**	150	300	300	100	50		900
n.a.	**LEIR**	50	50	50	50			200
n.a.	**AD**		70					70
		200	420	350	150	50		1170
	Personnel	100	300	300	250	50		1000
	total	300	720	650	400	100		**2170**
99166	ELENA	110						
99284	PSB	100	100	50				

Additional slides

Planned activities (from Nov 2015 meeting)

- Fully detailed snapshot of existing system:
  - roundup of old documentation
  - detailed list of spares
  - details of the synthetic B-train generation software
  - split up sensor output for measurements in parallel with a separate acquisition system
  - identification and removal of old/disconnected sensors inside the existing reference magnet

- Definition of FESA classes and OASYS signals
  (e.g. NMR output in the CCC, alarms based on difference between OP/SPARE chains, etc. etc.)

- Offline magnetic tests in bldg. 867:
  - NMR/FMR as field markers with the faster cycles
  - magnetic coupling between ring 1/4 and 2/3 possible impact on the MPS control system)
  - possibility/need of a high field marker (used in the past, then dropped)
  - impact of dynamics and hysteresis effects on the calibration of the new B-train
  - full characterization of new reference/spare bending
  - test of quadrupoles (field quality, dynamics, hysteresis)

- No beam tests with new system before end LS2 → test in advance as much as possible
  - test new B-train system in 867 with existing/new reference magnet
  - (partial) install of new B-train in 361, use existing sensors/add new ones in the free gaps to run in parallel with existing B-train (feedback to RF possible)
  - when new reference magnet in 245, test whole system with new POPS/another power converter