Safe Beam Energy Tracking

Etienne CARLIER, Gregor GRÄWER, Nicolas VOUMARD
& Runar GJELSVIK

AB/BT

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Outline

- How to obtain the “beam energy”
  - Overview, Principle, Errors
- Beam Energy Tracking System
  - Definition, Functions, Clients, Architecture
  - Reference & Interlocks
  - Safety
  - Performance
- Mains dependencies
- Injection inhibition
- Summary & Open issues

How to Get the Beam Energy?
Overview (1/2)

Beam energy information can be obtained

- Through a direct measurement
- From a standard LHC function generator
- From a direct measurement of the main bending magnet current

How to Get the Beam Energy
Overview (2/2)

- ➔ Direct beam energy measurement
  - Not possible at 1kHz frequency with sufficient precision
- ➔ Use of a function generator to obtain beam energy information
  - Implies a continuous management / commissioning of the extraction process with the different operation modes of the machine
  - Needs a second method to control the function generator
  - Not a real measurement of the beam energy
- ➔ Direct magnet current measurement that permits to bind rigidly the equipment deflection strength to the beam energy
  - More reliable approach
  - Modification of extraction optics / trajectory has to be managed by the system
  - Not a real measurement of the beam energy

How to Get the Beam Energy?
Principle

The Beam energy in a circular accelerator is defined by

$$\mathbf{E = 300\ q\ B_m\ \rho} \qquad (E >> E0) \qquad (1)$$

and is directly proportional to the bending magnetic field.

The magnetic field in a bending magnet is defined by

$$\mathbf{B_m \approx (2\ \mu_0\ n\ I)\ /\ h} \qquad (\mu_r >> 1) \qquad (2)$$

and is directly proportional to its current.

The **beam energy** in a circular accelerator **is** directly **proportional** to the **current** of its **main bending magnets**.

The relation between **main bend magnetic field** and **magnet current** can be precisely determined during main bending magnet **calibration measurements.**

How to Get the Beam Energy?
Possible Errors

- Orbit correctors:
  - Up to ±1% error on the estimated energy reference is possible due to orbit correction.
- RF frequency variation:
  - Up to ±0.8% error before beam losses occur.
- This can result in a relative error on the estimated beam energy up to ±1.6 %.

Unacceptable

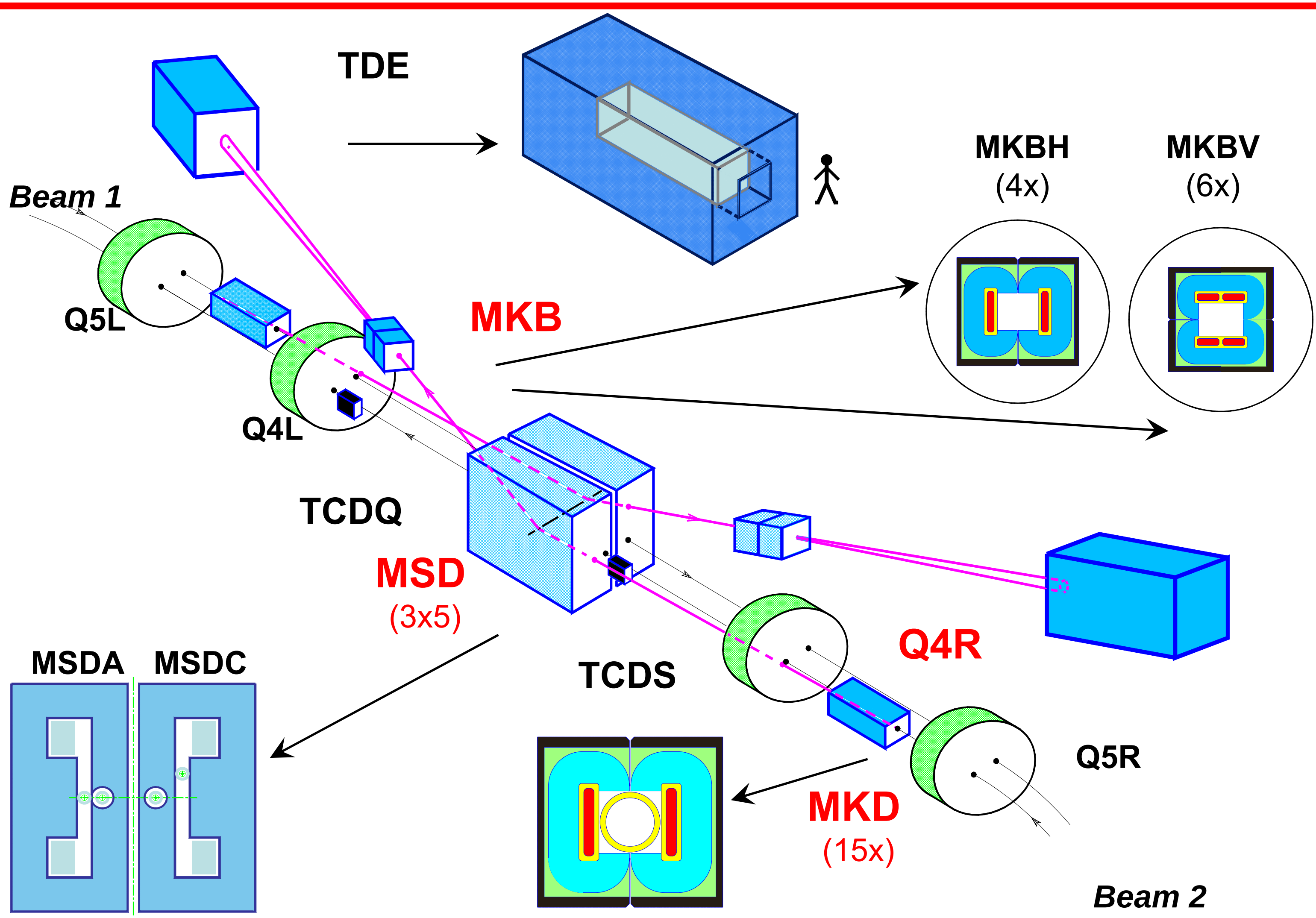
➔Interlock on integrated corrector field and on relative momentum change will be necessary to maintain the total relative error on estimated beam energy within ±0.8%.

Under study

Beam Energy Tracking System
Definition

The Beam Energy Tracking System (BETS) binds the deflection strength of each active sub-system of the LHC Beam Dumping System (LBDS) with the beam energy in order to get the correct extraction trajectory over the complete LHC operational range and under all operational conditions.

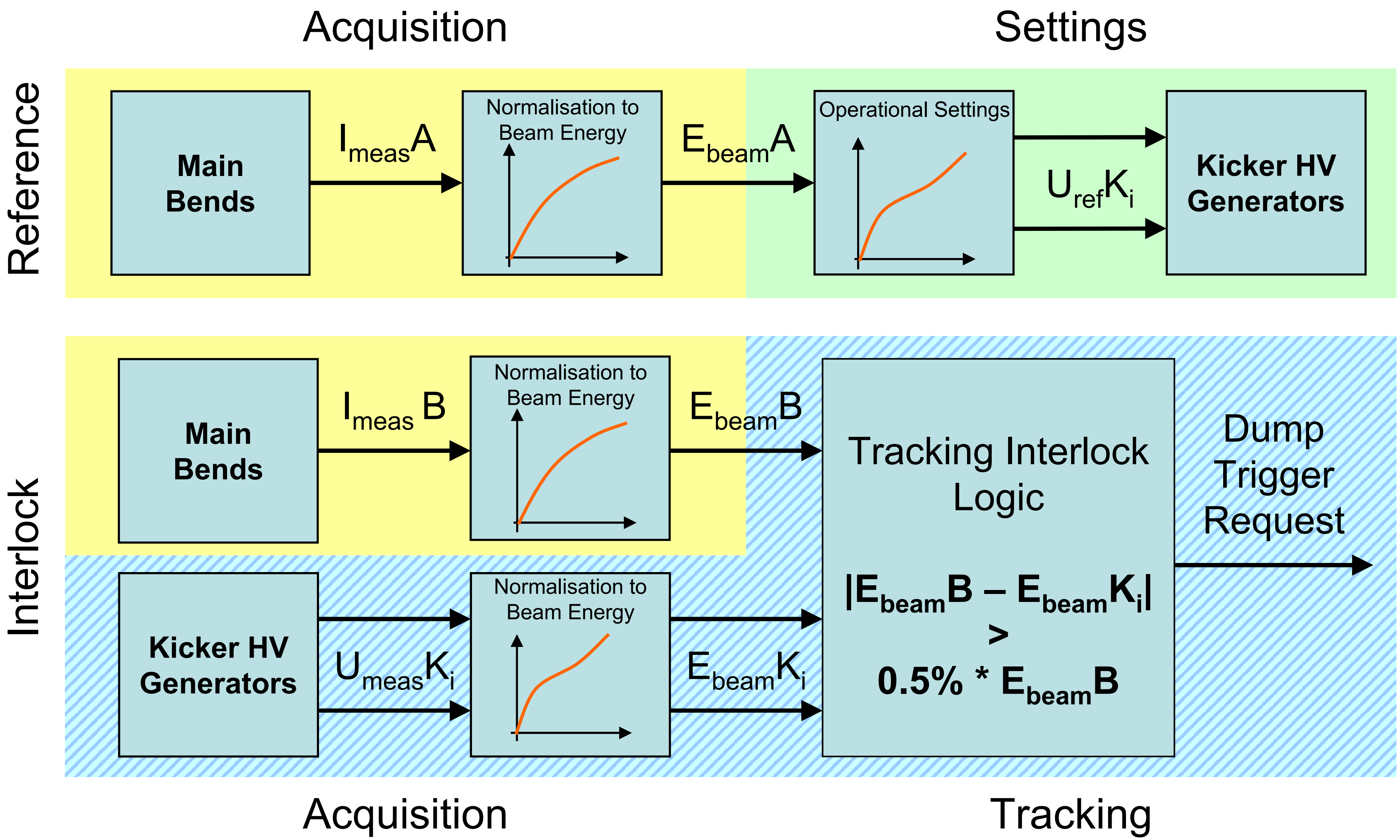
Beam Energy Tracking System
LHC Beam Dumping System



Beam Energy Tracking System
Functions

- Acquisition of the machine *"beam energy"*,
- Generation of the kick strength reference signals for LBDS extraction and dilution kicker high voltage generators w.r.t. the beam energy,
- Continuous surveillance that the charging voltages of the different capacitors within the kicker high voltage generators follow their references within predefined tolerance windows (extraction trajectory aperture),
- Continuous surveillance that the LBDS extraction septa and ring quadrupole Q4 currents are within predefined tolerance windows (extraction trajectory aperture),
- Generation of a dump request after detection of an upcoming tracking fault if the measured values are not within predefined tolerance windows relative to the beam energy,
- Distribution of the beam energy to external clients.

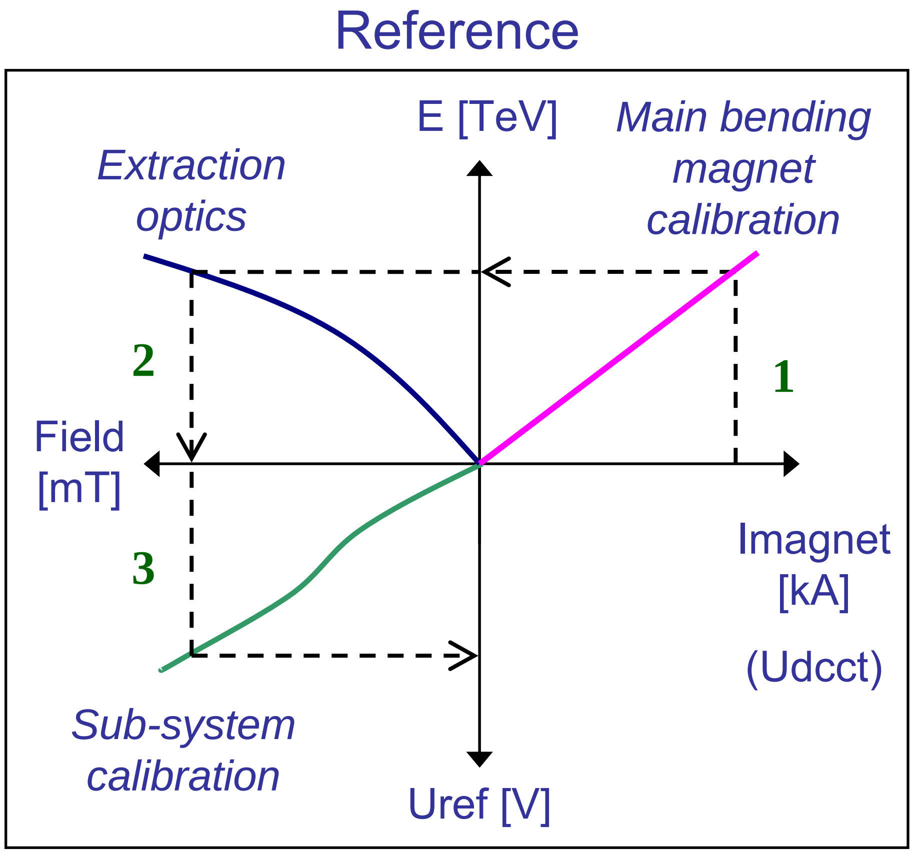
Beam Energy Tracking System
Principle

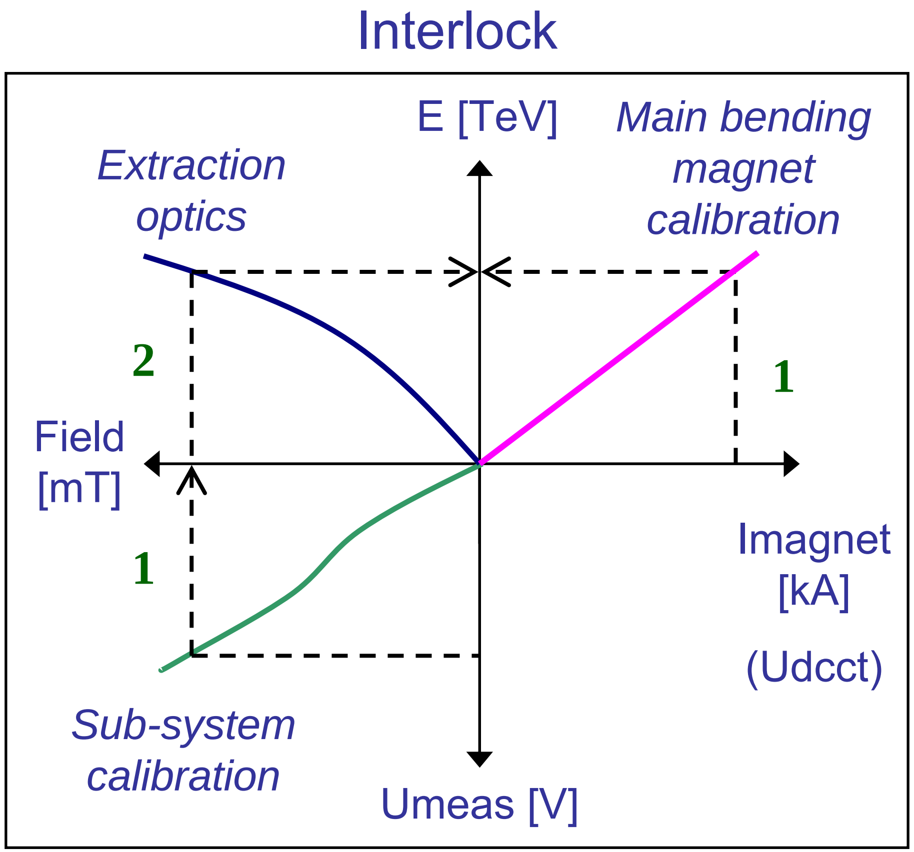


Beam Energy Tracking System
Input Signals

- At least, **two independent sources** of the "*beam energy*" are necessary in order to verify the correct operation of the Beam Energy Tracking System
  - One information will be used as **reference** signal for the generation of the kick strength references
  - One information will be used as reference for **interlock** logic
- All the interlock input signals will be normalised to values relative to their corresponding beam energy for cross-correlation and comparison
  - High precision calibration measurements

Beam Energy Tracking System
Signal Normalisation



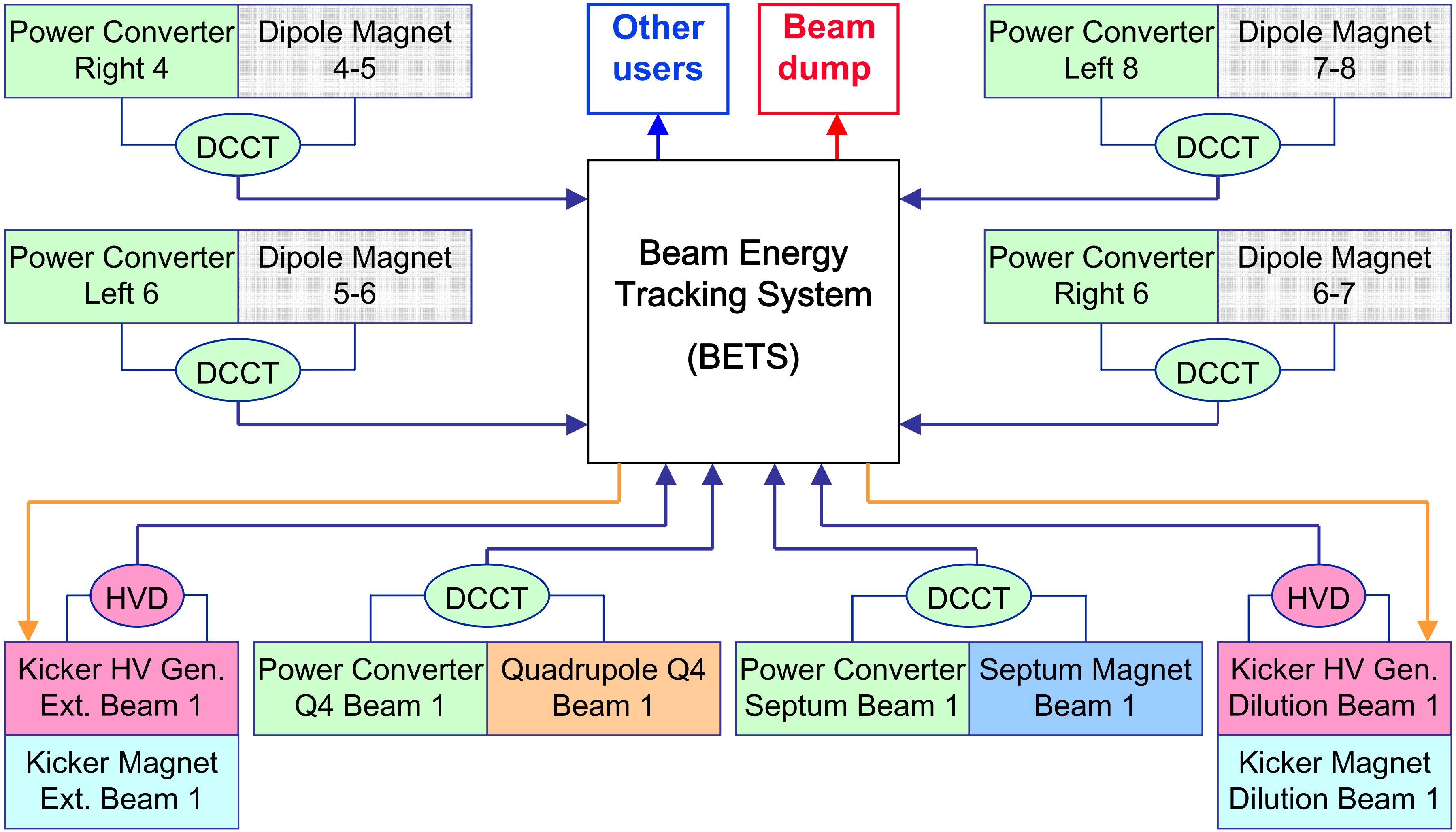


Reference and interlock systems rely on a precise knowledge of the magnetic characteristics of the different LBDS sub-system → Good calibration measurements over the complete operational range are mandatory.

Beam Energy Tracking System
Clients

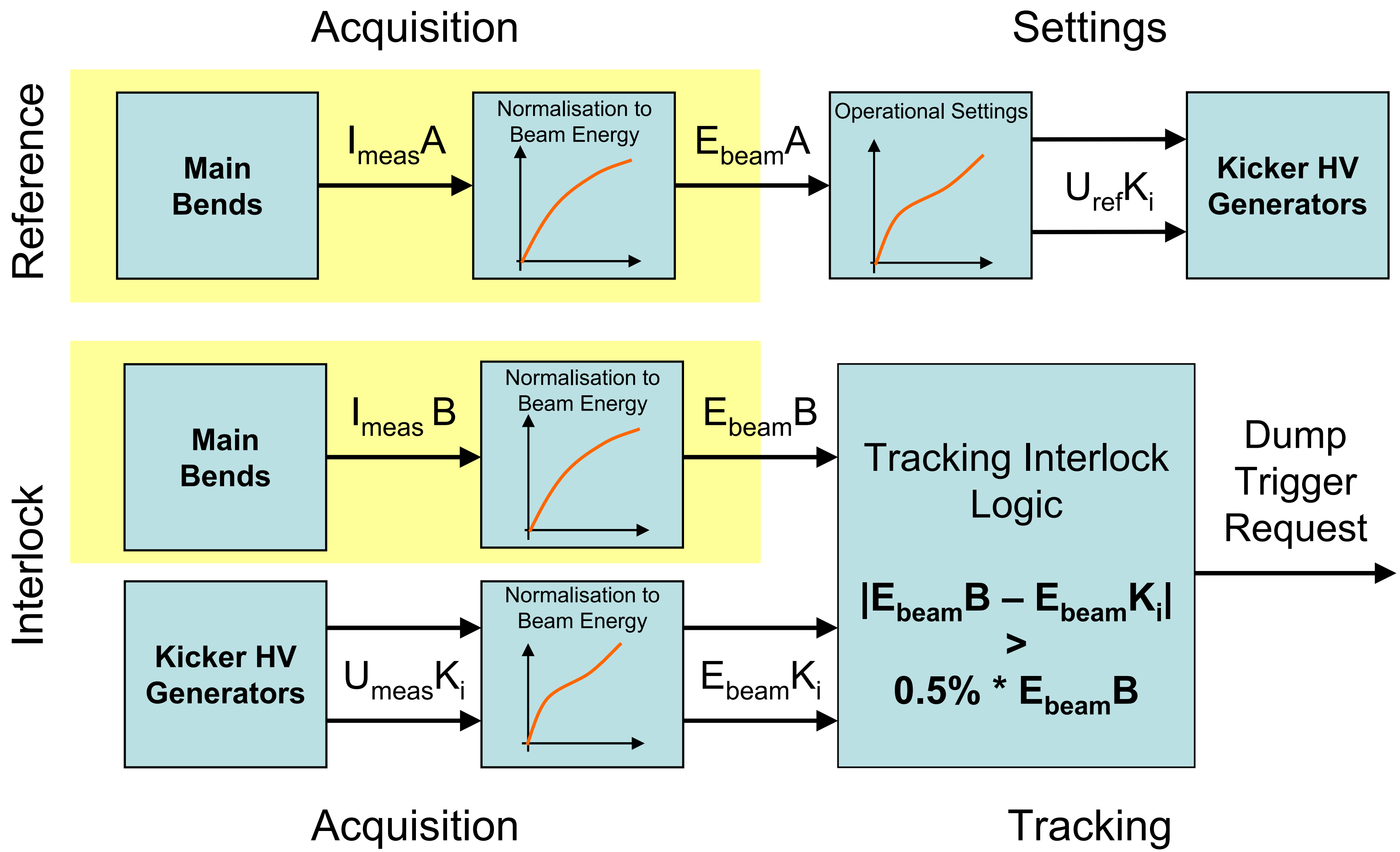
- LBDS
  - Extraction kickers → Reference & Interlock
  - Ring Quadrupole Q4 → Interlock
  - Extraction Septa → Interlock
  - Dilution kickers → Reference & Interlock
- Injection kickers
  - Injection inhibit
- Aperture kickers
  - Limitation of possible kick excitation w.r.t the beam energy (→ Jan UYTHOVEN's talk))
- Safe LHC Parameters
  - Safe Beam Flag (→ Bruno PUCCIO's talk)
  - Beam Loss Monitor (→ Bernd DEHNING's talk)
  - ….

Beam Energy Tracking System (BETS)
Relations



Beam Energy Tracking System

Beam Energy Acquisition



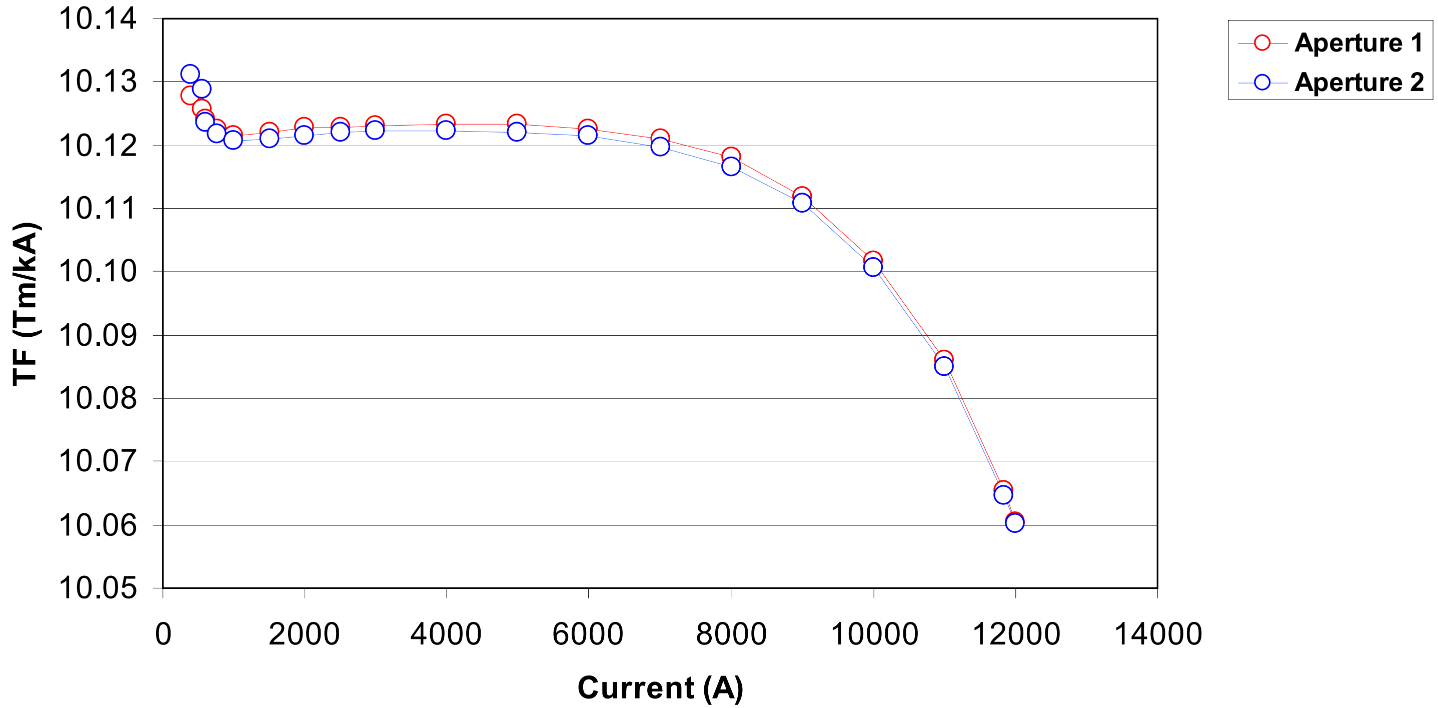
BETS – Reference

Beam Energy Acquisition

- The *“beam energy”* value used as reference will be retrieved from continuous measurements of the main bending magnet current from 4 independent power converters (20ppm accuracy) powering 4 independent octants.
  - 2 power converters for reference settings generation
  - 2 power converters for tracking interlock logic
- Within each power converter, the measurement of the main bending magnet current will be performed through redundant DCCTs with a precision of ±0.1%.
- These measurements will be dynamically converted through a look-up table into a normalised value proportional to the “*beam energy*”.

BETS - Reference

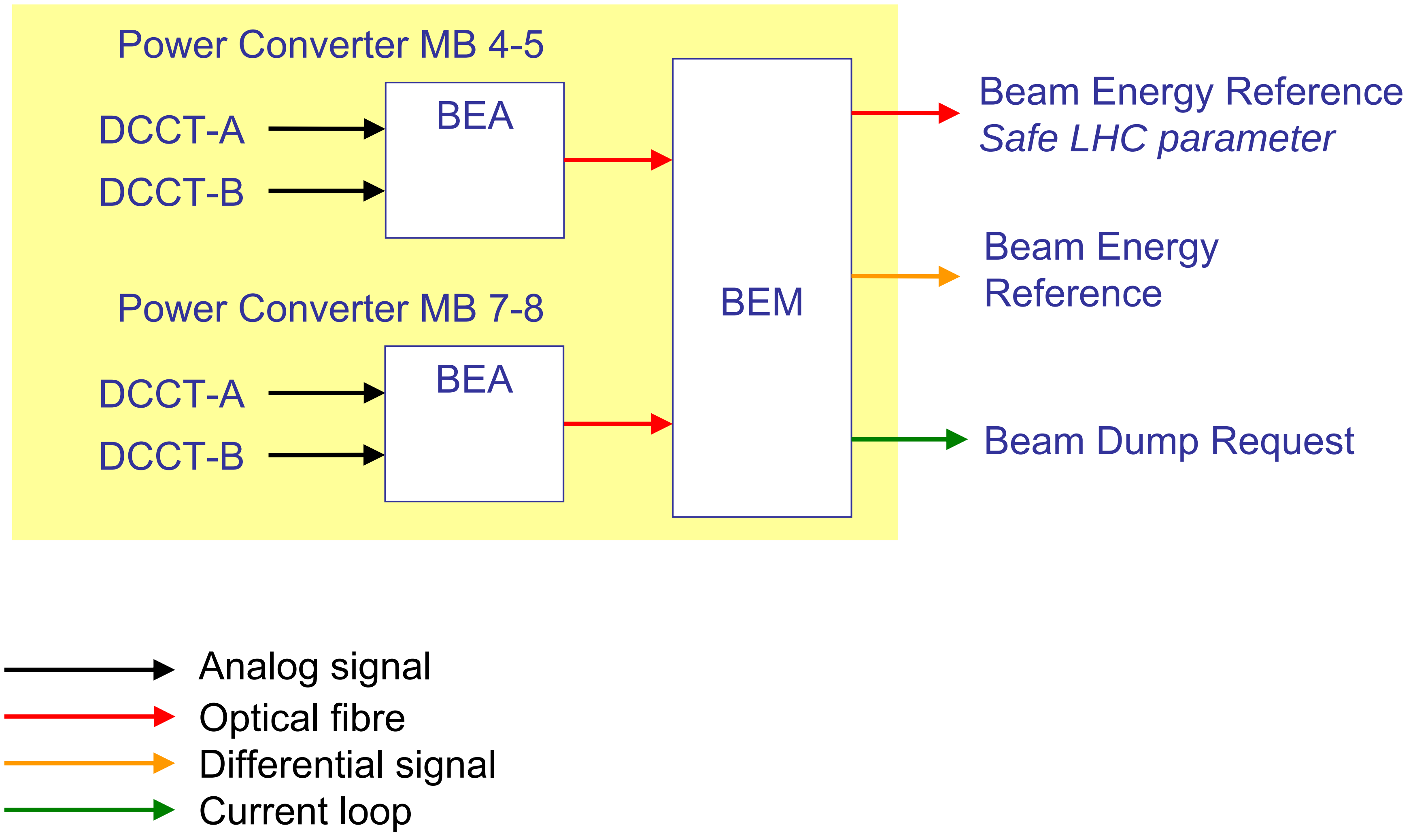
Main Bending Magnet Calibration



→Linear interpolation over the complete operational range gives an error greater than 0.1% (typ. ± 0.3%)

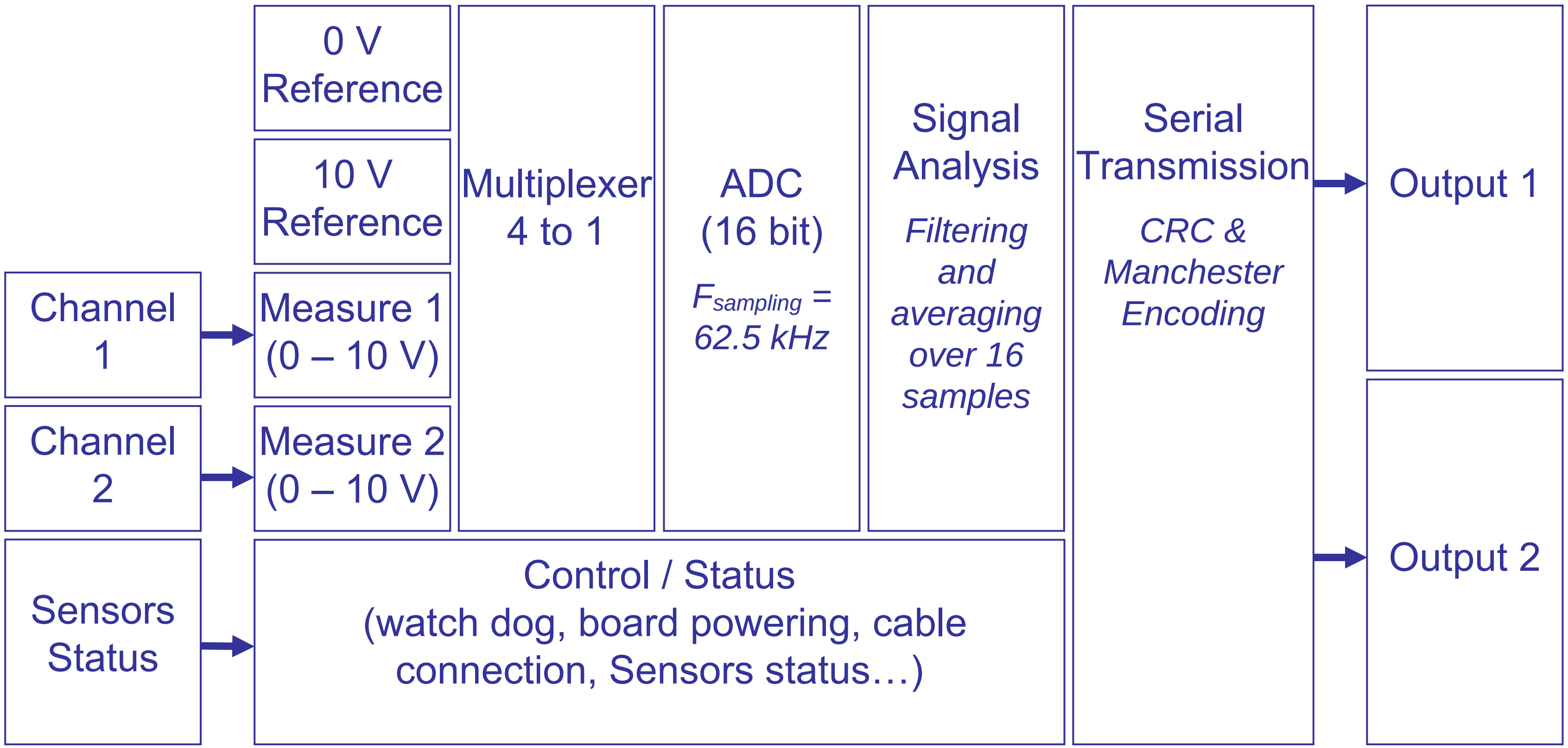
→Look-up table with linear interpolation between 32 reference points will be used in order to obtain an error smaller than ± 0.1%

BETS - Reference
Layout



BETS - Reference

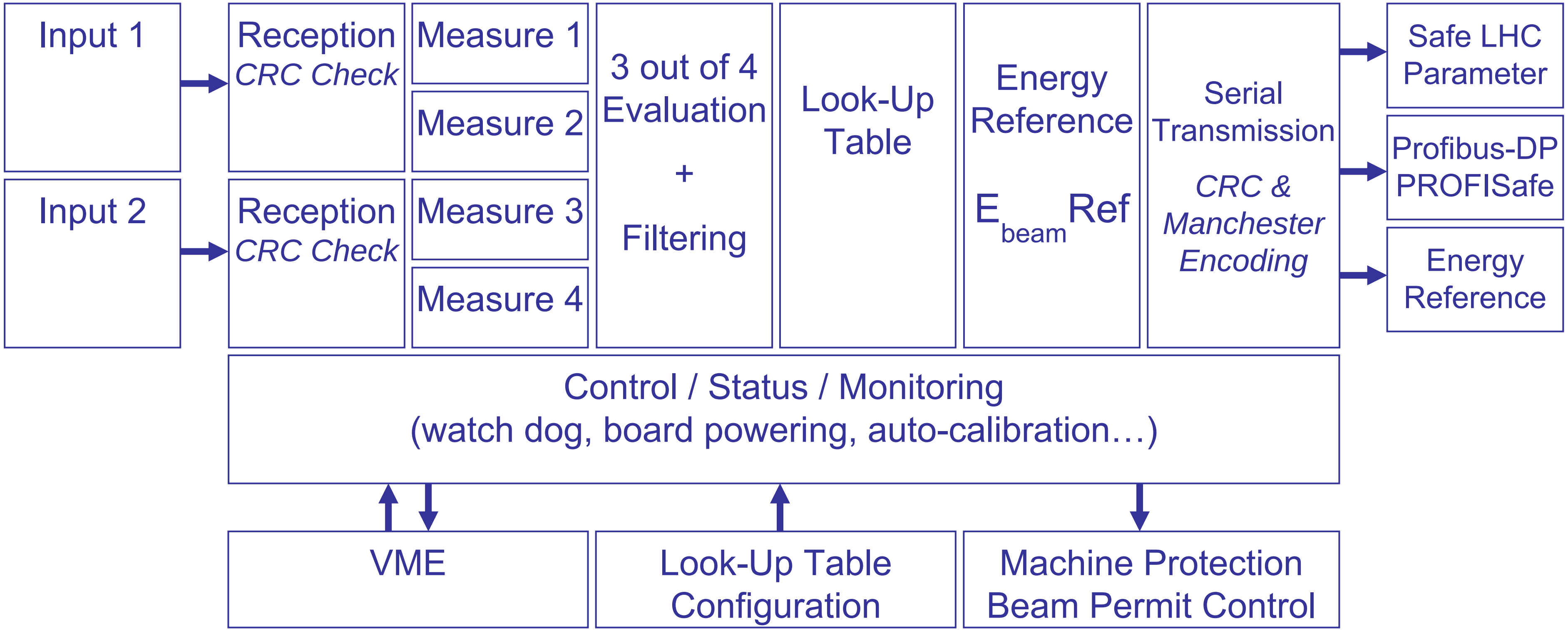
Hardware: Beam Energy Acquisition (BEA)



The BEA acquires and digitises 2 independent unipolar channels with 16bit resolution. Signals are digitally filtered before secure transmission through optical fibre. Two high precision reference signals are simultaneously digitised, modulated and transmitted in order to survey the linearity of the ADC and probing the transmission.

BETS - Reference

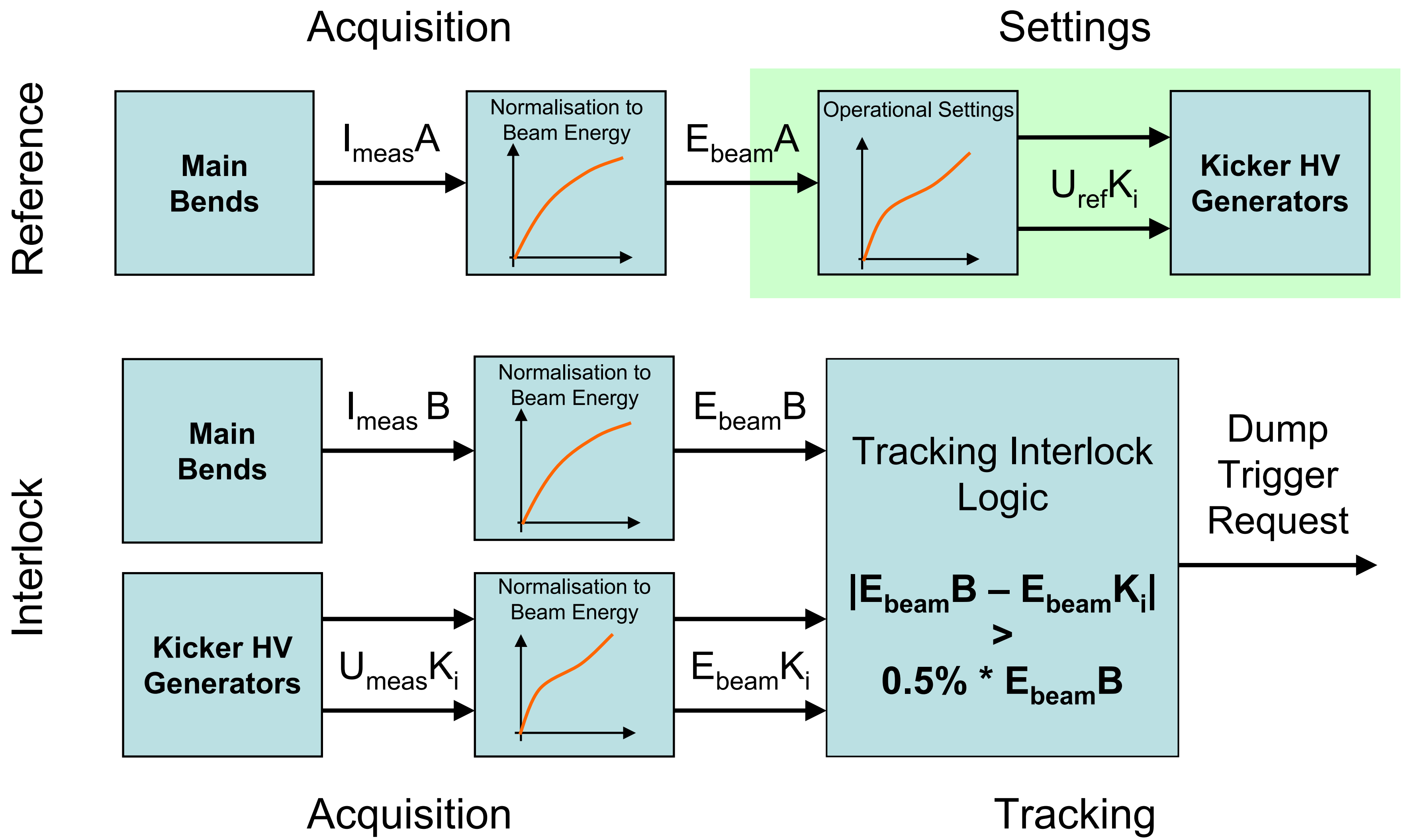
Hardware: Beam Energy Meter (BEM)



The BEM receives 4 digital measurements proportional to beam energy from BEA. These measurements are compared within the BEM with a 3 out of 4 logic and a relative error of ± 0.5%. Failure results in a beam dump request. The mean value of the 4 measurements is then converted into an absolute beam energy reference through a calibration look-up table.

Beam Energy Tracking System

Kicker Settings



BETS – Reference
Kicker Settings

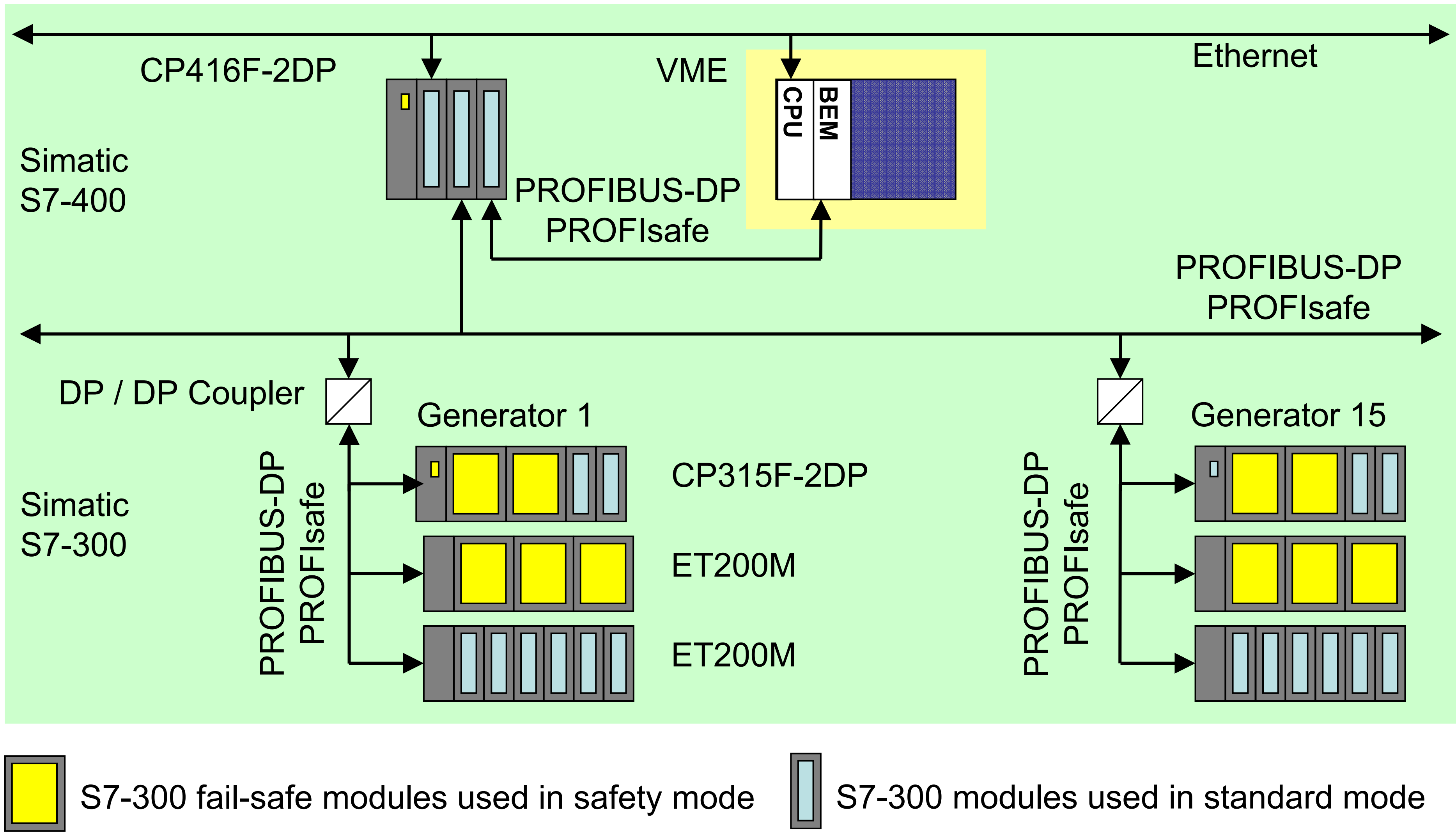
Generation and distribution of the kick strength reference signals will be based on :

- ➔Fail-safe SIEMENS SIMATIC S7-F Programmable Logic Controllers for the generation
- ➔Fail-safe communications between PLC and BEM via PROFIBUS-DP fieldbuses using PROFIsafe protocol for the distribution.

Due to the PROFIsafe protocol and the SIEMENS SIMATIC S7-F PLC family used in safety mode, any internal hardware failure or communication failures will safely issue a dump request by moving into a predefined safe state.

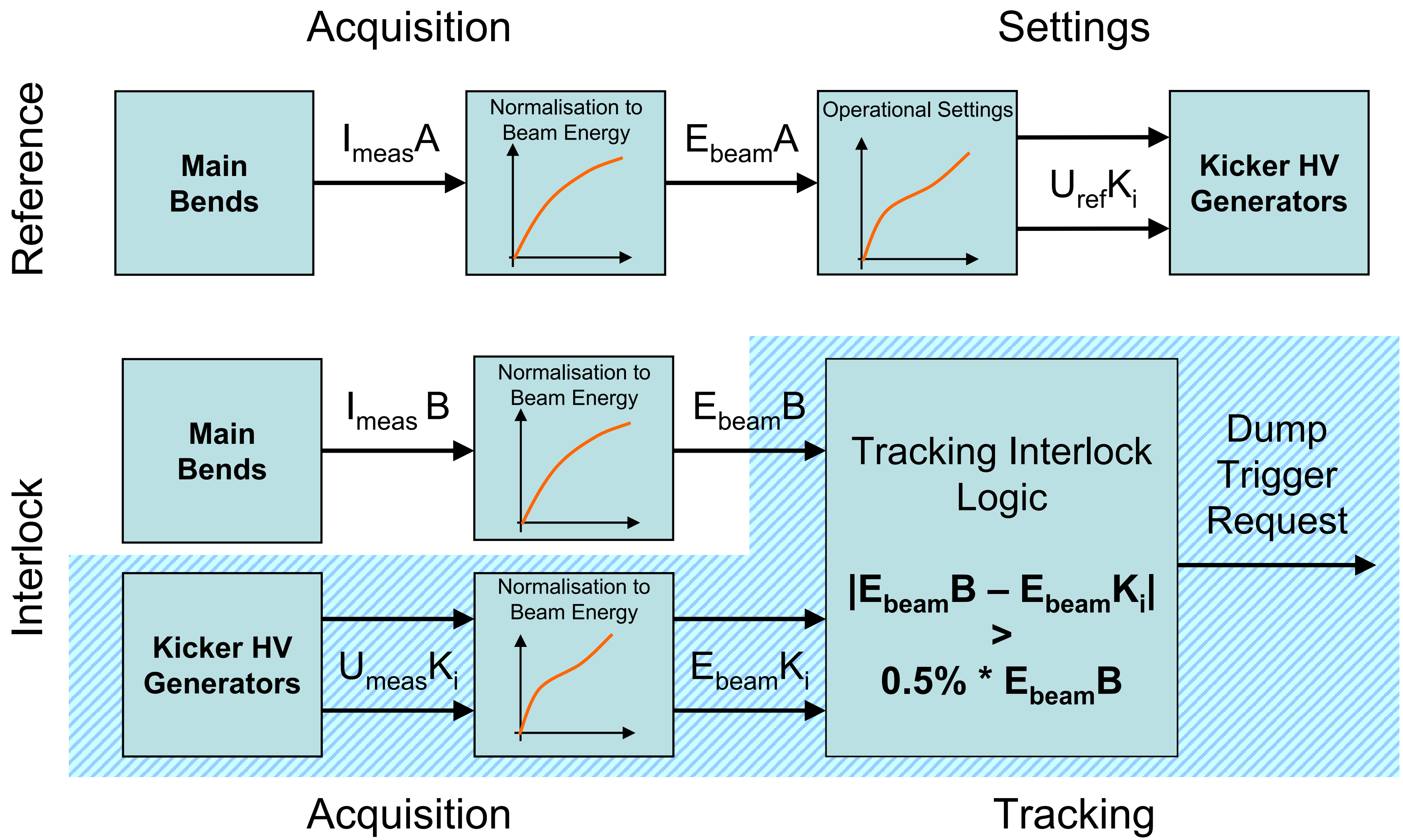
BETS – Reference

Kickers Settings Distribution - Layout



Beam Energy Tracking System

Interlock

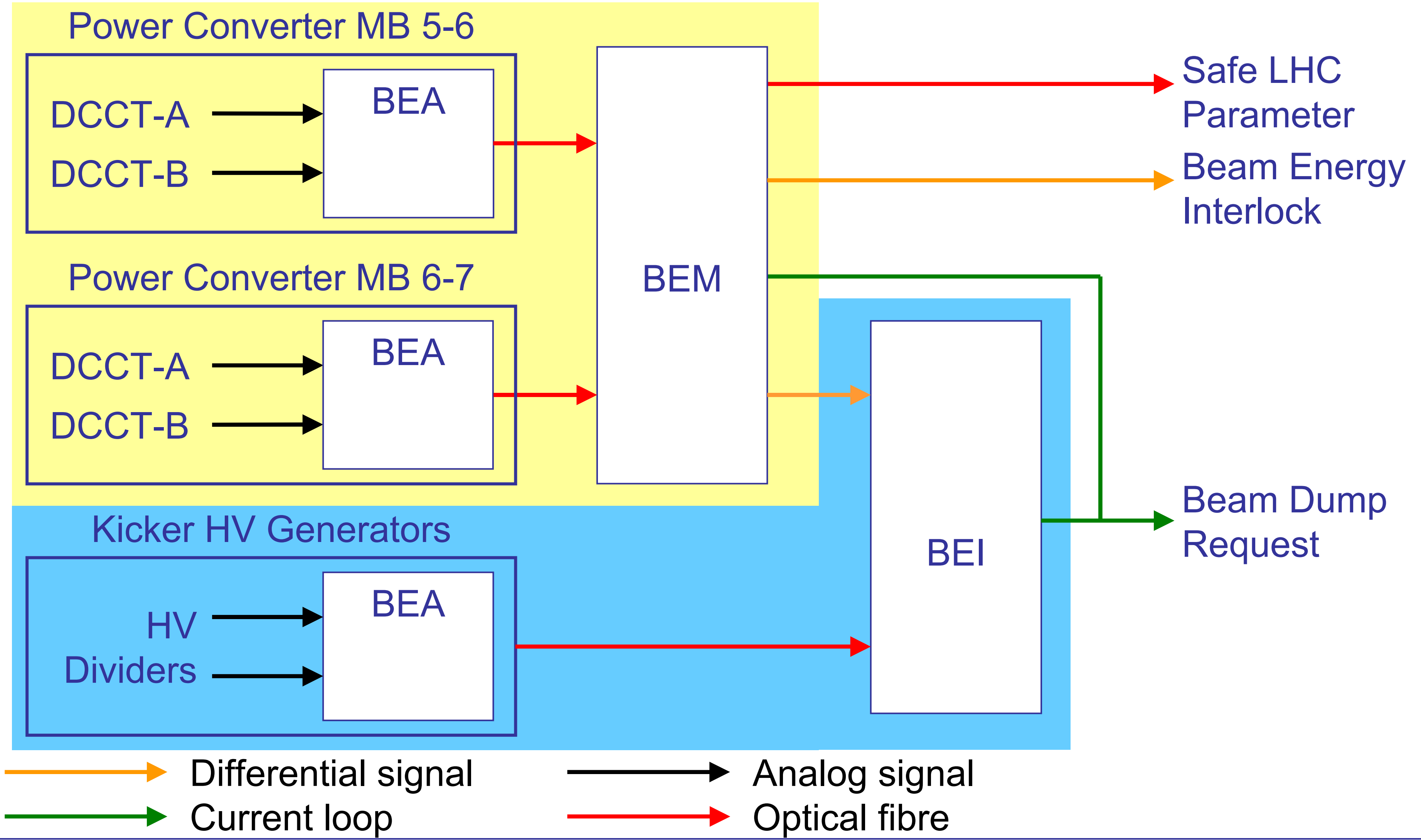


BETS - Interlock
General

- The Tracking interlock logic will be based on two redundant systems built on the basis of two different technologies:
  - One system will be based on dedicated hardware housed in a LynxOS VME front-end for the extraction kickers, the quadruplole Q4, the extraction septa and the dilution kickers,
  - One system will be based on fail-safe SIEMENS SIMATIC S7-F Programmable Logic Controllers for the extraction and dilution kickers.
- Both systems have to be continuously in agreement:
  - 2 out of 2 logic,
  - Independent and redundant sensors will be used,
  - In case of discrepancy within a system or between the two systems, a dump request will be issued.

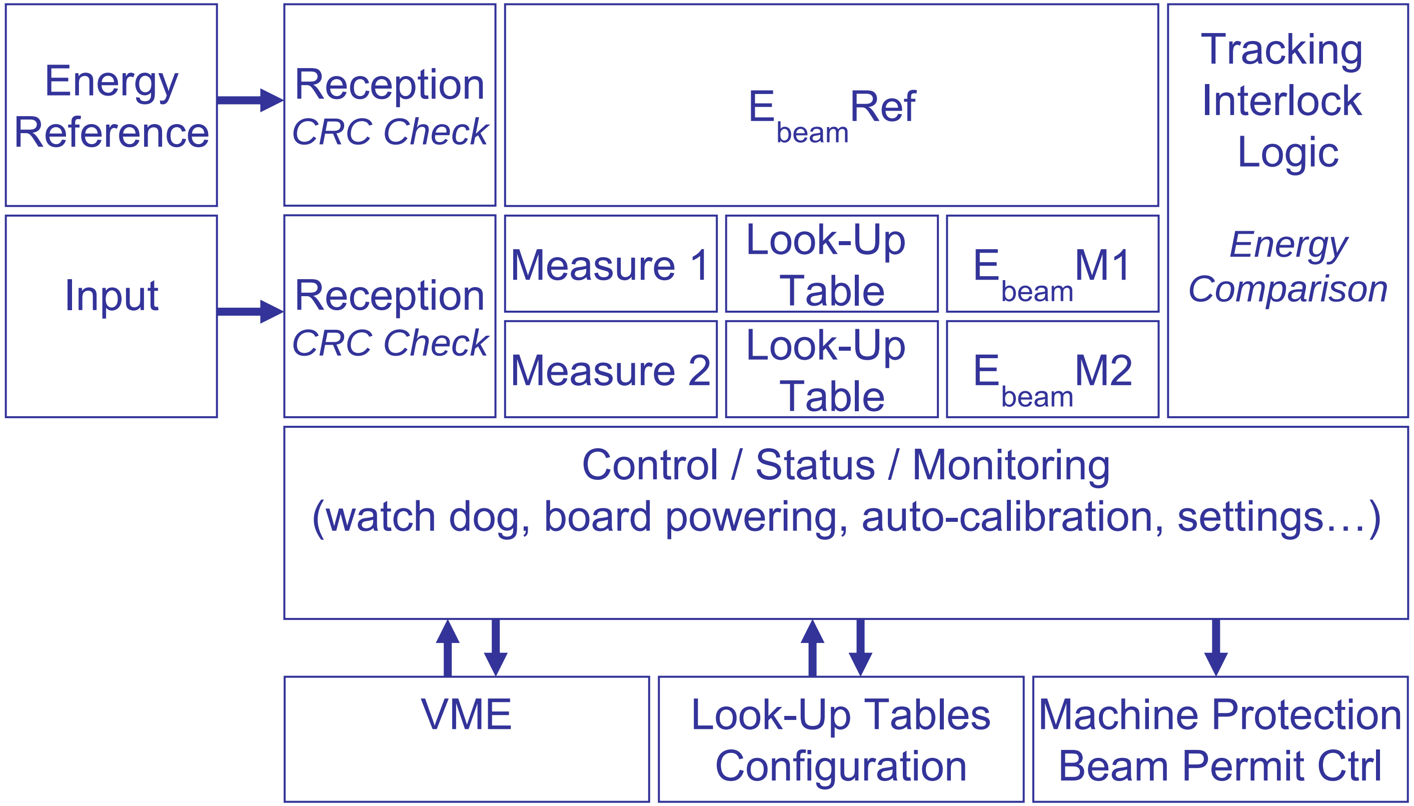
BETS - Interlock

Dedicated Tracking System - Layout



BETS - Interlock

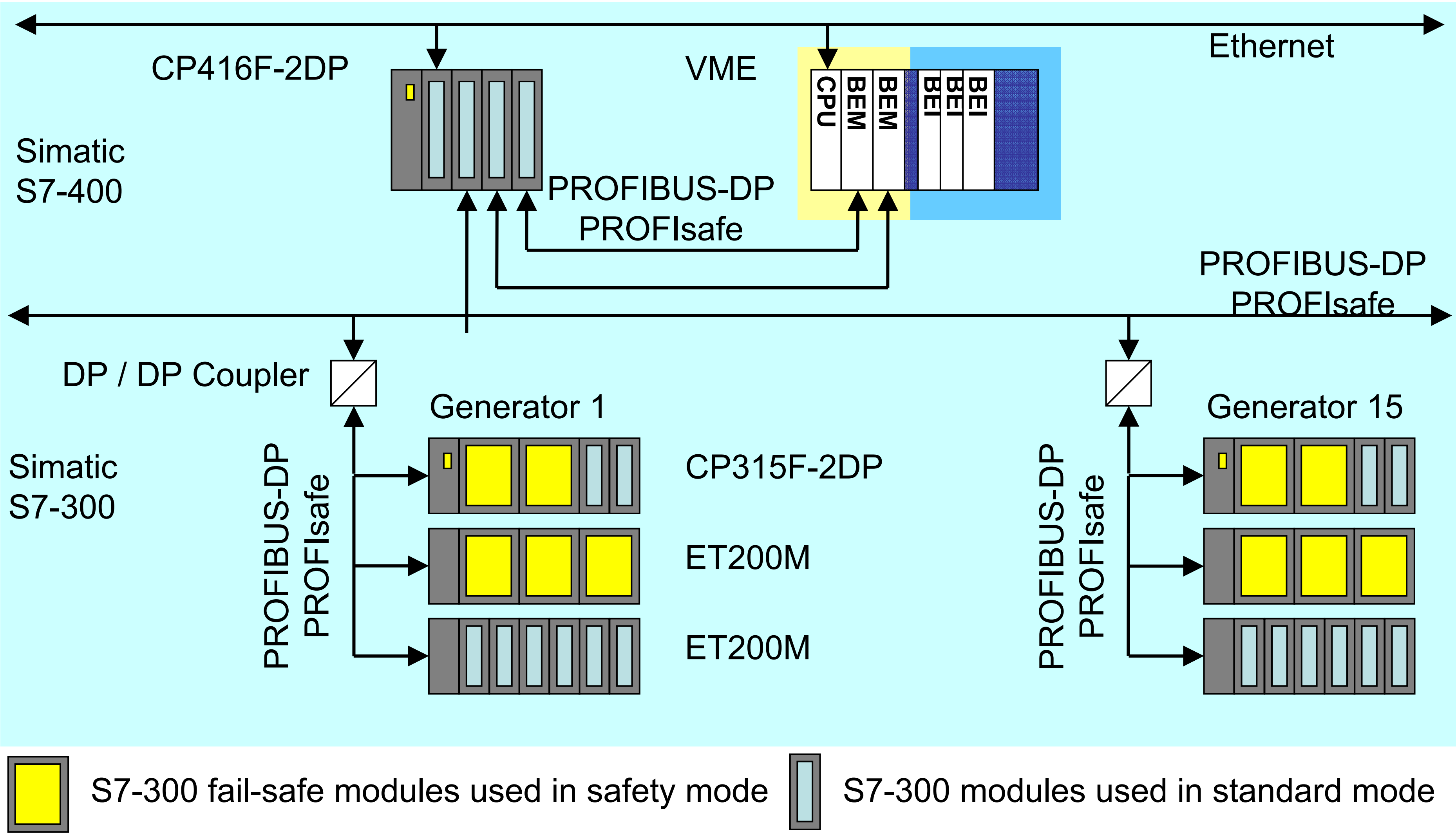
Hardware : Beam Energy Interlock (BEI)



The BEI receives the beam energy reference signal and two independent measurements. It normalises the two measures to values proportional to the energy through independent calibration look-up table. These normalised values are then compared with the reference signal and if a discrepancy larger than a predefined tolerance is detected, a dump request is issued.

BETS – Interlock

Fail-Safe Tracking System - Layout



Safety

- **BETS** is fully based on a **fail-safe** logic.
- All the electronic included within the **BETS** will be **powered** by 230V **Uninterruptible Power Supply** (UPS).
- BEM and BEI modules housed within **VME crate** will be **powered** by **redundant power supplies**.
- **Data transmission** between BEA, BEM, BEI and SLP will be based on **Manchester encoding** including a **Cyclic Redundancy Check** (CRC) for transmission error detection.
- **Look-up tables** will be **stored** in **EEPROM**. **Modification** of the tables will be **only possible locally** through an external RS232 interface.
- The use of **SIEMENS SIMATIC S7-F** Programmable Logic Controllers and **PROFIsafe** protocol over PROFIBUS-DP guarantees a Safety Integrated Level 3 (**SIL3**).

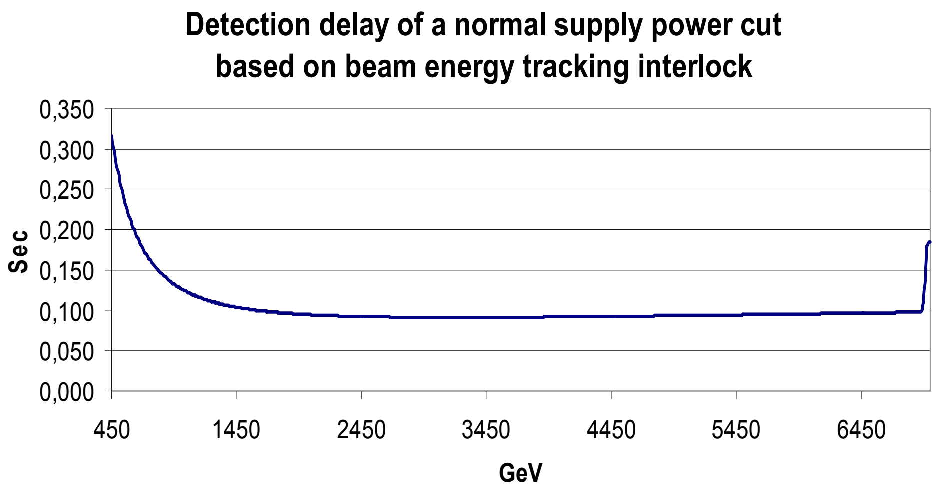
Beam Energy Tracking System
Parameters

Power converter DCCT precision	±0.1 %
Kicker HV divider precision	±0.2 %
BEA sampling frequency	65 kHz
BEA resolution	16 bit
BEA–BEM / BEI transmission rate	~100 kbit/s
Error during ramp (10 A/s)	< 0.01%
Bending magnet look-up table precision	±0.1 %
Kicker magnet look-up table precision	±0.2 %
Beam energy reference precision to SLP / BEI	±0.2 %
Beam energy reference error (with interlock)	±0.4 %
BEI tracking frequency	1 kHz
BEI tracking reaction time	1 ms
Bending magnet tolerance window	≥ ±0.3 %
Kicker magnet tolerance window	≥ ±0.5 %

Mains Instabilities

BETS Reference	Kicker Power Supplies	BETS Interlock	Dump Request
UPS	Normal supply	UPS	
		Active fail-safe redundant logic	

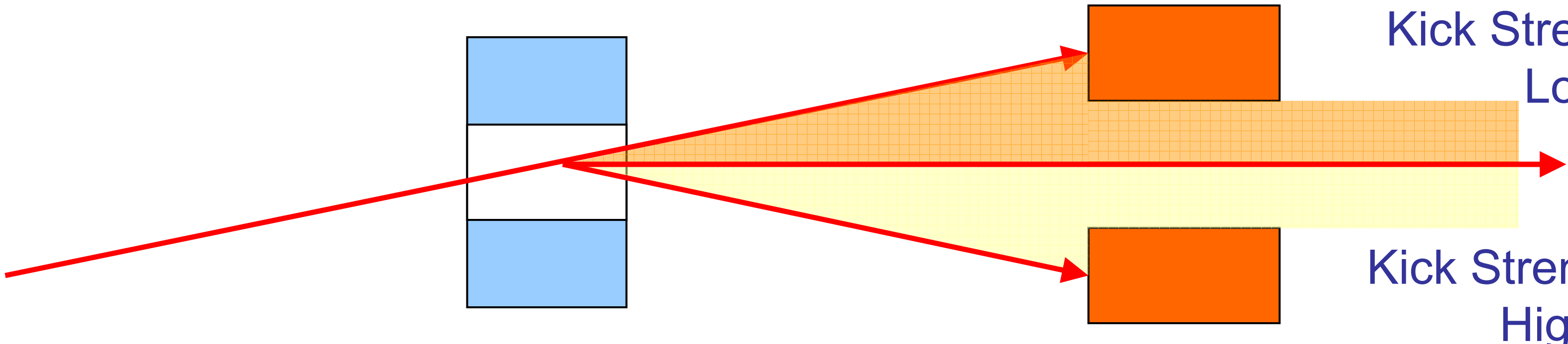
- **Normal supply failure**
  - BETS reaction time is deterministic
  - Detection delay depends of the sensitivity of the BETS interlock windows, generator impedance, high voltage power supply hold-up time, machine mode and energy…

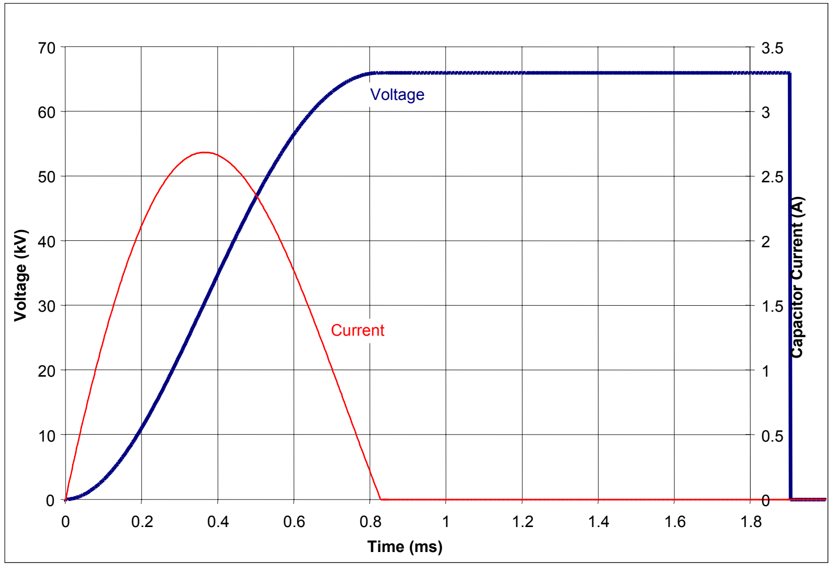


- **Uninterruptible supply (UPS) failure**
  - BETS reaction time is not deterministic
  - Detection delay depends of impedance of electronics circuits, failure sequence of micro-controller, low voltage power supply hold-up time….
  - BETS will fail due to the absence of power and issue a dump request (fail-safe logic)
  - A detection of the UPS failure faster than 80ms will be achieved through a continuous surveillance of the UPS voltage

Injection Kicker Inhibition

Resonant Charging Power Supply Tracking





Injection Process

Slow	-1000 ms	Start injection process
Slow	-750 ms	Charge primary capacitor bank
Slow	-2 ms	Trigger resonant charging
Slow	-1 ms	Control PFN secondary voltages
Fast	-10 µs	Start fast timing
Fast	0	Inject beam

Injection Kicker Inhibition

Resonant Charging Power Supply Tracking

Faults

- **Bad secondary voltage** (Vs) at the end of the resonance on one or on n PFNs (Faulty primary or secondary capacitor, Spark during resonant charging process…)
- **Bad reference settings** w.r.t the injection energy

Actions

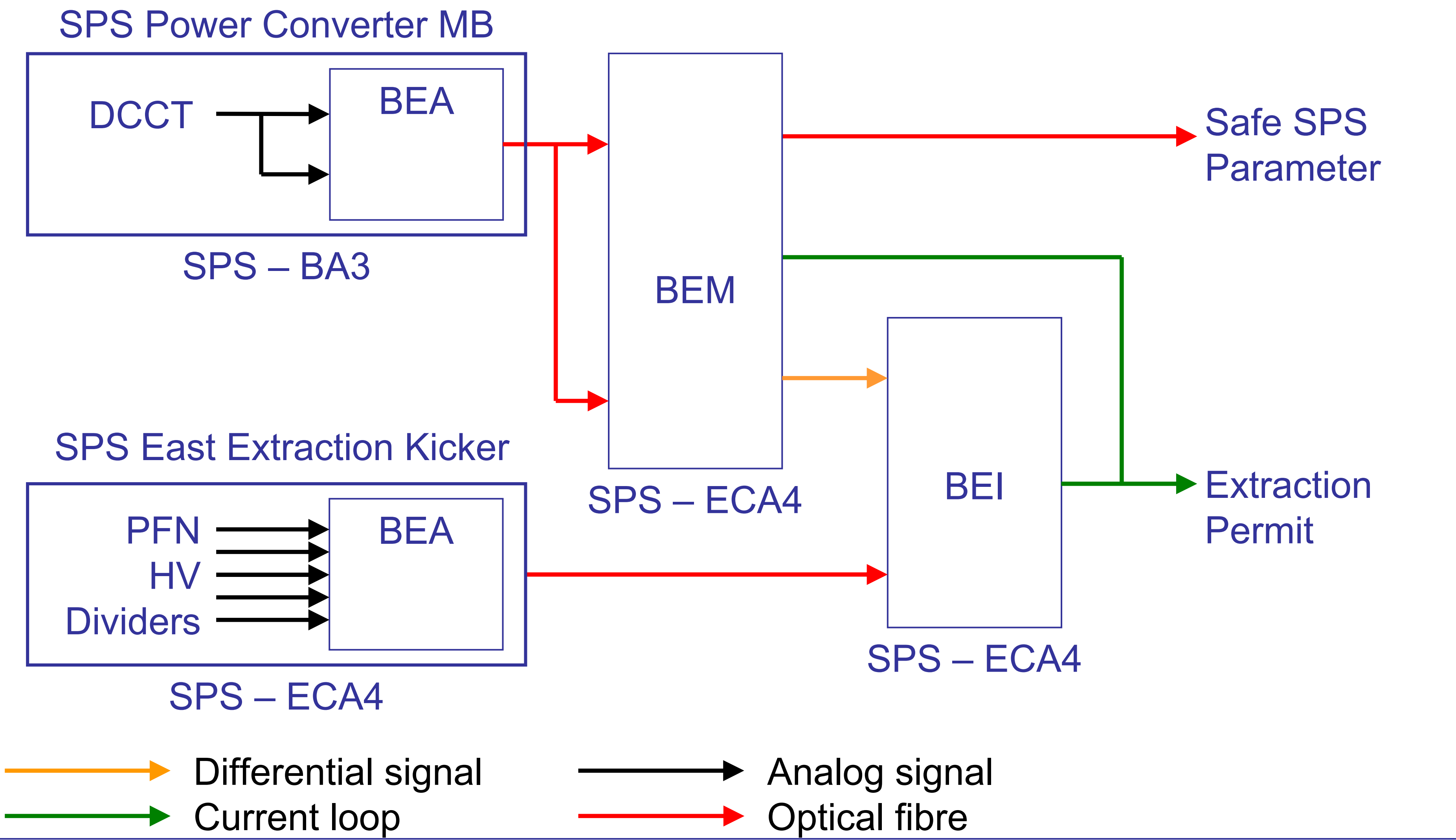
- **Tracking of the Vs with the machine energy** through the Beam Energy Meter (BEM) and the Safe LHC Parameter distribution between T = - 1 ms and T = 0 and **inhibit injection if an absolute discrepancy higher than 0.5 % is detected** between the Vs and the beam energy.
  - Automatic injection inhibit once acceleration has started
  - Redundant path to control at injection the correct operation of the beam dumping system beam energy tracking system

Reaction delay

- Injection inhibit possible up to **250 ns** before T=0

SPS Extraction Inhibit

Test 2006



Summary

- BETS will be built on the basis of a fail-safe logic
  - Each failure within the system will issue a dump request
  - Sensitivity of tracking tolerance windows could be an issue
- Tracking interlock logic will be based on a redundant approach relying on two different technologies
  - No “voting” is foreseen (nor possible)
- RAMS calculations are in progress
  - Part of the system is de-facto SIL3 with the use of SIEMENS S7-F Programmable Logic Controller
- BETS relies on a good knowledge of the magnetic characteristics of its different sub-systems over the complete LHC operational range
  - High precision calibration measurements are mandatory for all the sub-system included in the BETS.

Open Issues

- Acquisition of the beam energy relies on a single technology *(Bending magnet current + BEA + BEM):*
  - Conceptual design failure in this system can result in a common mode failure to the BETS reference and interlock logic.
- Absolute estimated value of the beam energy rely on external interlock *(Orbit corrector & Radio-frequency):*
  - The BETS is unable to detect and manage absolute beam energy variation induced by these systems.

How to Get the Beam Energy?
Principle (1/3)

Beam energy in a circular accelerator is defined by

$$\mathbf{E = 300\ q\ B_m\ \rho} \qquad (E \gg E_0) \qquad (1)$$

E	= Beam energy in GeV
E_0	= Beam rest energy
B_m	= Magnetic field in Tesla
ρ	= Bending radius in m
q	= Number of elementary charges in the particle ($q = 1$ for proton)

as ρ is fixed,

➔ the beam energy is directly proportional to the bending magnetic field

How to Get the Beam Energy?
Principle (2/3)

The magnetic field in a bending magnet is defined by

$$\mathbf{B_m \approx (2\, \mu_0\, n\, I) / h} \qquad (\mu_r >> 1) \qquad (2)$$

μ_0 = Permeability of vacuum
n = number of windings
I = Current
h = Dipole gap height

➔ The magnetic field in a bending magnet is directly proportional to its current

➔ The relation between magnetic field and magnet current can be precisely determined during main bending magnet calibration measurements