Sapienza Università di Roma
Dipartimento di Fisica
PhD school in accelerator physics XXX cycle

3rd year admission talk

Proposed title:

"Advanced beam diagnostics and beam protection for high-brightness electron-beam"

Supervisor: Luigi Palumbo
Co-supervisor: David Alesini

Outline

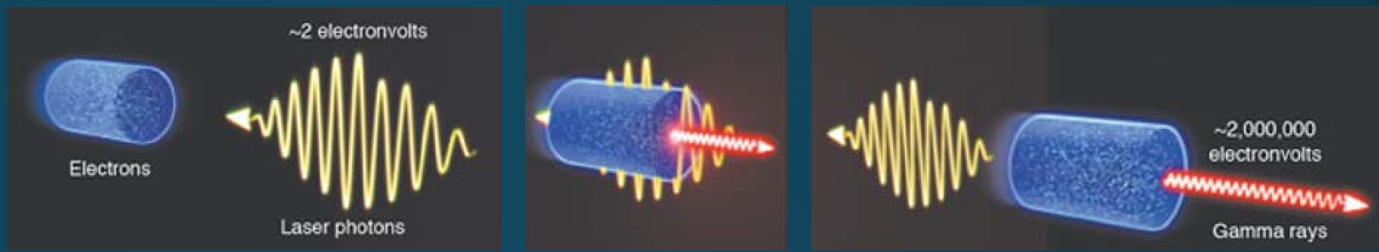
- ELI-NP GBS overview and layout
- Machine Protection System
  - Architecture design
  - Fast-Interlock
    - Real-time waveform mask
  - Magnets and Vacuum PLCs
  - Supervisor
    - Distributed Cherenkov Beam Loss Position monitor
    - Hall probe monitor
  - Next steps
- Electron beam performance monitor

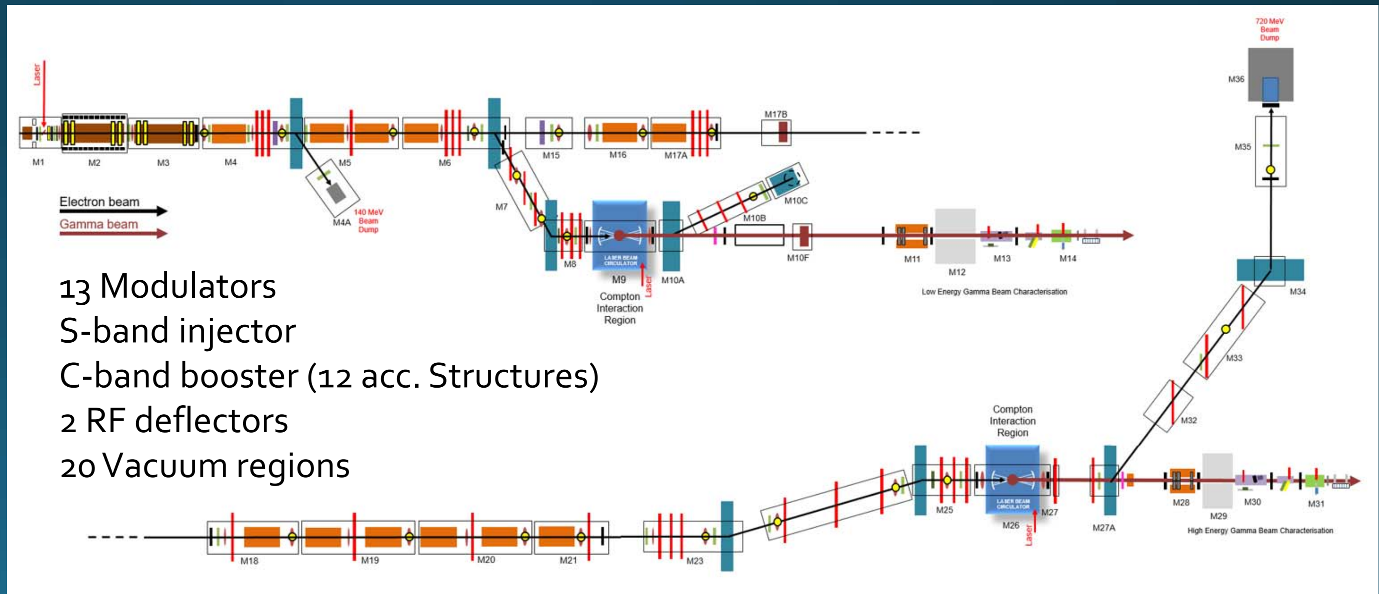
ELI-NP Gamma Beam Source

Gamma beam params	
Energy	0.2 – 20 MeV
Spectral density	$0.8 - 4 * 10^4 \frac{ph}{s * eV}$
Bandwidth (RMS)	< 0.5 %
Peak brillance	$> 10^{20} \frac{ph}{s*mm^2*mrad^2*0.1\%}$
Spot size	10 – 30 µm

Electron beam params	
Energy	75 – 740 MeV
Bunch charge	25 – 400 pC
Number of bunches/pulse	32
Bunch distance	16 ns
Bunch length	100 – 400 µm
Pulse length	512 ns
Energy spread (RMS)	0.04 – 0.1%
Norm. Emittance	0.4 mm * mrad
RF repetition rate	100 Hz

Compton back-scattering gamma source from the interaction of an high brightness electron beam and high power laser pulse.



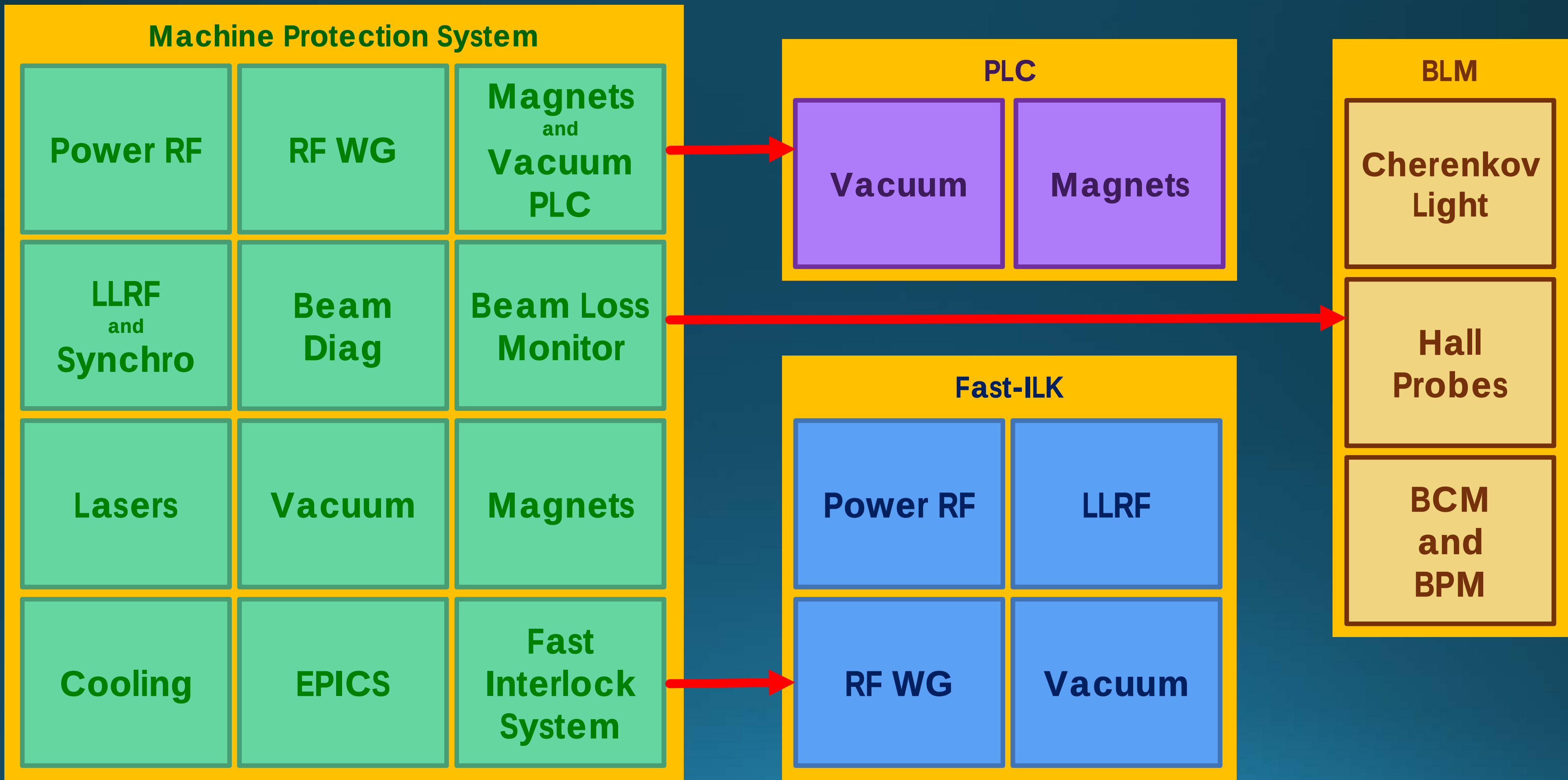


13 Modulators
S-band injector
C-band booster (12 acc. Structures)
2 RF deflectors
20 Vacuum regions

MPS: Architecture design

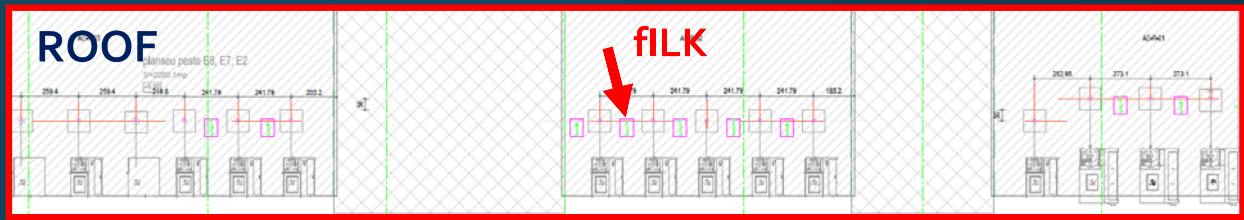
- **Integrated with all machine sub-systems**
- **Fast response** to protect critical system (less then 10 ms)
- **Robust** with a failsafe design and rich self-diagnostics
- **Smart** configurable logic matrix
- **Flexible** easily modify, extend and optimize

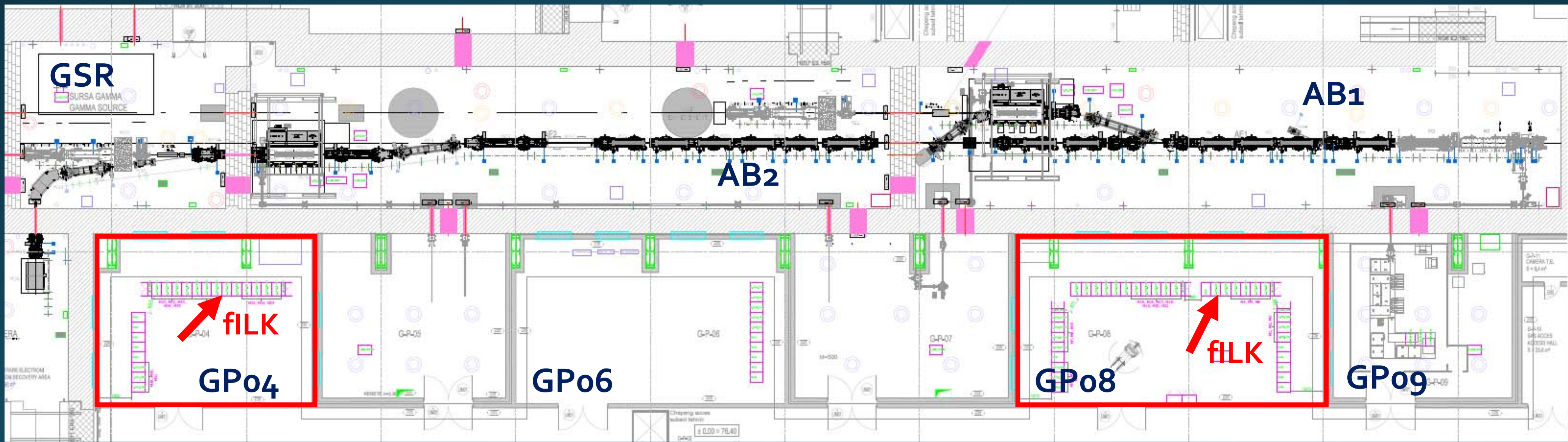
MPS: Architecture design



MPS: Fast-Interlock system topology

- real-time FPGA-based
- distributed I/O framework
- hardwired to critical system
- avoid single point of failure





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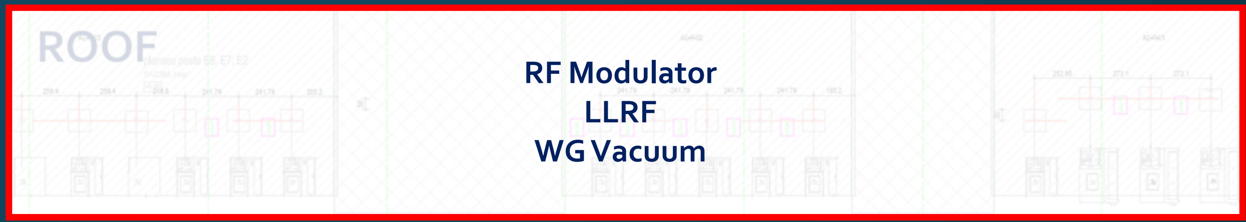

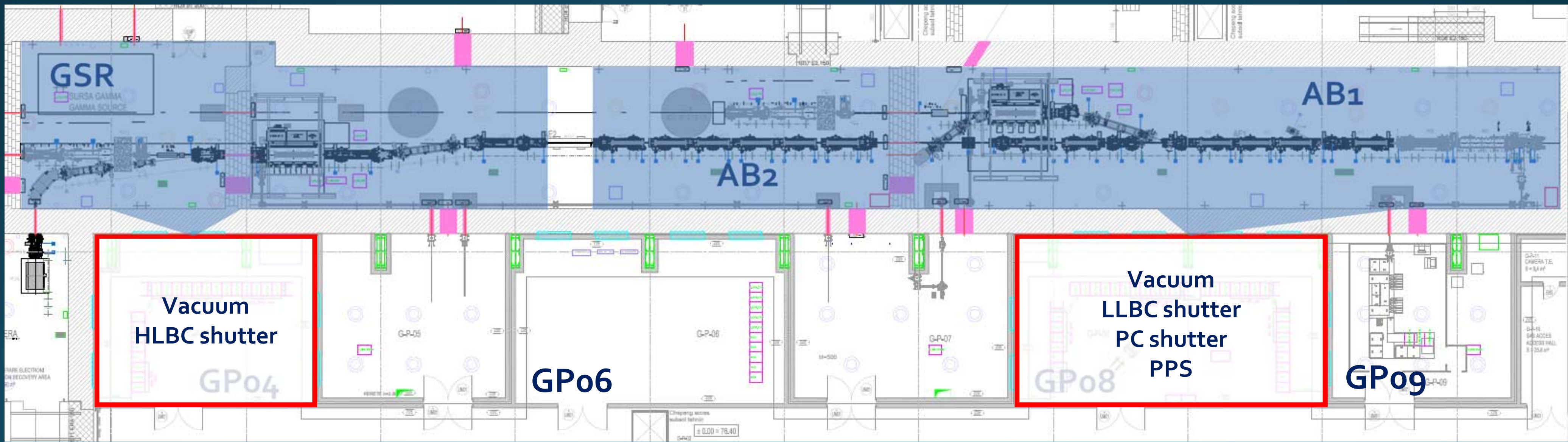

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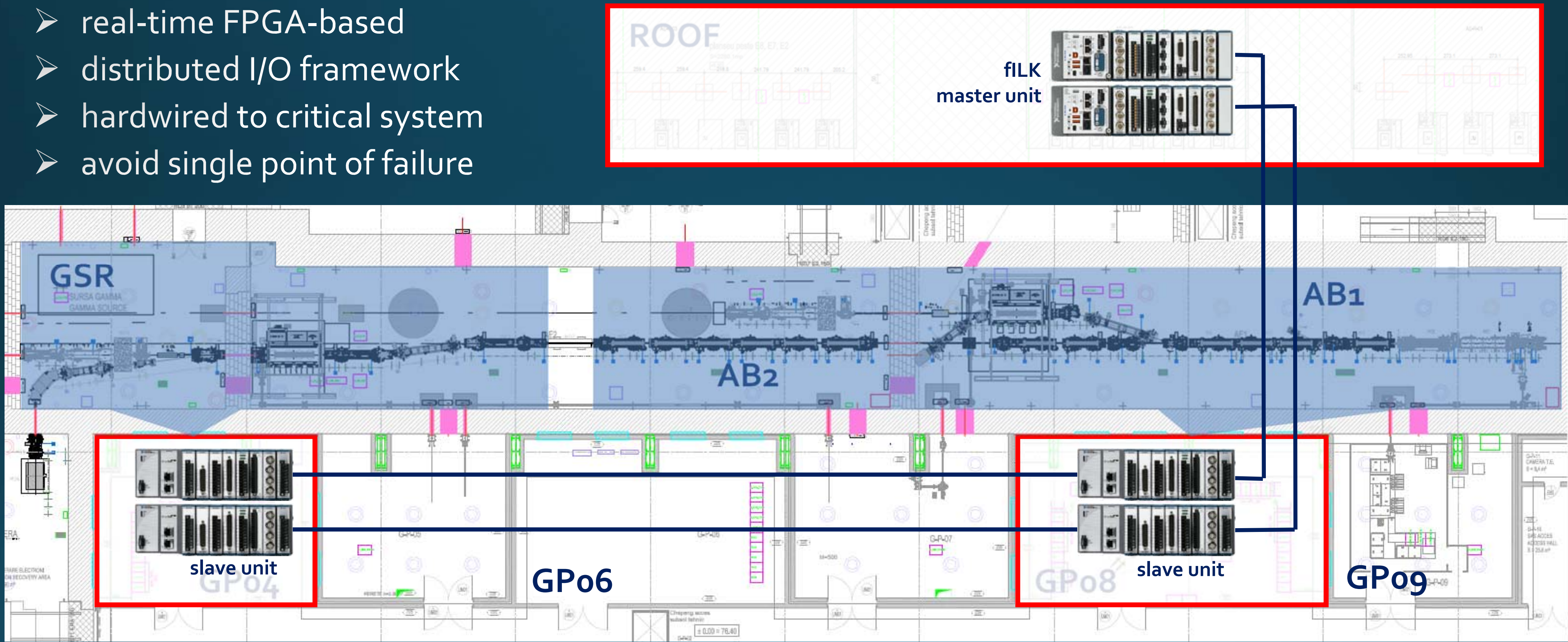


MPS: Fast-Interlock performance

- **Principal features:**
  - Each Fast-ILK system monitors a region of vacuum from different gauges and ion-pumps then if one of these has a failure this affects only one Fast-ILK system.
  - The Fast-ILK system handles vacuum events from accelerating cavities, WGs, LBCs, Gamma diag. and transfer lines.
  - The Fast-ILK system provides safe procedures for modulators conditioning or normal operation operating on LLRF.
  - The Fast-ILK system try to dissect the vacuum region where a vacuum leak is detected and closing the RF Gun valve.
  - The Fast-ILK system operates as front-end of Personnel Protection System for RF systems.

- **Performance:**
  - EtherCAT network latency: less then 100 μs (jitter less then 1 μs)
  - Detection time:
    - Vacuum gauges: ~20 ms
  - **Execution time (Fast-ILK): less than 1 ms**
  - Execution time (devices):
    - Modulator: + 10 μs,
    - LiberaLLRF: + 10 μs,
    - Lasers shutters: (TBD),
    - Pneumatic valves: + 25 ms (PLC) + 1 /2 s (for DN40/63 valves)

MPS: Fast-Interlock WFM mask

Scope of work: monitor real-time RF-signals to detect anomalous vacuum activity in WG and accelerating structures and operate RF systems in less than 10 ms.

Specifications:

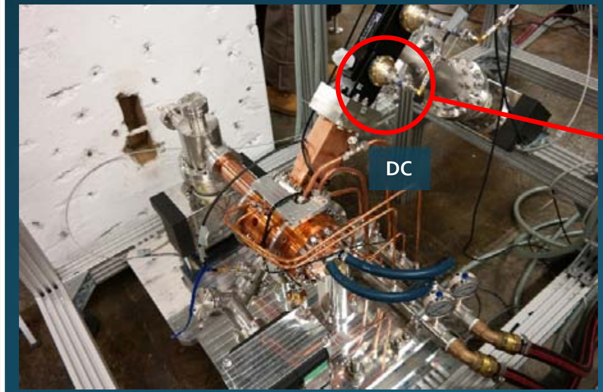
- Sample real-time 1,5 µs reflected RF signal from a directional coupler;
- Analyze sampled signal;
- Trip RF Modulator in less than 10 ms.

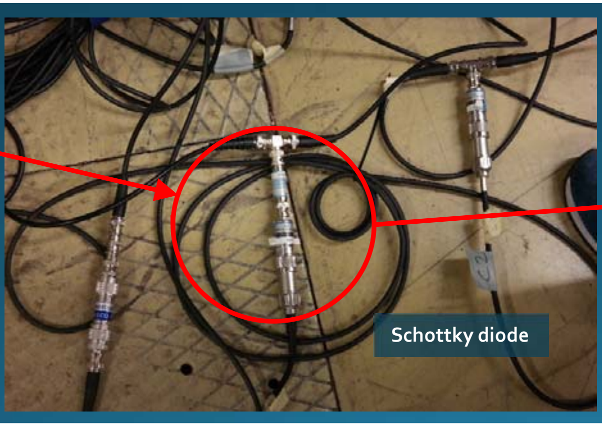
ELI-NP RF-GUN

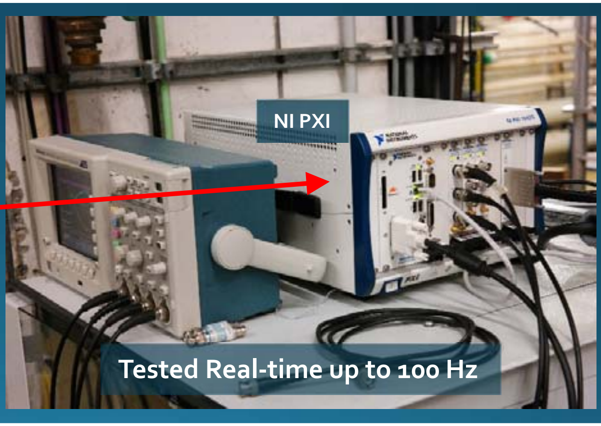
Rep. Rate	100 Hz
Working mode	Π mode (SW)
Max RF input	16 MW
RF peak field	120 MV/m
Filling time	420 ns
Unloaded Q factor	15000

RF-Gun conditioning Bonn 12/2015

Prototype







Digitizer specs:

Sampling Rate	2 GS/s
Sample depth	10-bit
BW	1,5 GHz
Memory	16 MB
Cost/channel	7,5 k€

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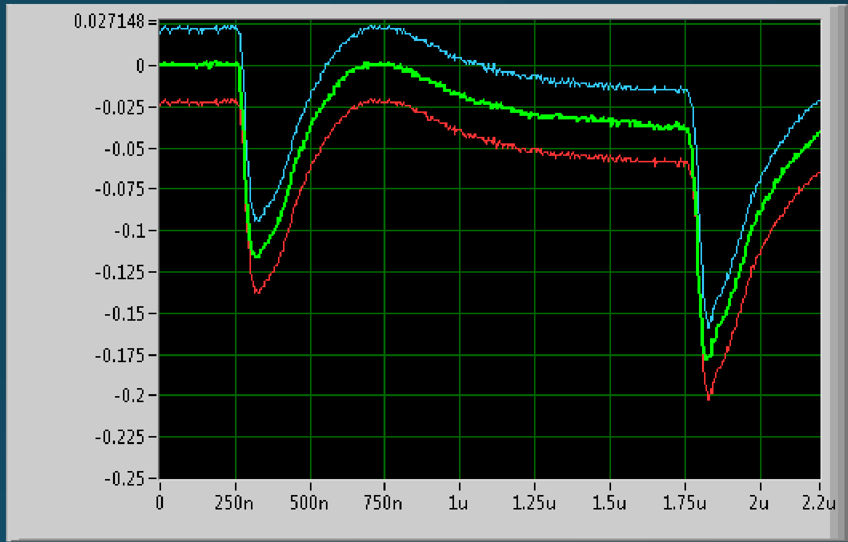
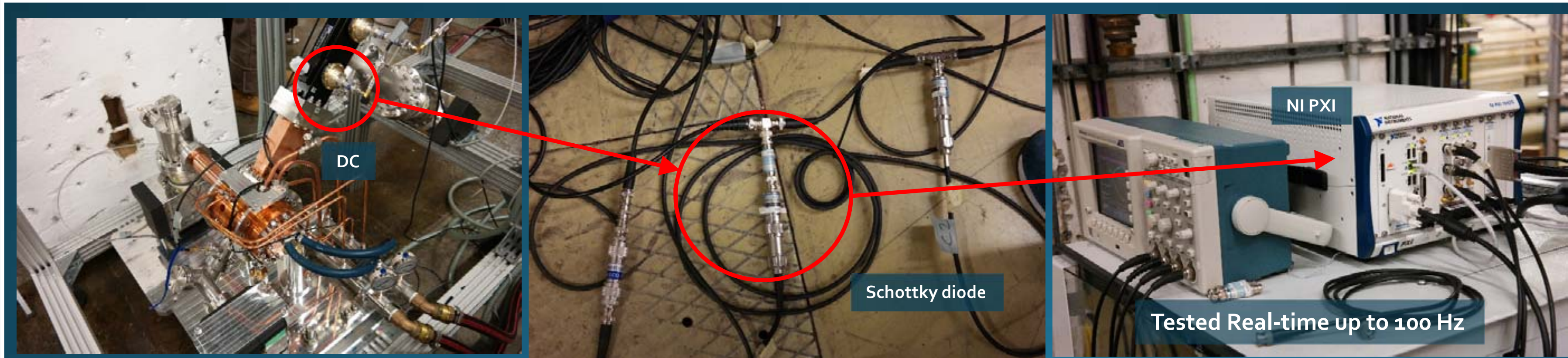


Healthy signal

Upper mask
Lower mask
Reflected RF

Prototype



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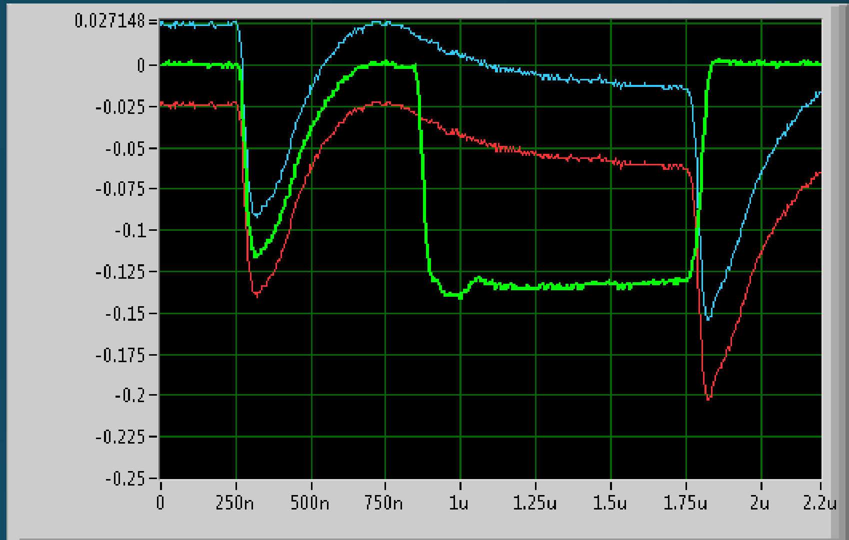
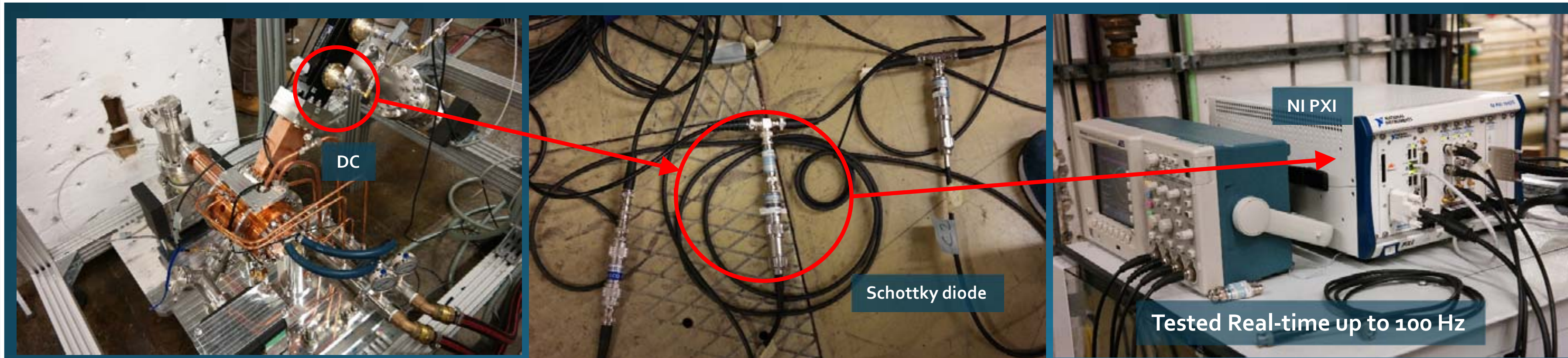


Prototype



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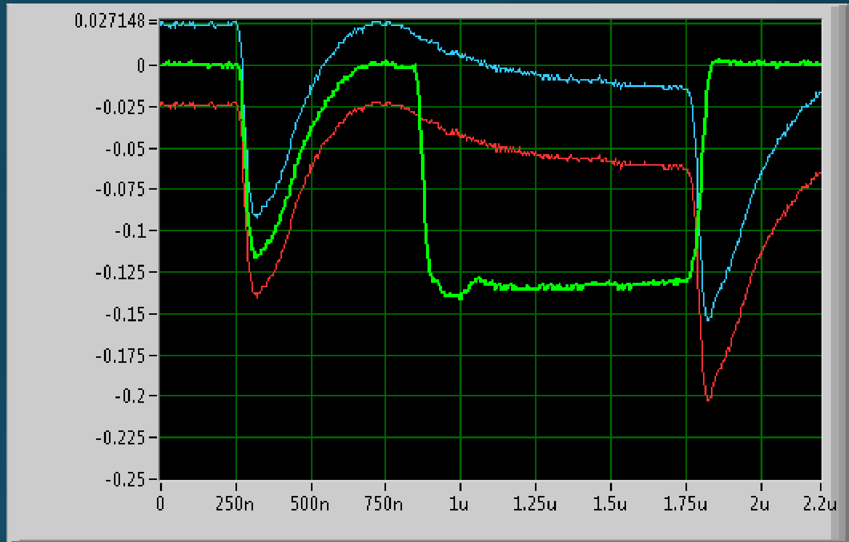
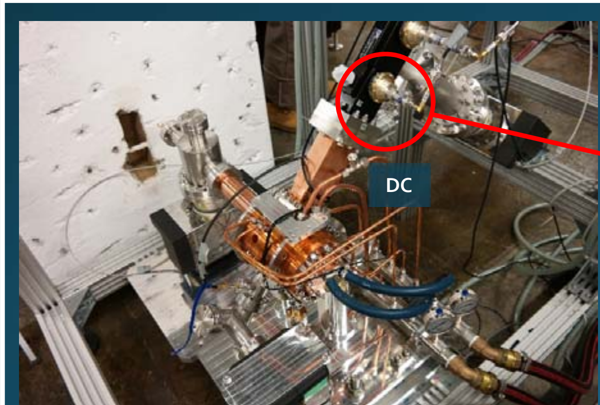
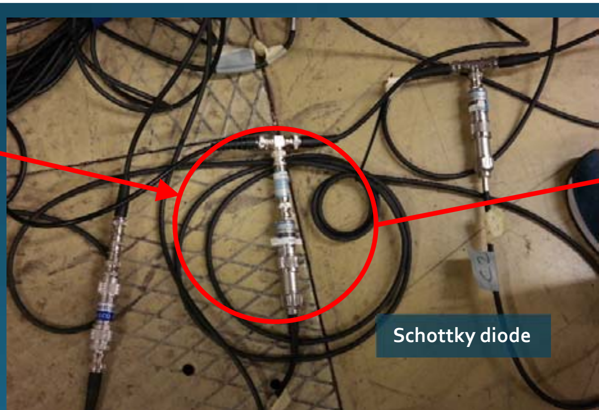


Bad signal

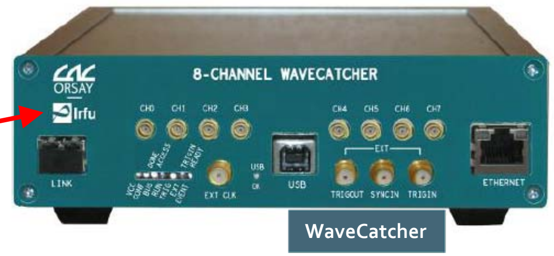
Upper mask
Lower mask
Reflected RF

Final design





Tested Real-time up to 1 kHz!



"The WaveCatcher family of SCA-based 12-bit 3.2 GS/s fast digitizers"
D. Breton, E. Delagnes, J. Maalmi, P. Rusquart

Digitizer specs:

Sampling Rate	3,2 GS/s
Sample depth	12-bit
BW	0,5 GHz
Memory	128 B
Cost/channel	400 €

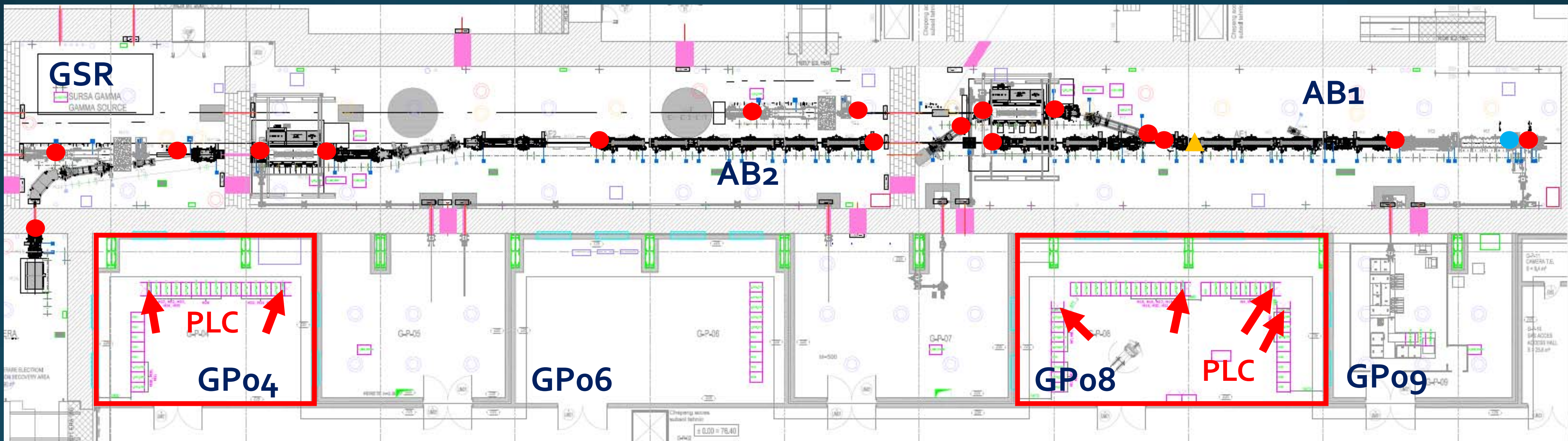
MPS: Magnets and Vacuum PLCs

Specifications:

- 20 Omron PLC distributed among the technical rooms.
- 20 Vacuum regions
- 17 valves drived from boundary vacuum gauges.
- Interfaced with the EPICS network and Fast-ILK.
- VAT Fast Closing Valve system in M1 with dedicated vacuum gauge in M6 (distance ~16 m).

Performance:

- Detection time:
  - Vacuum gauges: ~60 ms,
  - Fast Valve vacuum gauge: 2 ms
- Execution time:
  - ~25 ms + 1 /2 s (for DN40/63 valves),
  - Fast Valve shutter: 5 ms (able to stop shockwave from both interaction point: from gauge to shutter a Mach-2 shockwave require 30 ms).



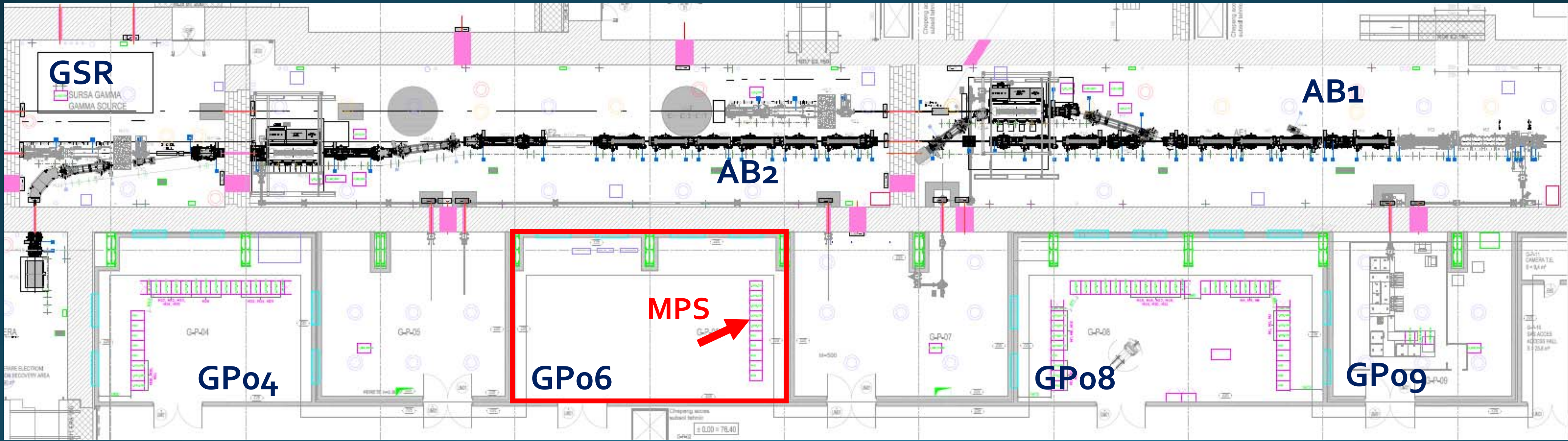
MPS: Supervisor

Specifications:

- 1 + 1 (auxiliary) IOC running in parallel servers.
- Integrated in the EPICS network: able to reach all sub-systems.
- Interfaced with MPS sub-systems:
  - interlock hardware (Fast-ILK and PLCs)
  - Interlock software (EPICS)
  - BLMs

Performance:

- EPICS network latency: ~100 ms,
- Execution time: less then 10 ms



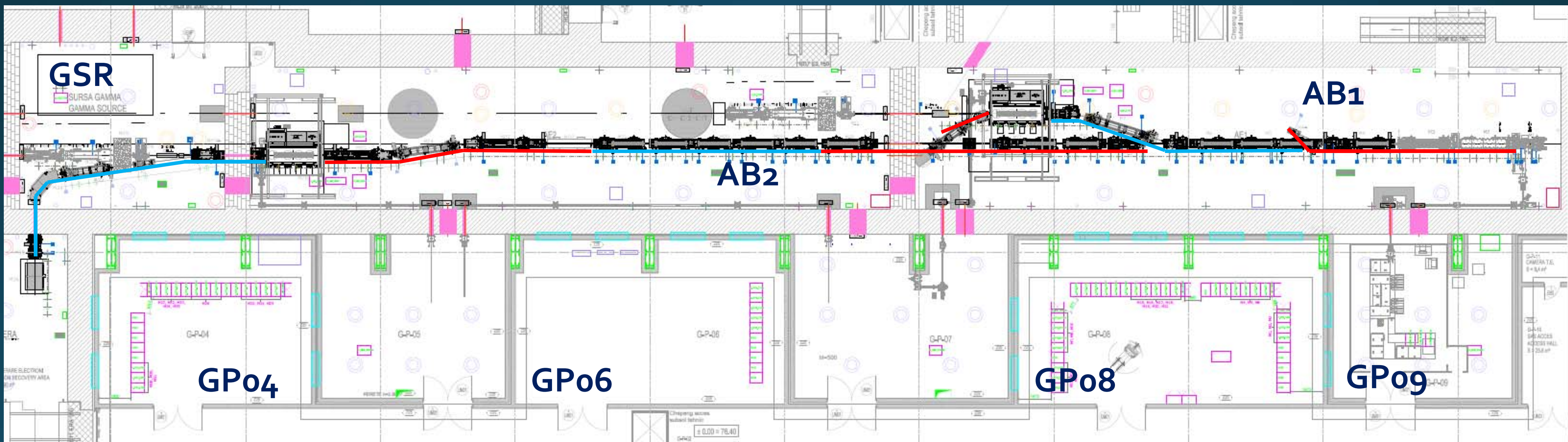
MPS: Supervisor Distributed Chernkov BLPM

Scope of work: map beam loss along whole accelerator to enable operation for machine and personnel safety.

Specifications:

- Locate beam loss and the involved device of lattice.
- Trip RF-Gun and Photo Cathode laser.

Split the facility in different trunk (max. length of 20 m) avoid background saturation due to the dark current transport.



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$$\cos\theta_C(\lambda) = \frac{1}{\beta n(\lambda)}$$

Cherenkov cone semi-angle

$$\cos 0 = \frac{1}{\beta n(\lambda)} \qquad \beta = \frac{1}{n} \approx 0{,}7$$

Cherenkov energy threshold

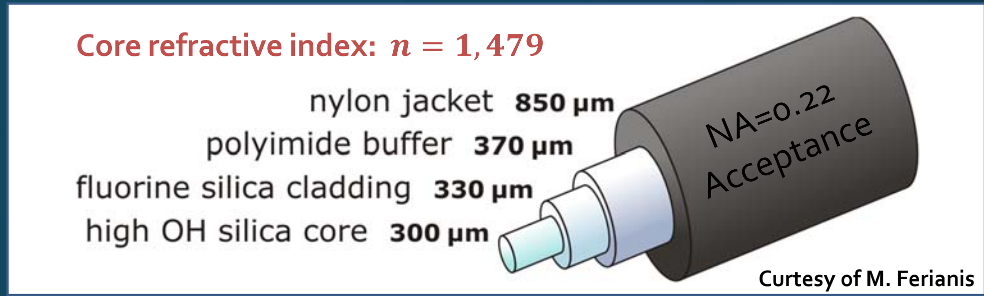
$$\theta_C = \begin{cases} 17° \; if \; \beta \approx 0{,}7 \\ 48° \; if \; \beta \approx 1 \end{cases}$$

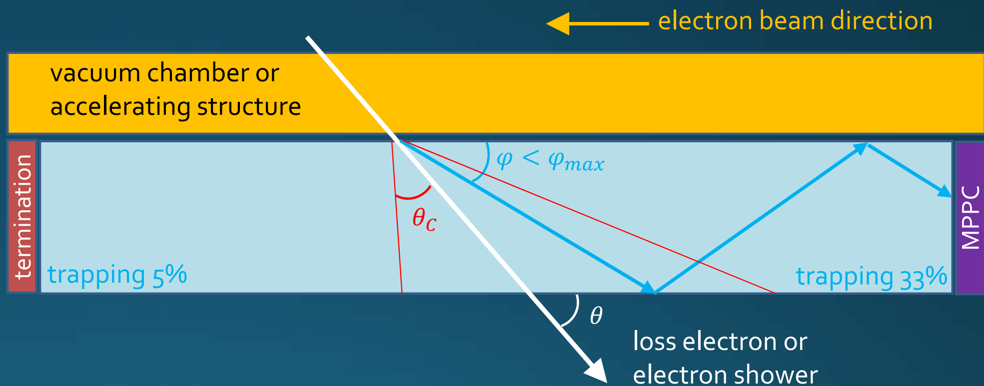
$$\varphi < \varphi_{max} = \sin^{-1}\frac{NA}{n} = 8{,}4°$$

Total internal reflection limit angle

$$\theta = \begin{cases} [8{,}6° - 25{,}4°] \;\; if \; \beta \approx 0{,}7 \\ [40{,}6° - 56{,}4°] \; if \; \beta \approx 1 \end{cases}$$

Charged particles angle through the fiber (to be trapped from sensor side, other side is suppresed by critial angle cut)





$$\frac{dN}{dx\,d\lambda} = \frac{2\pi\alpha}{\lambda^2}\sin^2\theta_C = \begin{cases} 2\,\frac{ph}{mm} \; if \; \theta_C = 17° \\ 13\,\frac{ph}{mm} \; if \; \theta_C = 48° \end{cases}$$

Cherenkov photons from a single charged particle

$\lambda = [400\,nm - 500\,nm]$
Light wavelength

α
Fine structure constant

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"The WaveCatcher family of SCA-based 12-bit 3.2 GS/s fast digitizers"
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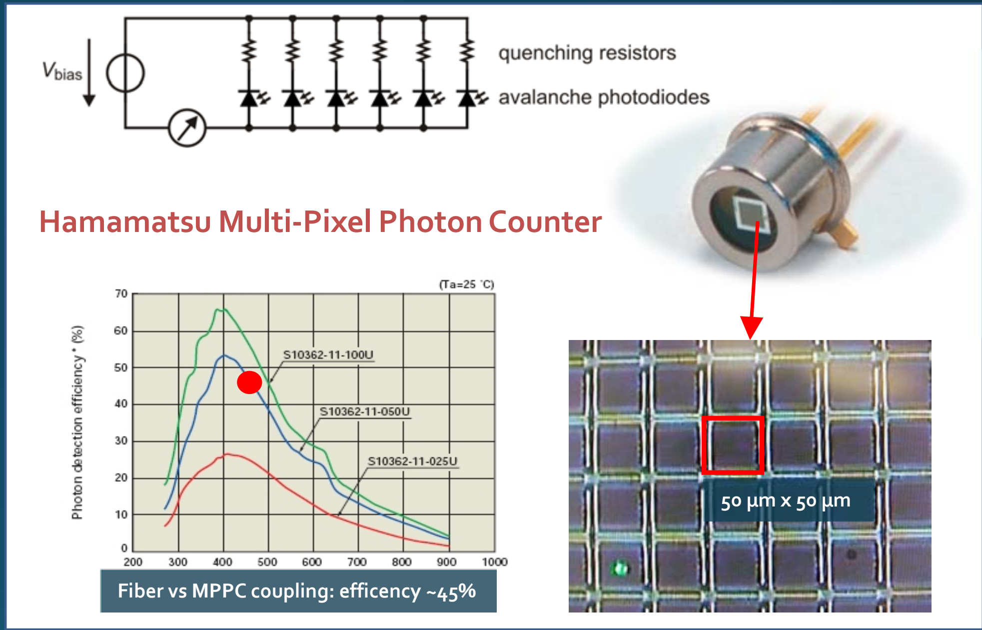
Digitizer specs:

Sampling Rate	3,2 GS/s
Sample depth	12-bit
BW	0,5 GHz
Memory	128 B
Cost/channel	400 €

$$\Delta s = \Delta t \, c \left(\frac{1}{\beta} + n\right)^{-1}$$

Optical fiber nominal longitudinal resolution

@3,2 GS/s time-of-flight resolution ~4 cm



- Array of 400 avalanche photodiodes (APDs) connected in parallel
- Reverse bias (photon causes APD breakdown)
- Photomultiplier-like gain ($10^5 – 10^6$)
- Insensitivity to magnetic field
- Time resolution: rise time 100 ps
- Compact and Low cost

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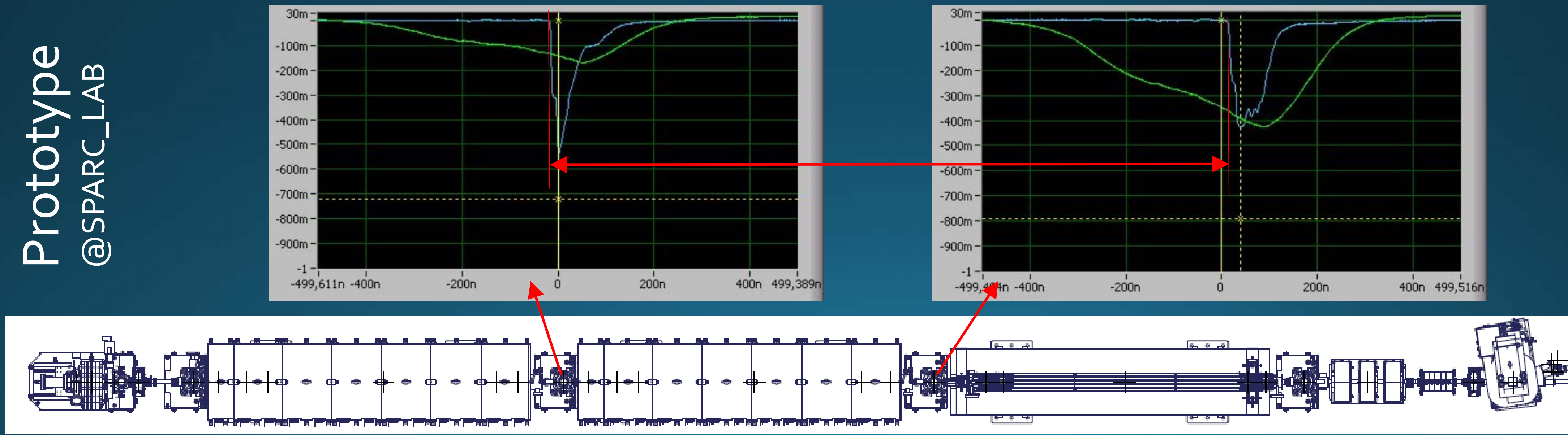
Distance between AC2FLAG and AC3FLAG

Distance from CAD	3,5 m
Time-of-flight difference	~ 30 ns
Reconstructed distance from Cherenkov BLPM	~ 3,6 m
Sampling rate	1 GS/s
DAQ accuracy	+/- 15 cm

Prototype
@SPARC_LAB

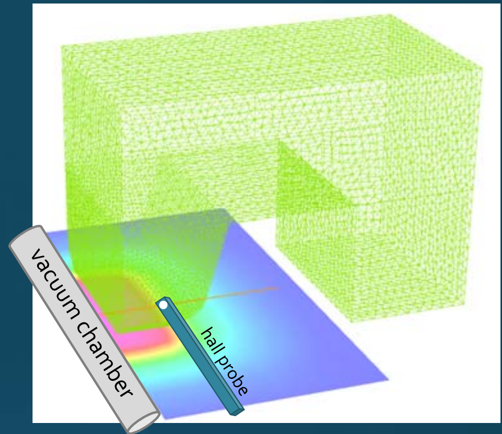


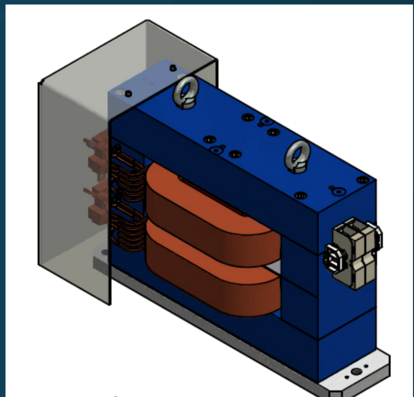
MPS: Supervisor Hall Probes

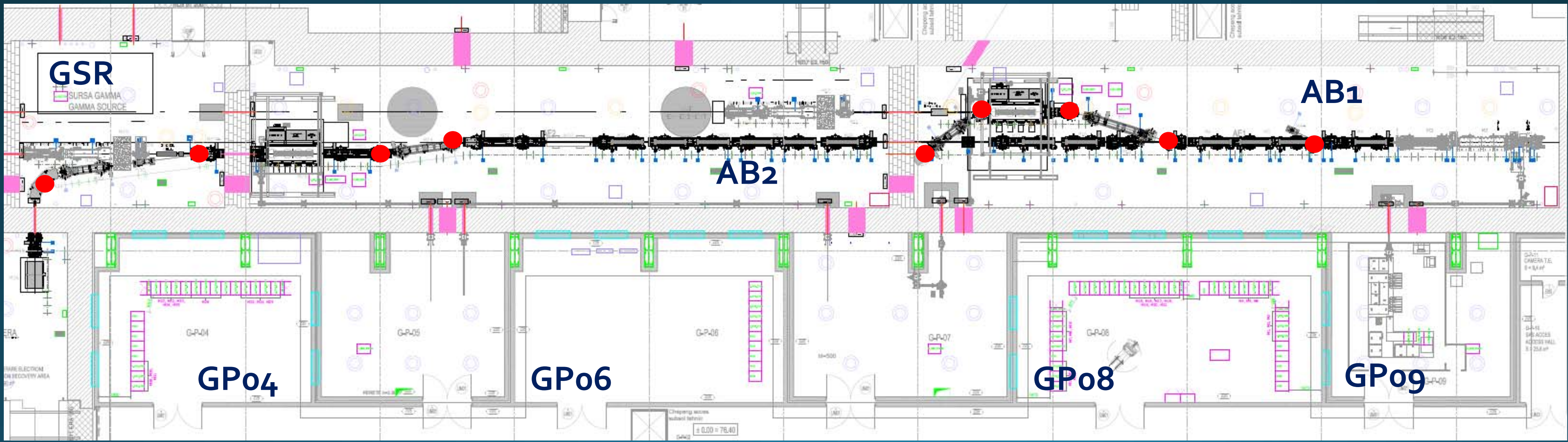
Scope of work: monitor B field inside the 9 dipoles to verify the matching between magnet field and power supply current set-point.

Specifications:

- Acquire bipolar B field between 0.4 T and 1.6 T;
- Convert probe signal from raw data to supplied current.
- Trip RF-Gun and Photo Cathode laser.




Curtesy of A. Vannozzi



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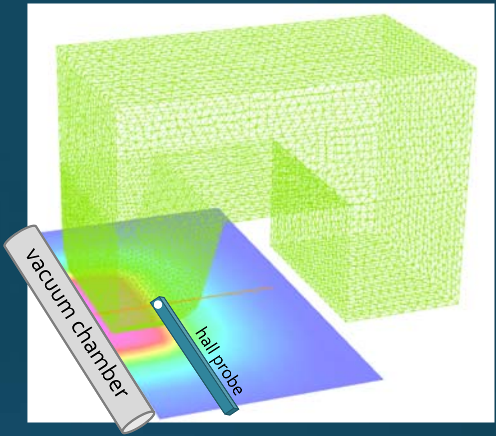
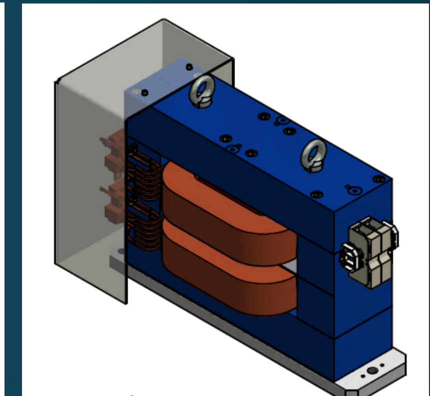




Curtesy of A. Vannozzi

Hall probe specs:

Full scale	+/- 2 T
Signal Amplitude	+/- 10 V
BW	200 kHz
Noise	< 1 mV_{p-p}
Working temp.	10 – 50 °C

→

DAQ specs:

Signal Amplitude	+/- 10 V
Sample depth	16-bit
BW	10 MHz
Accuracy	+/- ~2 mV
Accuracy (B field)	+/- ~4 G

→

1 Calibration

Lookup table to convert from signal amplitude to magnetic field.

→

2 Calibration

Dipole excitation curve (provided by manufacture) to convert magnetic field to supplied current.

→

Monitor

Check mismatch between power supply and Hall probe current set-point.

MPS: Next Steps

- Fast-ILK – Finalize FPGA software development
- Waveform Mask – ready!
- Supervisor – Finalize software development
- Cherenkov BLPM – Calibrate all optical fiber + MPPC setups with a pulser
- Hall probes – Calibrate probe + magnet + power supply
- Tuning and Site Acceptance Test

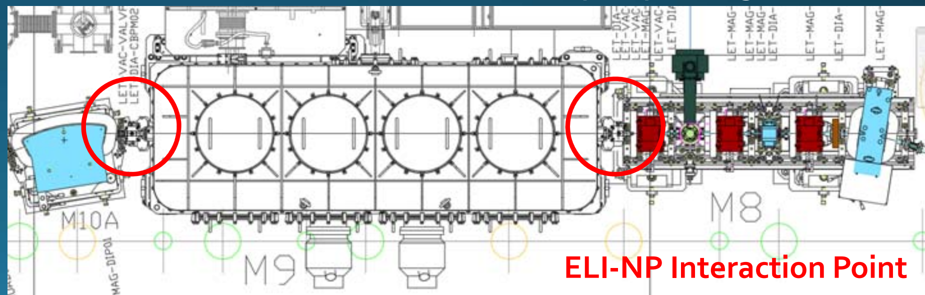
Electron beam performance monitor

- Scope of work:
  - Electron beam current monitor
  - Electron beam position monitor
  - Electron beam sigma monitor
  - Non-intercepting measure
  - Low-Q to measure multi-bunch beams (ELI-NP like)
  - Real time

- EM Design
- Mechanical design
- Test

Next year!

This device can monitor the electron beam just before and after the IP to handle the quality of the gamma source



Thank you for the attention.