Beam Positions Monitors developments for LIPAC

I. Podadera, J. M. Carmona, A. Ibarra, J. Molla

CIEMAT

17 January 2011

Outline

- IFMIF and LIPAC
- BPM's requirements @ LIPAC
- Pickups design
- Test bench
- Electronics measurements
- Conclusions & Next steps

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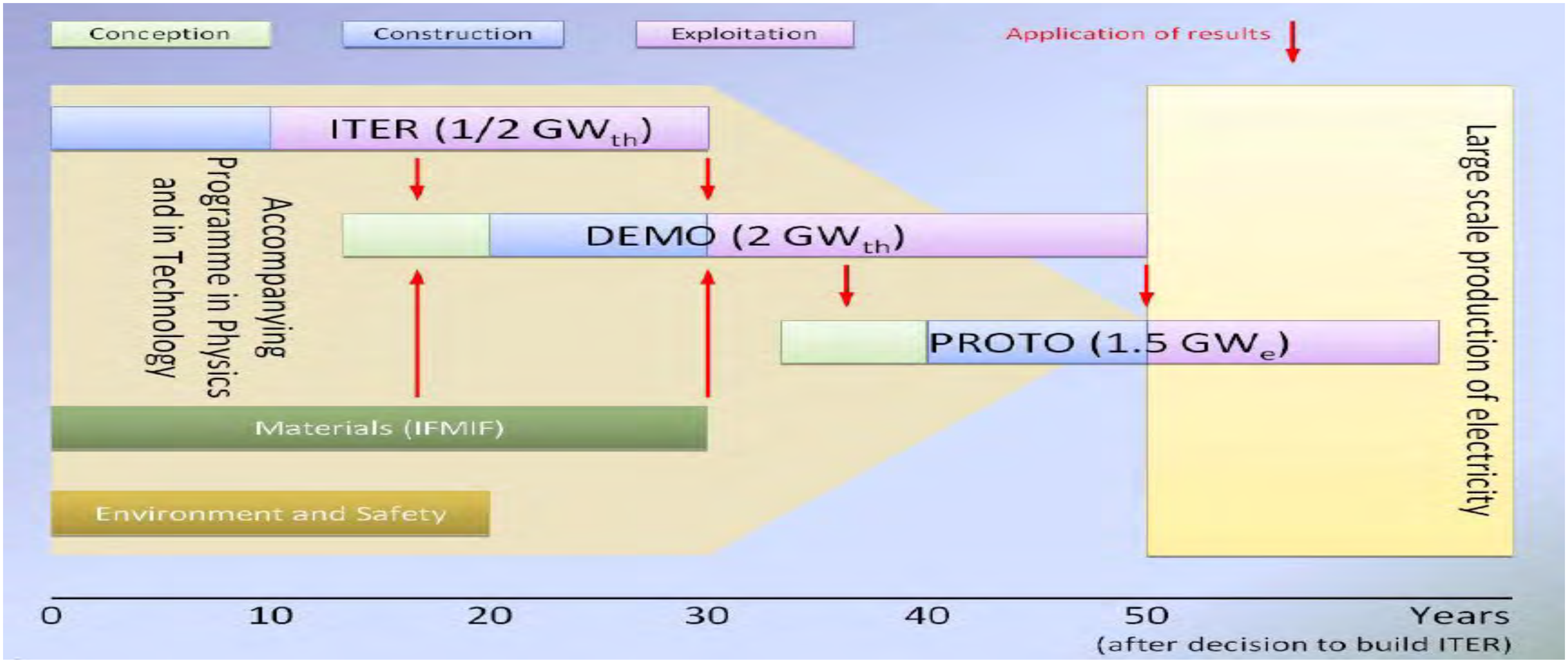
IFMIF Goals

International Fusion Materials Irradiation Facility

Characterization of materials envisaged for future fusion reactors.
Study and analysis of the behaviour of materials under a high flux of neutrons (10^{18} n/m^2/s).

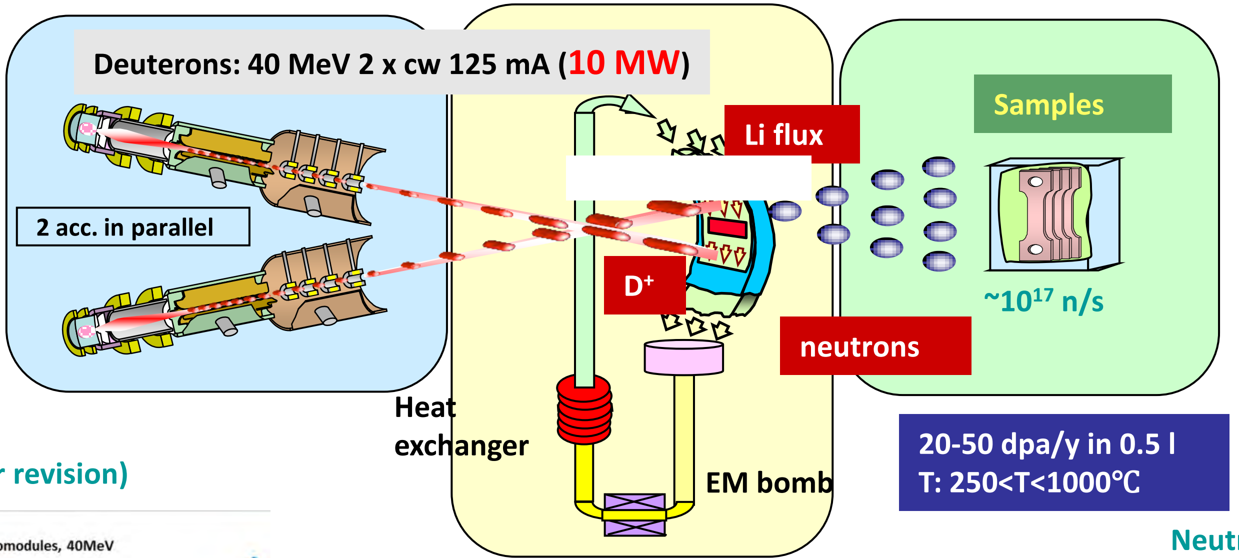


P. Garin, *IFMIF: status and developments*, EPAC08, p. 974 (2008)

IFMIF design

Overall facility availability >70%

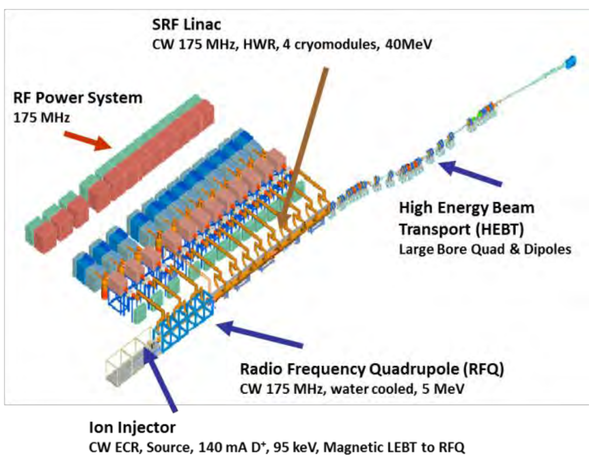
Accelerator | **Target** | **Irradiation module**



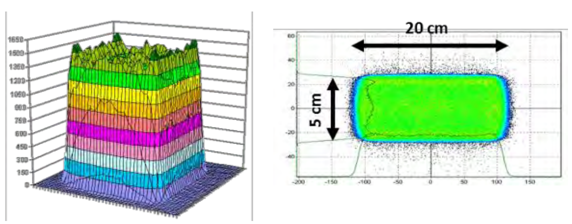
20-50 dpa/y in 0.5 l
T: 250<T<1000°C

Heat extraction by fast liquid Li

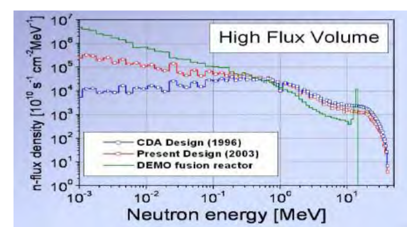
Accelerator (under revision)

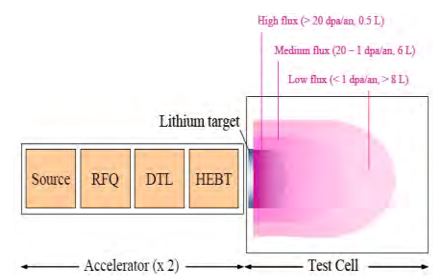


Beam footprint at interaction point



Neutron flux density



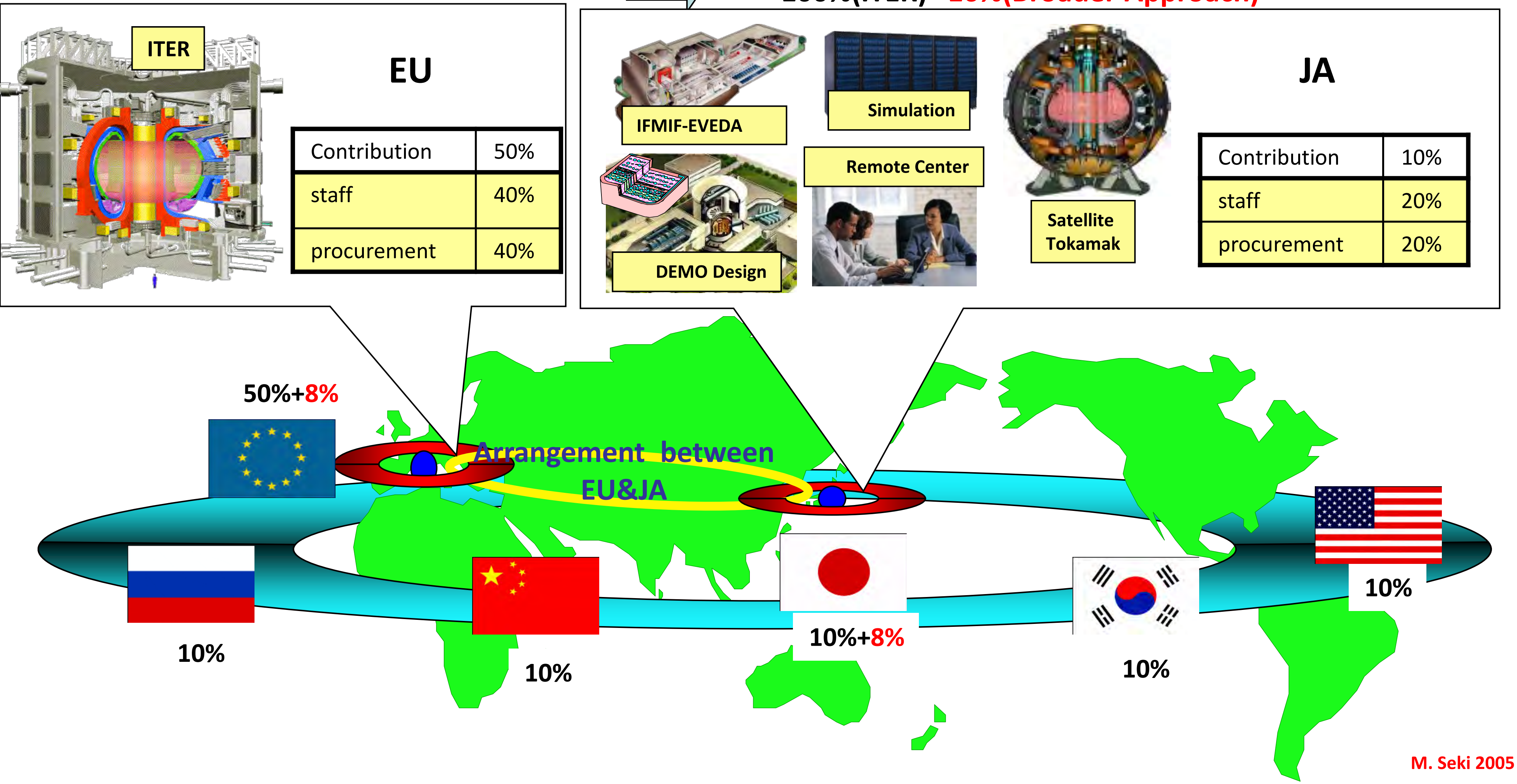


P. Garin, *IFMIF: status and developments*, EPAC08, p. 974 (2008)

Broader Approach Projects

Contribution : (50% + 8%:EU)+(10%+8%:JA)+10%x4(US,RF,KO,CN)

100%(ITER) +16%(Broader Approach)



Contribution	50%
staff	40%
procurement	40%

Contribution	10%
staff	20%
procurement	20%

M. Seki 2005

IFMIF-EVEDA LIPAC Accelerator

EVEDA phase

Engineering Validation and Engineering Design of the IFMIF project

LIPAC project

Linear IFMIF Prototype Accelerator

Goals

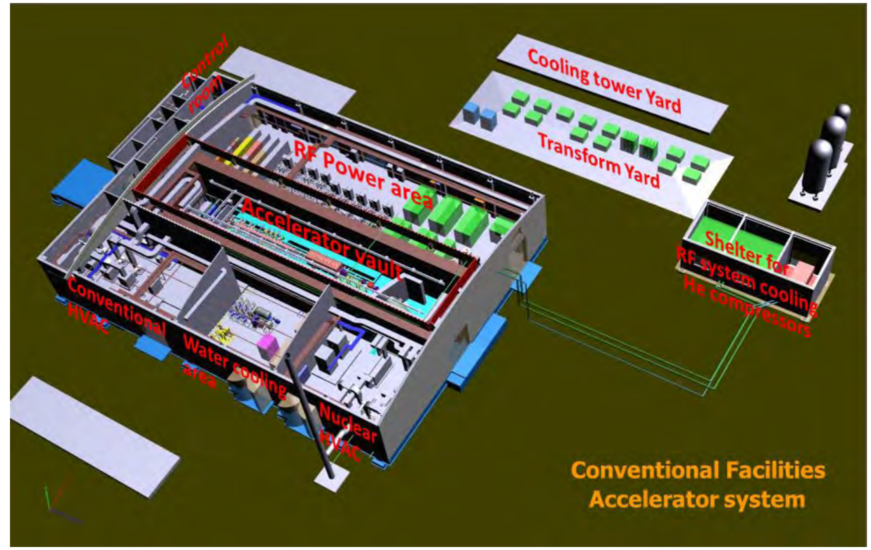
- to validate the technical options with the construction of a prototype accelerator.
- Input to produce the detailed integrated design of the future IFMIF accelerator.

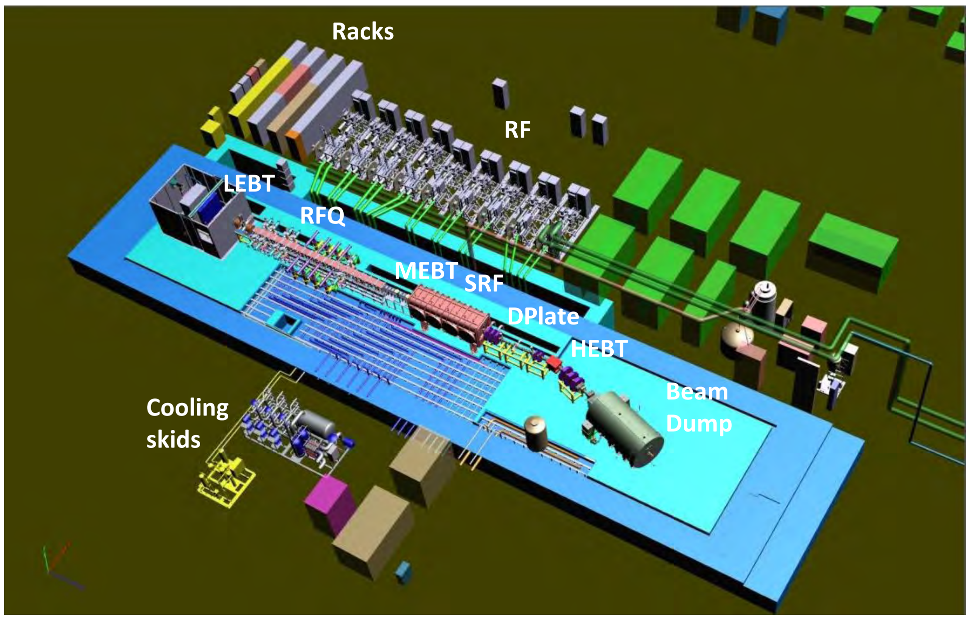
Main specifications

- Installation in Rokkasho-Japan from 2013.
- manufacturing and tests of a prototype accelerator (1:1) with 9 MeV final energy.
- Nominal operation: Deuterons, 125 mA cw, 9 MeV.
- Commissioning phase: 10 mA-125 mA, pulsed mode down to >100 μs, 0.1% duty cycle.

A. Mosnier, A. Ibarra, A. Facco, *The IFMIF-EVEDA accelerator activities*, EPAC08, p. 3539 (2008)

LIPAC Rokkasho building





Ion especies	D^+ (nom. op.) p, H_2^+ (comm.)
CW current (nominal)	125 mA
RFQ output energy	5 MeV
SRF output energy	9 MeV
RF frequency	175 MHz
Bunch width (min/max)	0.1-3 ns
Duty factor (min/max)	0.1%/CW
Pulse length (min/max)	~100 μs/CW
Beam power	1.125 MW

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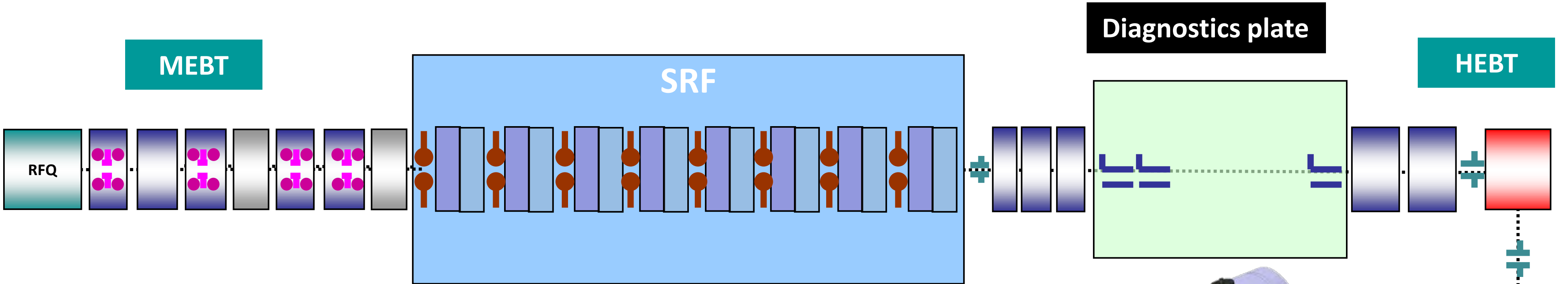
Measurement objectives of BPM's at LIPAC

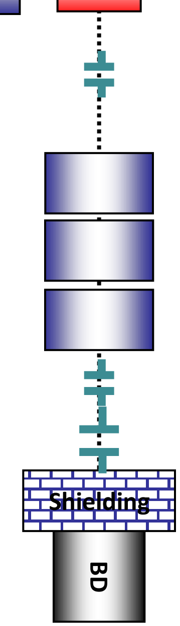
To detect dipole errors along the beamlines and cryomodule by measuring the position of the transverse beam centroid

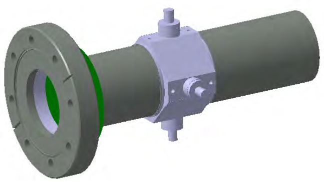
To measure the mean energy at the Diagnostics Plate

To tune the cavities with the beam phase

Layout



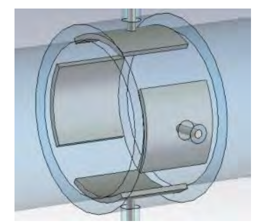




MBPM

CBPM

DBPM



HBPM

Region	BPM acronym	Aperture	Number	Symbol
MEBT	MBPM	48 mm	4	
SRF	CBPM	50 mm	8	
Diagnostics plate	DBPM	100 mm	3	
HEBT	HBPM	40/130/150 mm	1/2/2	
TOTAL			**20**	

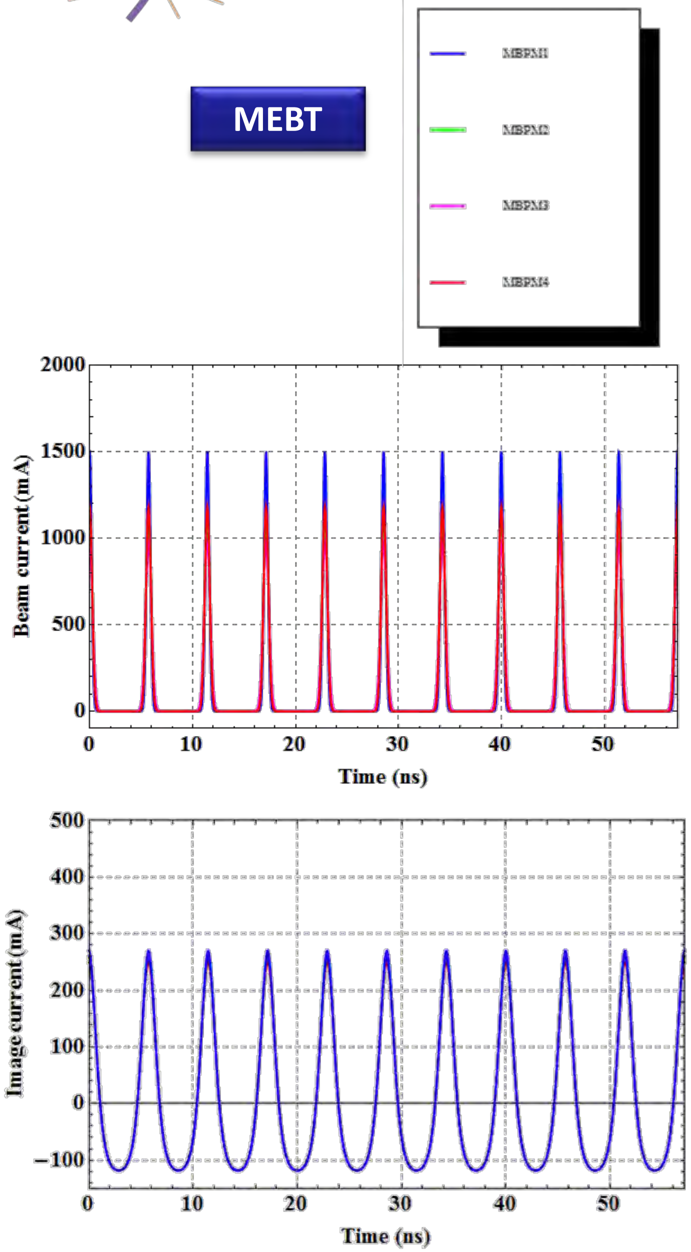
Beam dynamics requirements

Location	β (%)	Transverse size (mm)	Bunch length (mm)	Current (mA)	Aperture (mm)	Measurement type	Range	Precision	Resolution
MEBT	7	1/5	4/6.5	125	50	Position	0 to 5 mm 5mm to BSC/2	0.1 mm 0.5 mm	0.01 mm 0.05 mm
						Phase			
						Current	0.01 to 150 mA	0.001 to 0.1 mA	0.001 to 0.1 mA
SRF	7/10	3/3	2.5/2.8	125	49	Position	0 – 5 mm 5mm to BSC/2	0.25 mm 1.0 mm	0.025 mm 0.1 mm
						Phase		2 deg	0.3 deg
						Current	0.01 to 150 mA	0.001 to 0.1 mA	0.001 to 0.1 mA
DP & HEBT	7*/10	3/10	2/40	125	40/150	Position	0 – 5 mm 5mm – to BSC/2	0.1 mm (tbc) 1 mm	0.01 mm (tbc) 0.1 mm
						Phase		1 deg	0.1 deg
						Current	0.01 to 150 mA	0.001 to 0.1 mA	0.001 to 0.1 mA

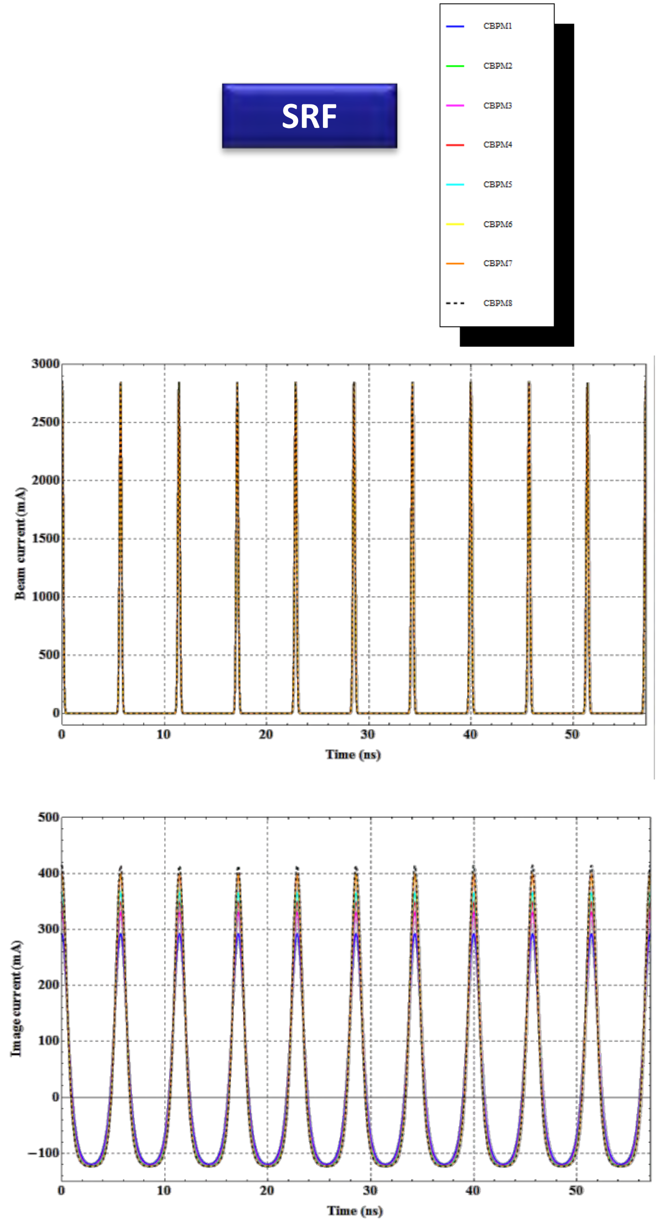
**RFQ commissioning* — *RFQ commissioning

Image currents

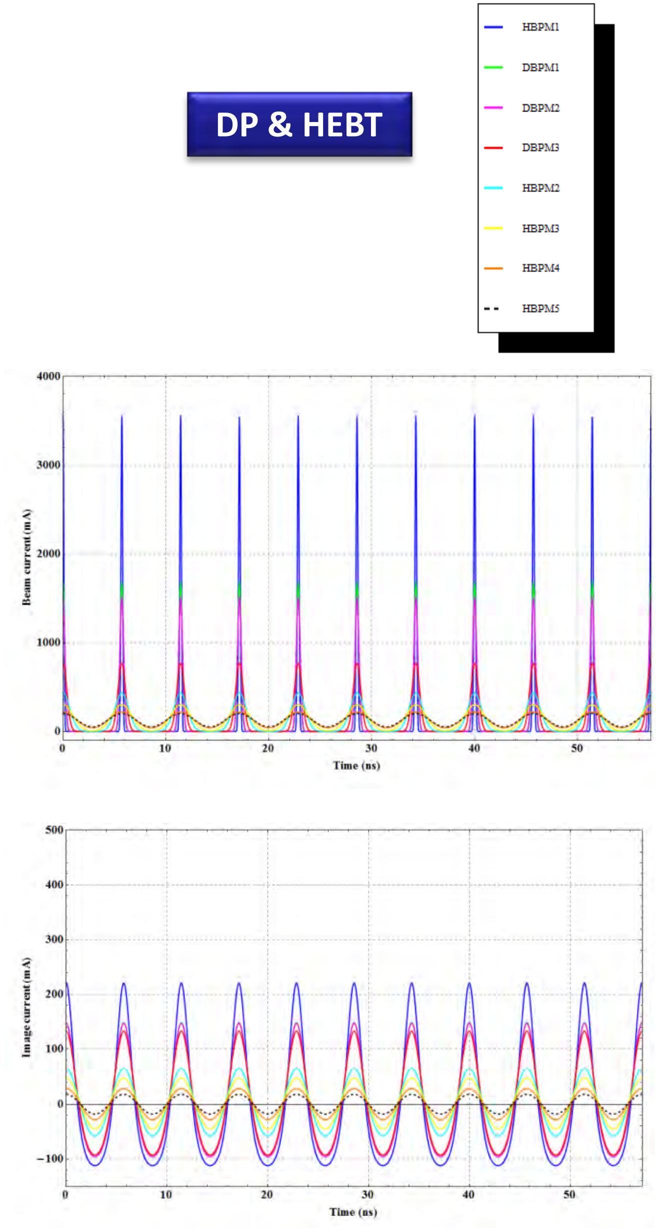
MEBT



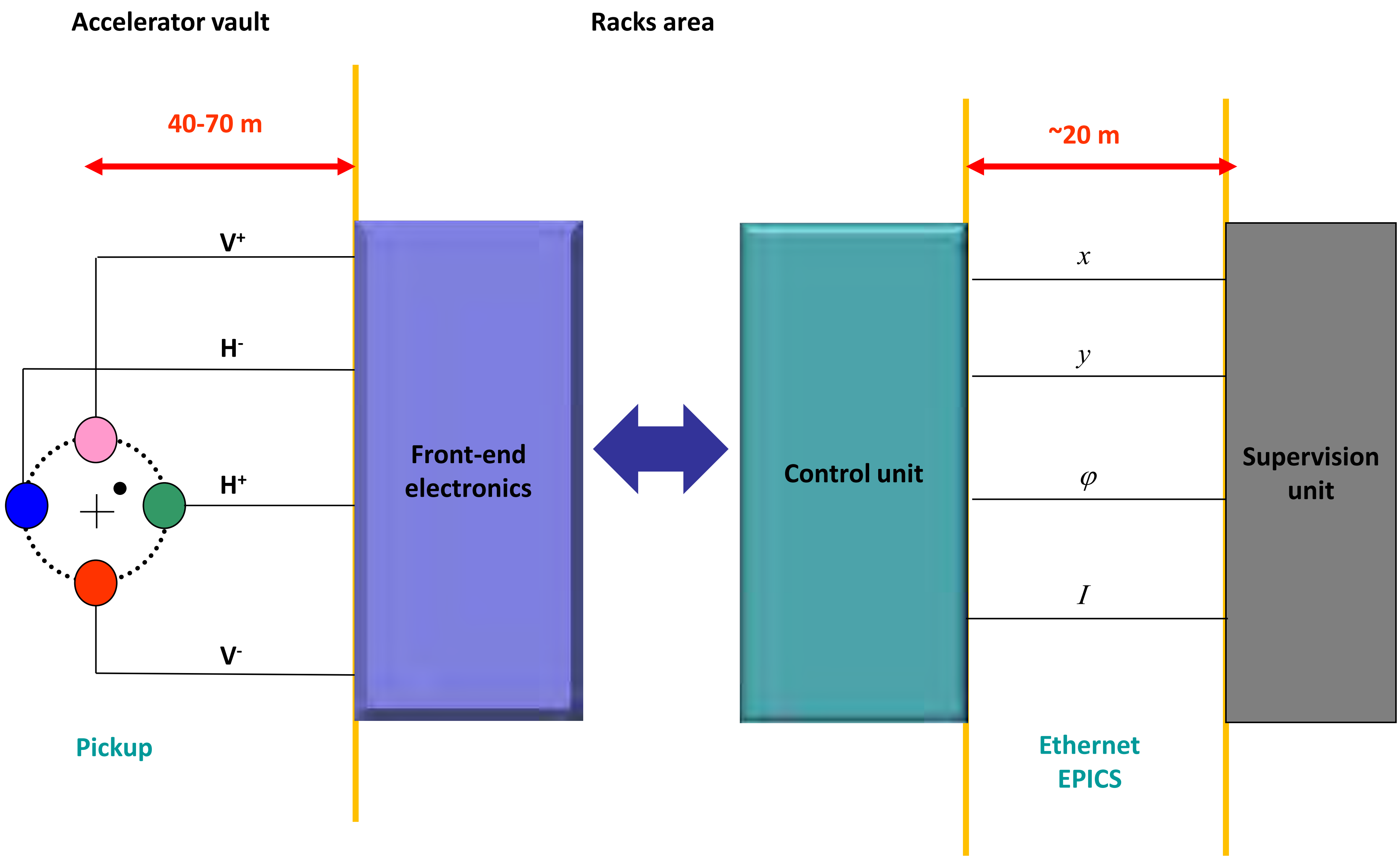
SRF



DP & HEBT



System description



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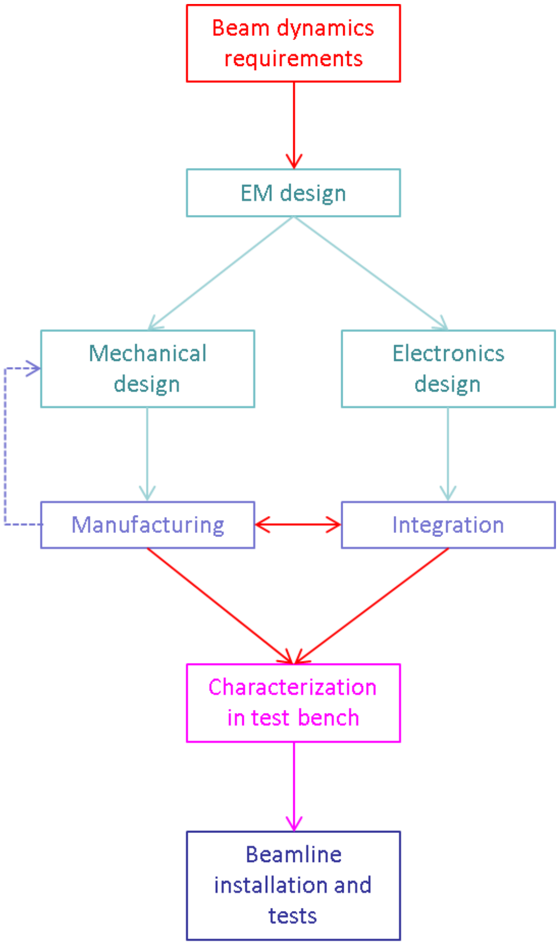
BPM's design



	Shoe-box (linear capacitive)	Capacitive/Button	(micro)Stripline
Linearity	Good	Fair/Poor	Fair
Sensitivity	Good	Fair	Fair
Phase accuracy	-	Medium	Good
Space required	Big	Medium/ Small	Small
Spray particles sensitivity	High	Medium (50 Ω)	Low
Mechanical complexity	High	Medium/ Medium	Low
Reliability and maintenance	Bad	Bad/ Good	Medium

MEBT, SRF (↑ Capacitive/Button)

Diagnostics plate (↑ (micro)Stripline)

MBPM design

Pickups in the middle of each MEBT magnet: electrode connection between poles of the quadrupolar yoke (based on SPIRAL2 design*).

Welded electrodes are chosen to reduce the transverse PU size

Good alignment required with the magnetic quadrupole axis: laser tracker targets in pickup and magnet and separate mechanical supports.

Non-magnetic materials are used to avoid perturbing the magnetic field of the magnet.

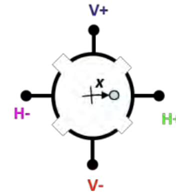
Capacitive BPMs are the preferred option: high beam current makes signal strength sufficient and the required radial space is smaller

The geometry is optimized using a 3D code

Results with a realistic simulated beam fit quite well with analytical expectation except some simulation noise.

**P. Ausset, DITANET workshop on High Intensity Proton Beam, 2011*

Centered beam



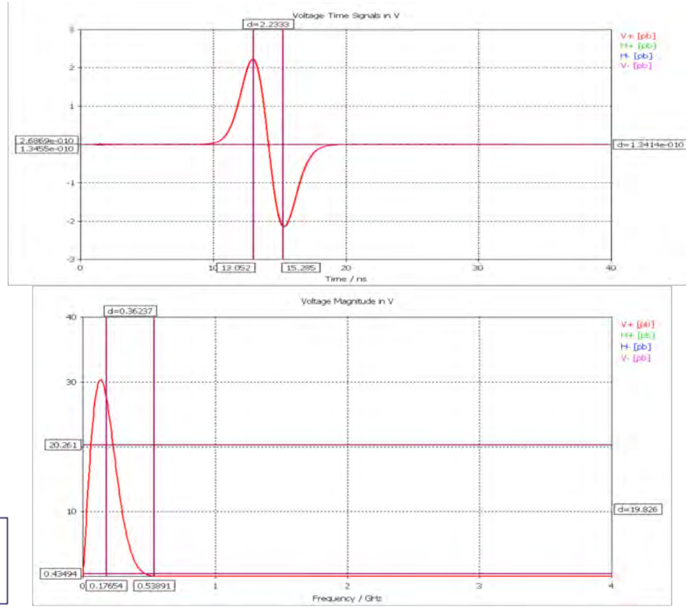
β=0.0748
I= 125 mA
s= 25 mm

Electrode
l= 39 mm
D= 100 mm

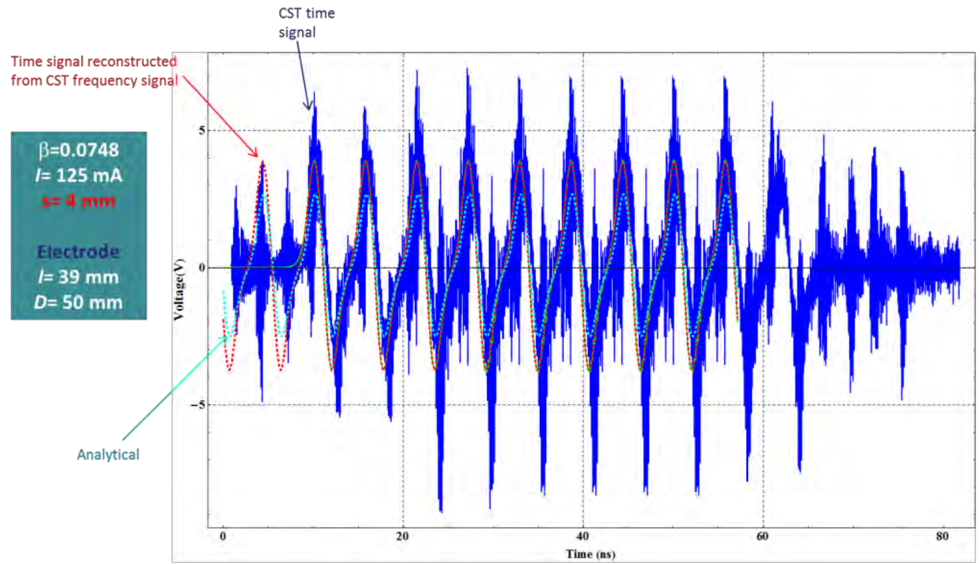
CST Particle Studio simulations

EM design permits the use of first harmonic by the electronics in case RF leakage from bunchers@ 175 MHz is too high

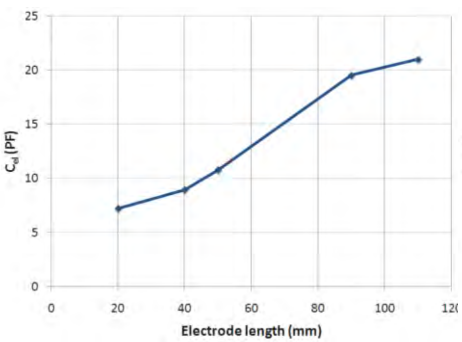
EM simulation (long bunch)



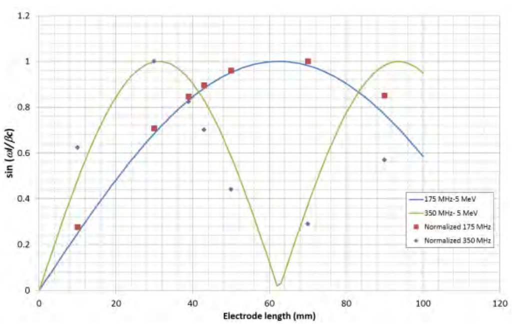
Comparison of analytical and 3D simulations (real bunch length)



Capacitance optimization



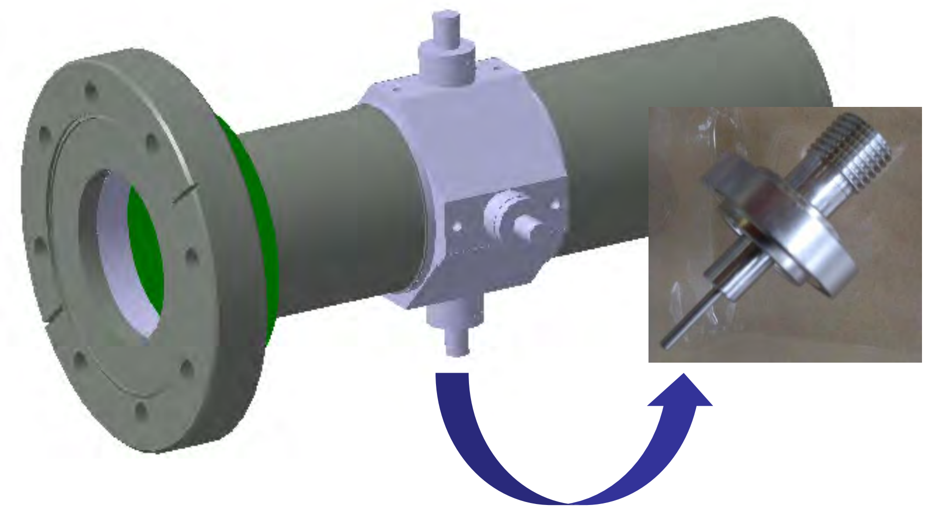
Length optimization

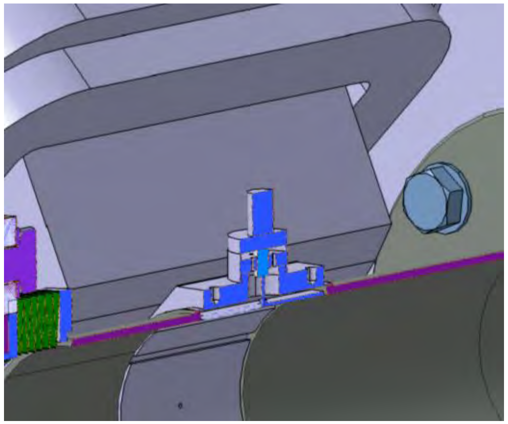


MBPM status

The mechanical design is almost completed

A prototype will be manufactured in next months for validation of the characterization and the integration in the magnet

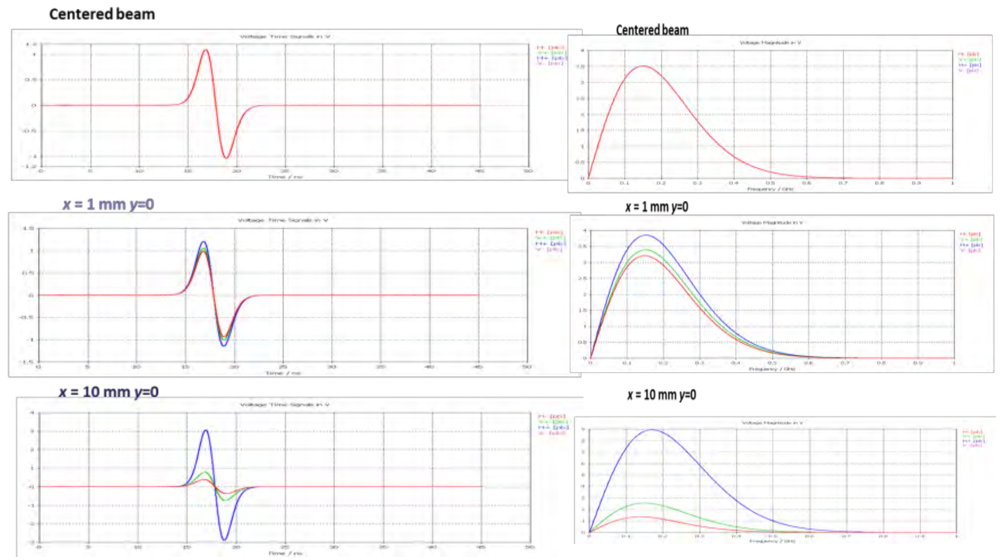


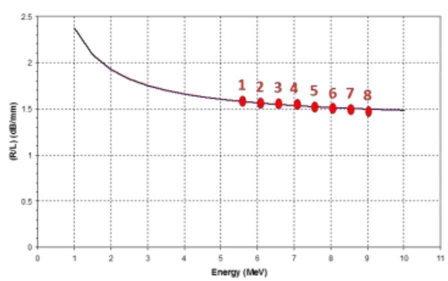


CBPM design

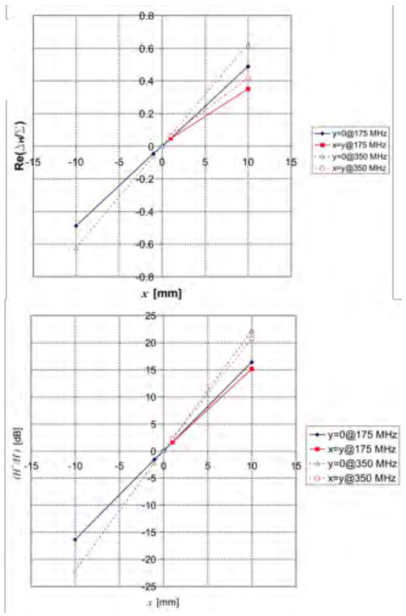
- 8 BPM's: One pickup in each cavity + solenoid lattice in the sc LINAC
- Removable buttons have been chosen to minimize the maintenance impact inside the cryomodule
- Use of same buttons than for LHC* (high reliability!): analytical and 3D simulations show the adequance for LIPAC
- Sensitivity of each BPM is different (dependance on beam energy)

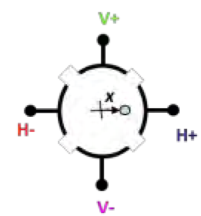
**see C. Boccard talk*





Energy *E*	5 MeV
Bunch length σ	15 mm
Simulated $S_{\Delta/\Sigma}$@175 MHz	0.0489 mm^{-1}
Simulated S_{dB}@175 MHz	1.6394 dB/mm
Analytical S_{dB}@175 MHz	1.57984 dB/mm
Simulated $S_{\Delta/\Sigma}$@350 MHz	0.0621 mm^{-1}
Simulated S_{dB}@350 MHz	2.2098 dB/mm
Analytical S_{dB}@350 MHz	2.1856 dB/mm

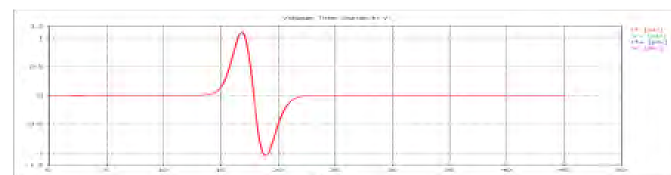




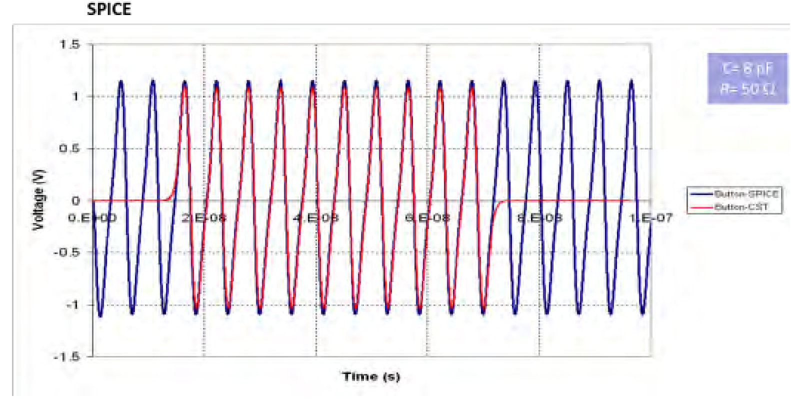
β=0.0728
I= 125 mA
s= 15 mm
x=0 mm
y=0 mm

LHC button
d= 24 mm
D= 49 mm

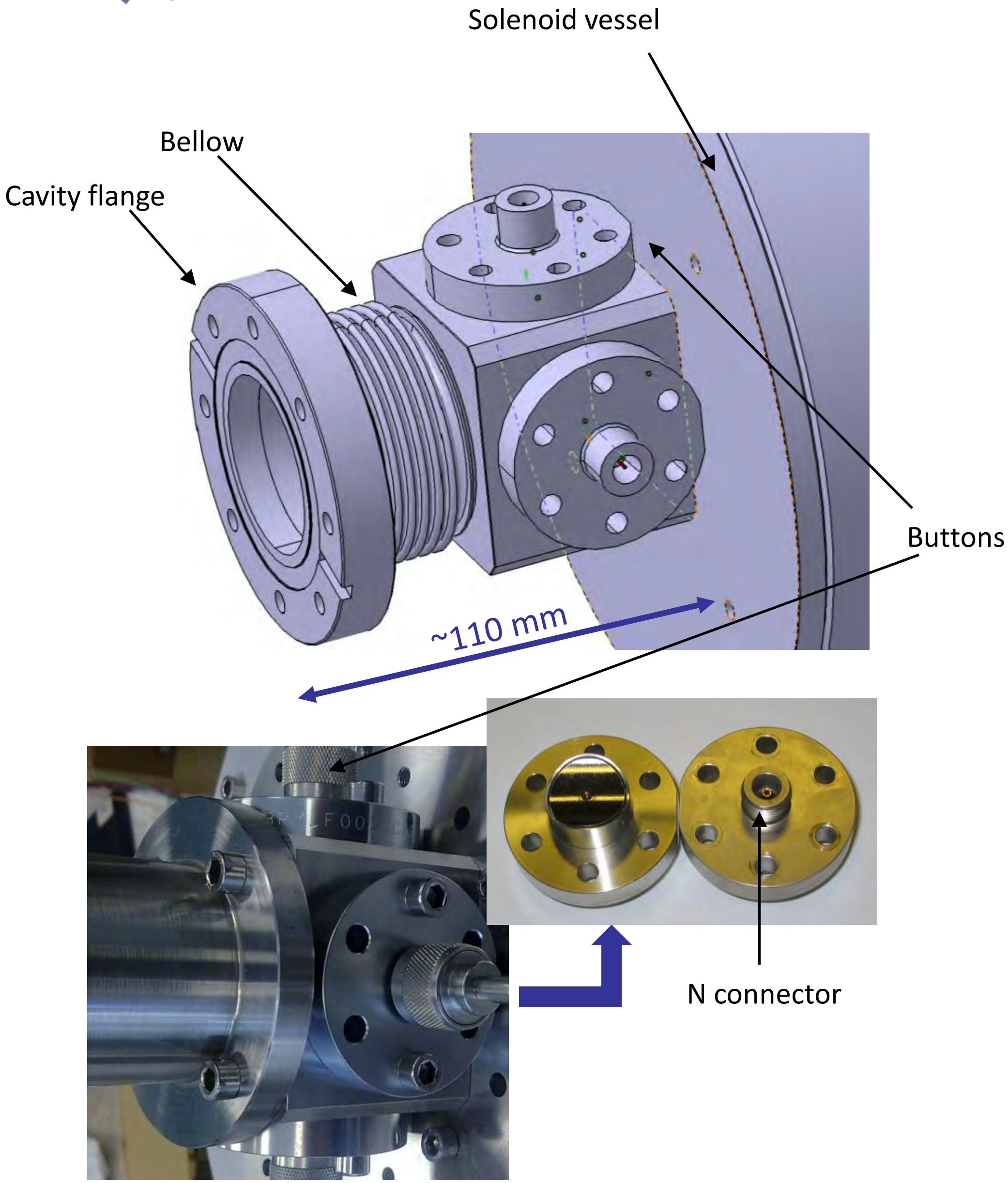
CST Particle Studio



SPICE



CBPM status



Buttons have been manufactured with the same characteristics than LHC buttons: 24 mm diameter and 49 mm aperture diameter (60º angle).

Helicoflex seals aluminium plated type HN100 for the button flange

Type N connectors for the button feedthroughs: button- male, cable- female.

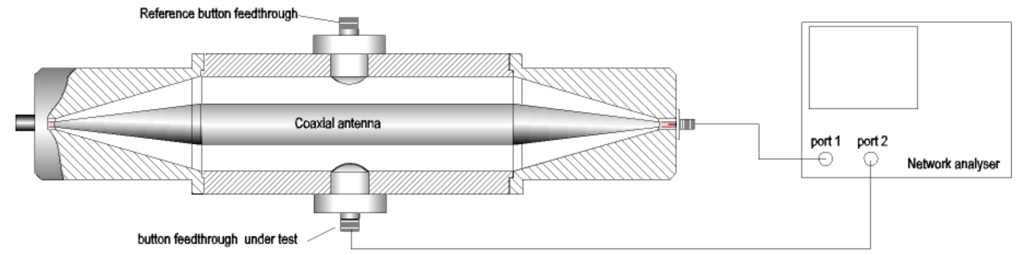
BPM body is manufactured together with the solenoid flange and welded to the rest of the helium vessel

The buttons have been tested at CERN and a prototype has been manufactured and characterized in CIEMAT (see later)

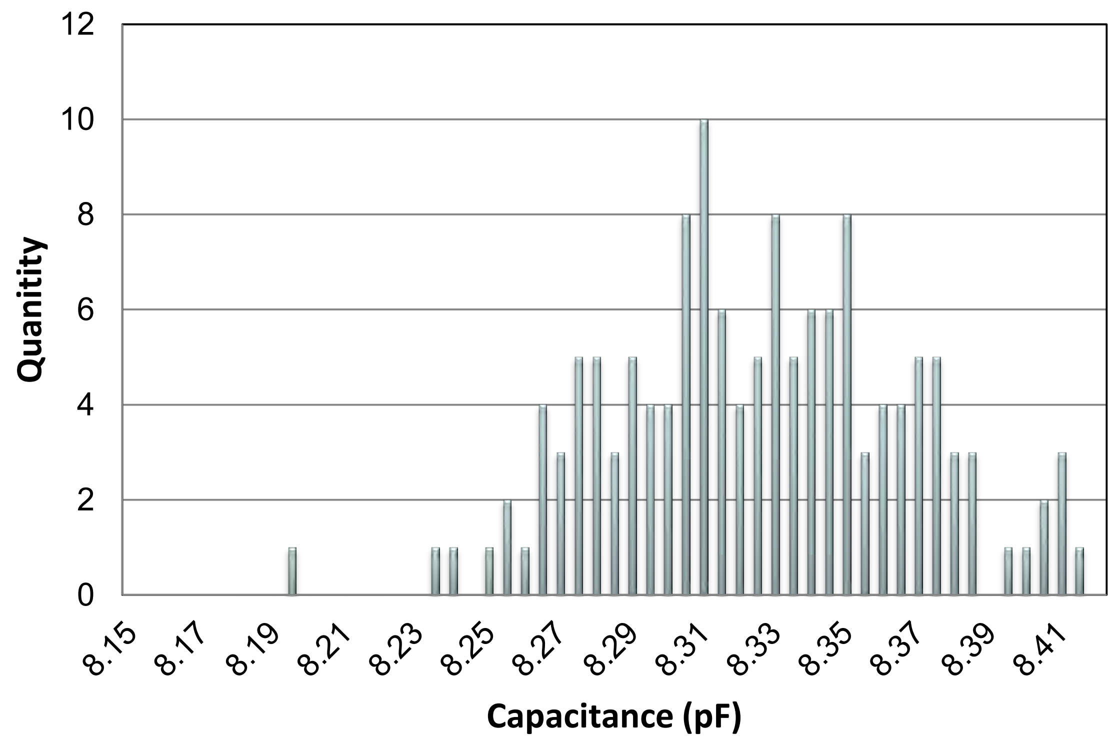
A prototype of the solenoid + vessel + BPM will be manufactured in the next months

Buttons acceptance tests

- Capacitance pairing to obtain better accuracy on the signal strength and position measurement
- Complete series tested at CERN (J. Albertone, C. Boccard and I. Podadera)
- Test at CERN test bench developed by J. Albertone and C. Boccard
- Good agreement with the past results
- Few problems detected with a couple of buttons
- Four largest capacitance picked for CBPM prototype (more flexibility for pairing later): see results later



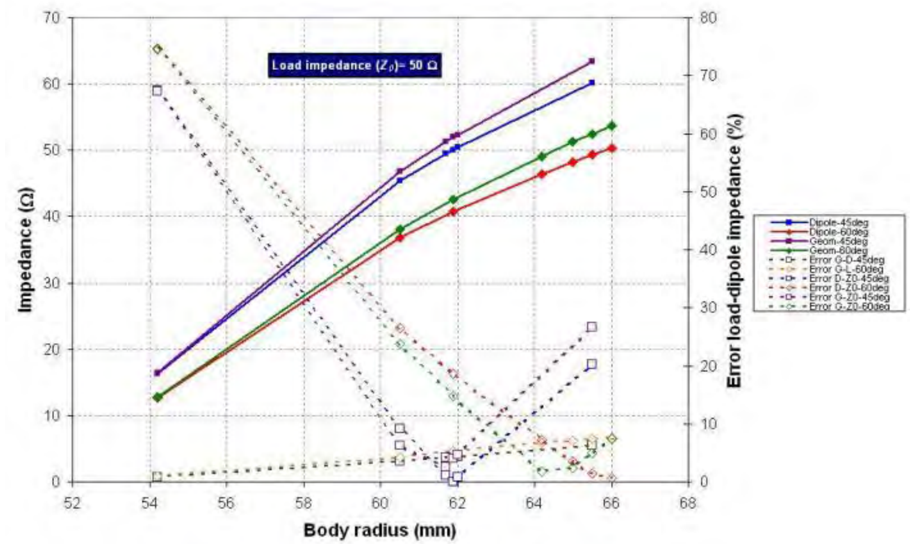
C. Boccard, CARE proceedings, Lueneburg, 2007



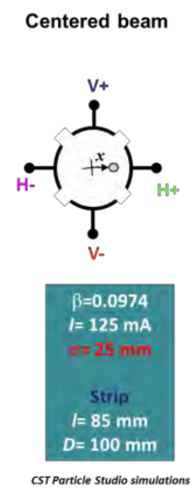
DBPM design

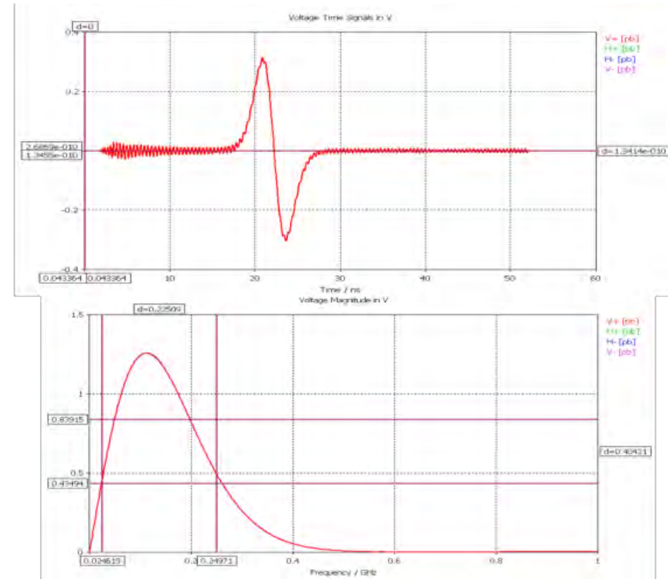
- 3 BPM's: for beam tracking and measurement of mean energy
- Shorted striplines are chosen since they should have less phase dependence for offset positions than other pickups
- Geometry is optimized for sum mode impedance operation (dipole or quadrupole modes negligible)
- 3D simulations confirm the good response but only long bunches simulated
- Simulations are being refined to take into account real mechanical geometry

Geometry optimization with 3D code

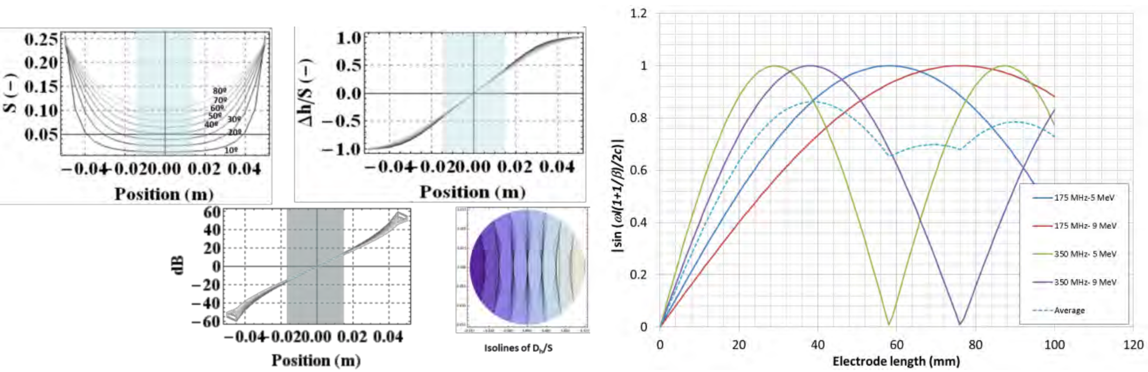


3D simulations (long bunches)

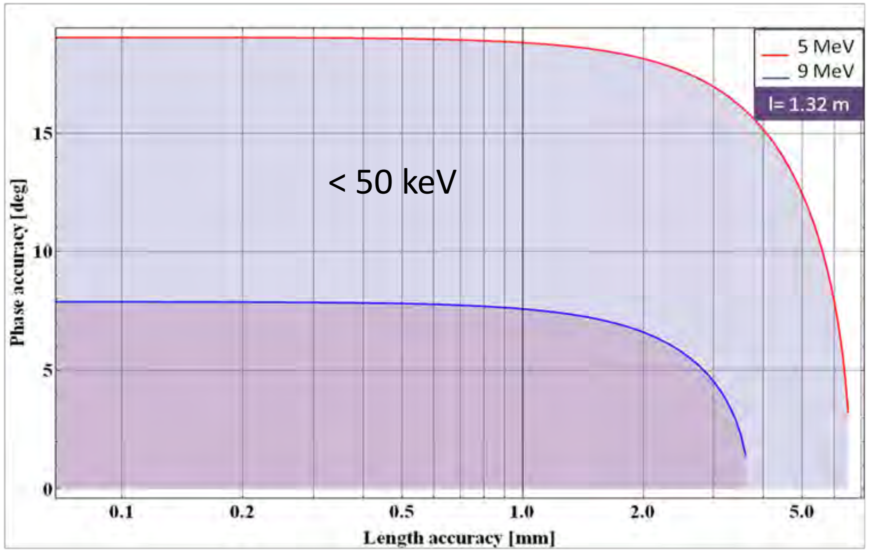




Analytical geometry optimization

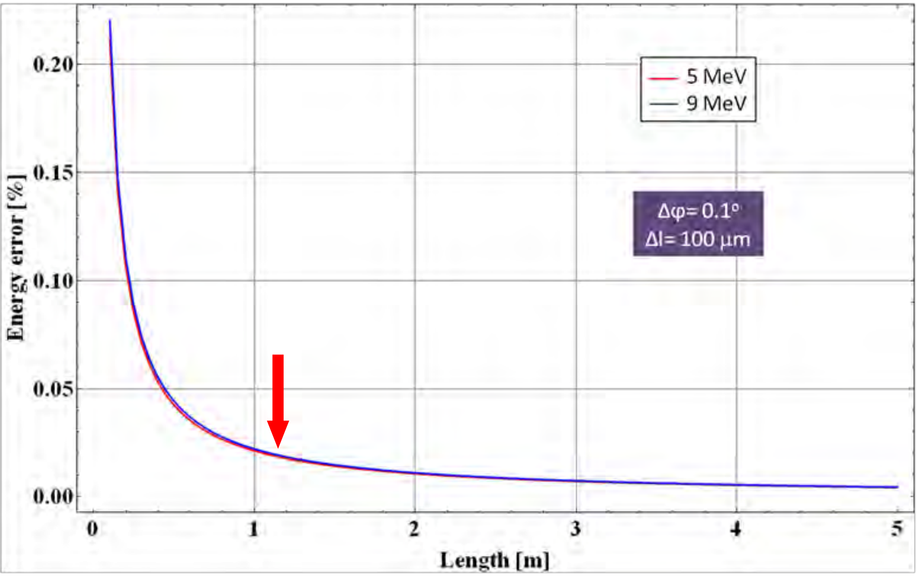


Mean energy measurement

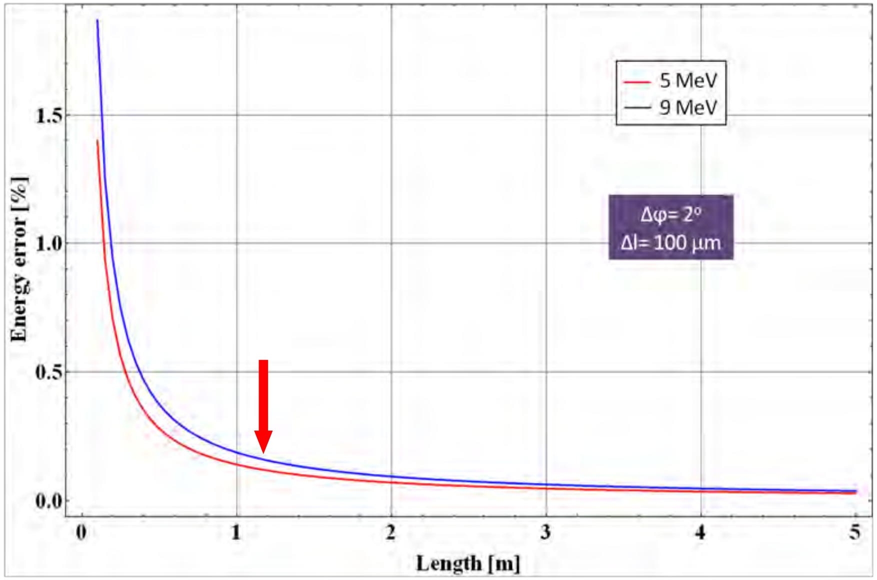


Three BPM's are better in the diagnostics plate for the TOF measurement.

Good alignment and distance measurement of three BPM's is required.



~2 keV @ 5/9 MeV



~20 keV @ 5/9 MeV

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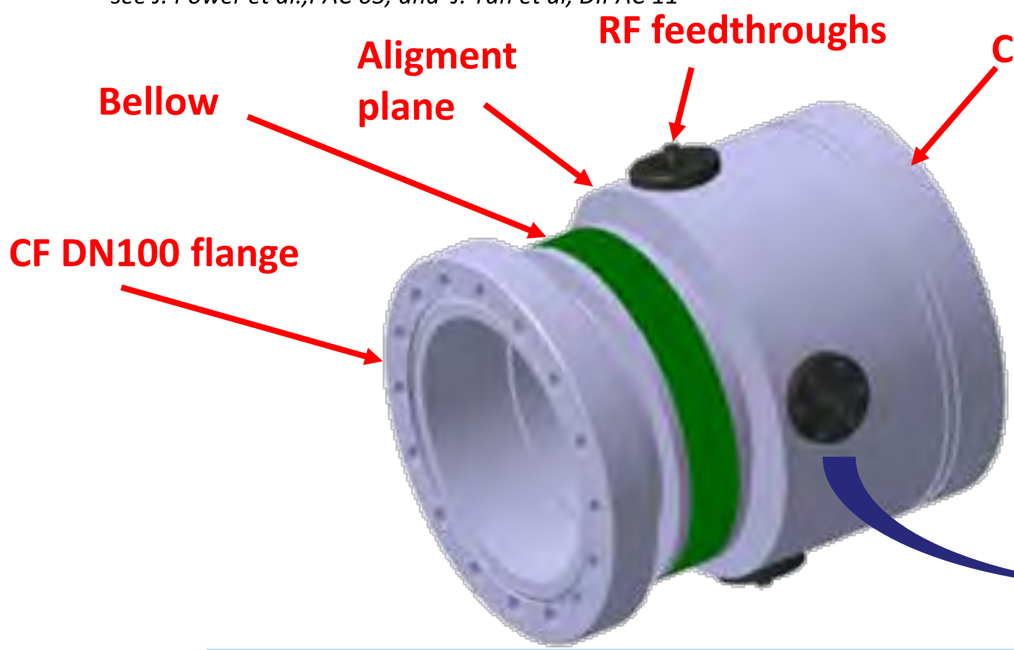
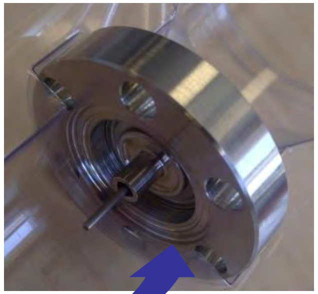
DBPM status

- The mechanical design is almost completed (similar to SNS or LINAC4)*
- A prototype will be manufactured in next months
- CF feedthrough: removable for easy maintenance
- Bellow for DN100 flange
- Reference surfaces for alignment and mechanical support

**see J. Power et al.,PAC'03, and J. Tan et al, DIPAC'11*





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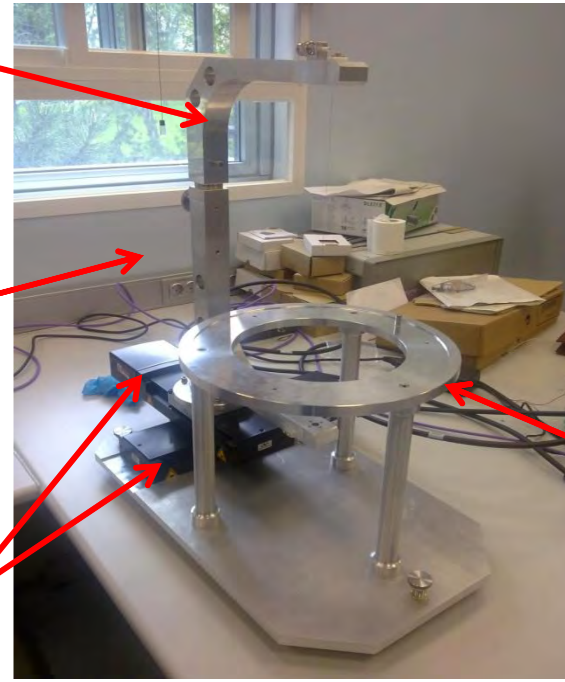
Test bench design

Although it is not straight forward to extrapolate the wire method results to low-beta beams...

A test bench has been constructed at CIEMAT to characterize all the IFMIF/EVEDA BPM's before installation in Rokkasho

It is possible to characterize the following parameters of the BPM's:

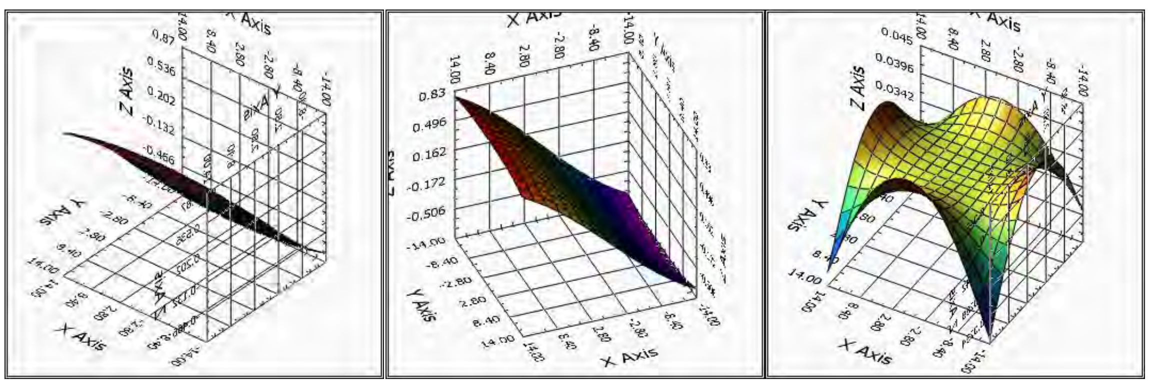
- Electrical center.
- Sensitivity.
- Linearity.
- Resolution.
- Mechanical and electrical stability.



Setup:

- Two micromovers (5 μm accuracy, orthogonality 50 μrad)
- BPM support.
- Wire support.

Characterization of proto CBPM



Plot of measured Δ/Σ in horizontal and vertical and Σ

Sensitivity
12.8 mm

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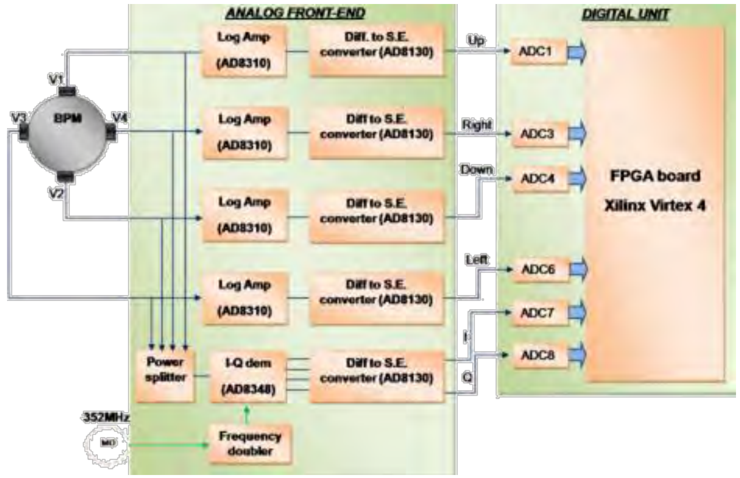
Tests of ESS Bilbao electronics

D. Belver et al., IPAC 2011



ESS-Bilbao is developing a prototype of acquisition electronics for the LIPAC BPM's based on their experience with ISIS LLRF

The electronics is based on an analog IQ demodulator for phase measurement and log amps for position measurement

The digital unit is connected to an industrial PC which interfaces the instrument with the EPICS framework.

Measurements have been carried out with a CBPM prototype and the CIEMAT test bench.

Digital unit

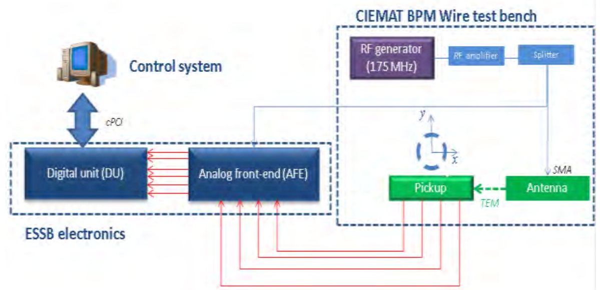
DU is a Lyrtech VHS-ADC board, including a high performance cPCI FPGA based on Xilinx Virtex-4 and an Analog to Digital Converters (ADC) → 8 channels, 14 bits resolution sampling up to 105 MHz. Signals linearization and calibration to compensate the errors of the measurements → offset compensation and blocks to obtain the beam phase (arctan(Q/I)) and the position (Δ/Σ algorithm).

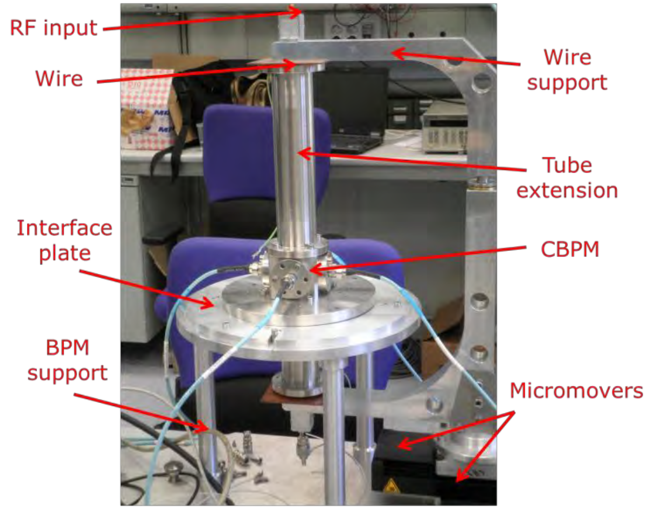
Analog front-end

The AFE unit is based on two different boards :

1) **To measure position**: A 4-channel logarithmic amplifier (log amp AD8310, high dynamic range of 95 dB and bandwidth from DC to 440 MHz) and a differential to single-ended converter (AD8130) board connected to each pickup button (central board of the AFE unit).

2) **To measure phase**: An IQ demodulator (AD8348) board fed by the sum of the 4 button signals of the CIEMAT wire test bench and the same differential to single-ended converter AD8130 (boards on the left).





Experimental setup used in the CIEMAT tests.

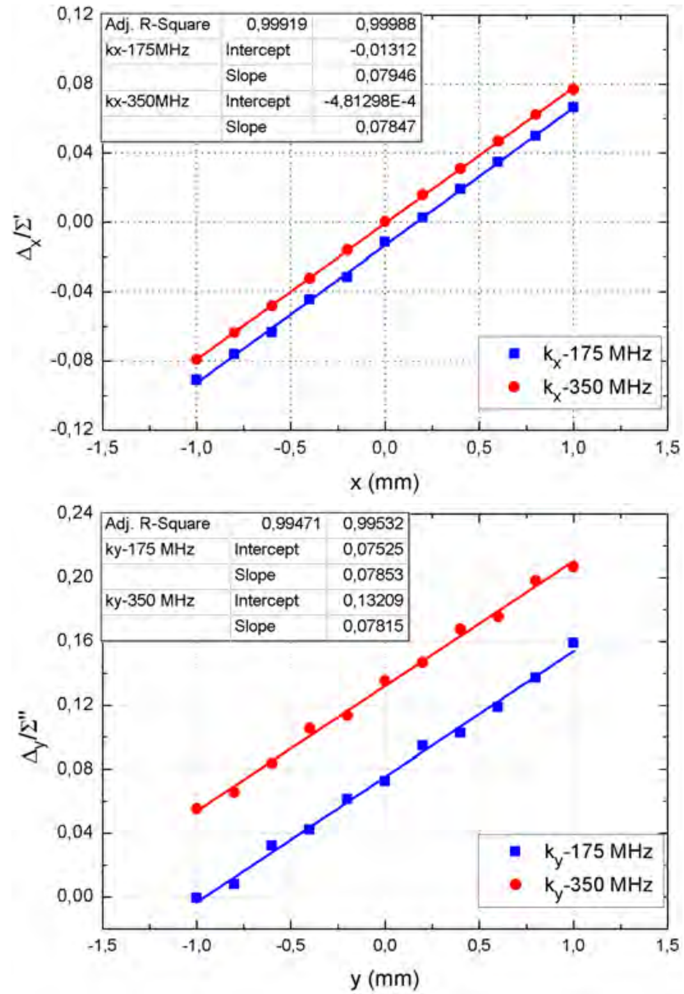
Sensitivity results

D. Belver et al., IPAC 2011

The test bench has been used in order to measure the relation between the variation of measured position signal and real position movement. In the center region of the pickup, the position is related to the measured button signal as:

	175 MHz	350 MHz
K_x [mm]	12.58	12.74
K_y [mm]	12.73	12.79

The obtained results are now very similar to the expected ones and the Libera Single Hadron Pass H measurements (beginning 2011).



Sensitivity of the BPM for both directions *x* (up) and *y* (down), at 175 and 350 MHz.

Resolution

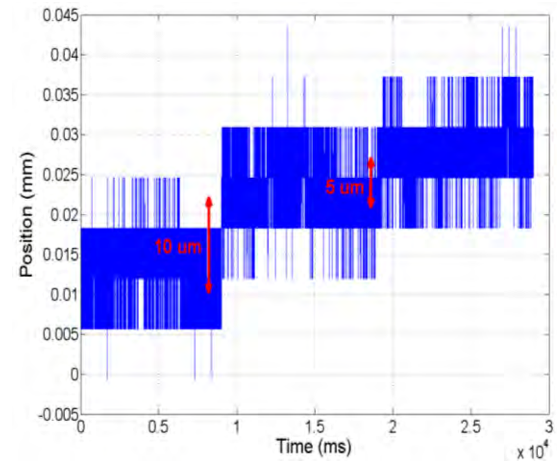
D. Belver et al., IPAC 2011

The minimum position change that could be detected with the electronic system has been analyzed in two ways:

-Observing the standard deviation of a series of position data acquired at the center position.

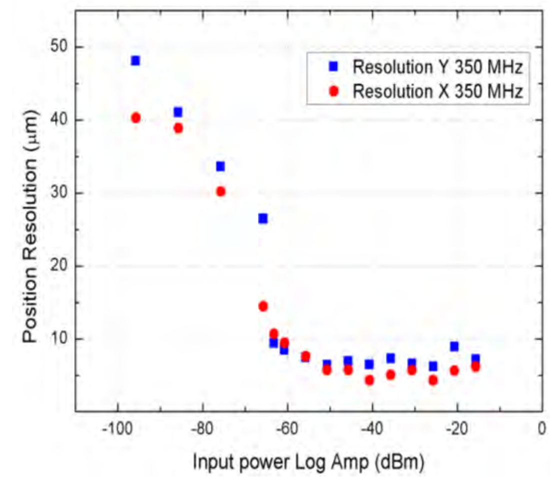
- Measuring the long-term stability using long-term data (~1 hour). Results are affected by drifts in the electronics due to the temperature change (8 ºC).

The resolution has been measured as function of the input power and also the sensitivity of the BPM electronics at the level of 5-10 µm.



Sensitivity of the BPM electronics, measured up to 5 µm.

Parameter	Level 175 MHz	Level 350 MHz	Requirement
X position resolution [µm]	4.33	5.48	10
Y position resolution [µm]	6.19	6.86	10
X position stability [µm]	13.70	-	100
Y position stability [µm]	20.78	-	100
Phase resolution [°]	0.1	0.2	0.3



Position resolution at 350 MHz for both directions *x* (red) and *y* (blue).

Future developments ESSB

Work in phase measurements in Bilbao lab.

Adaptation of test bench to beam bunch-like shapes.

Test new IQ demodulators.

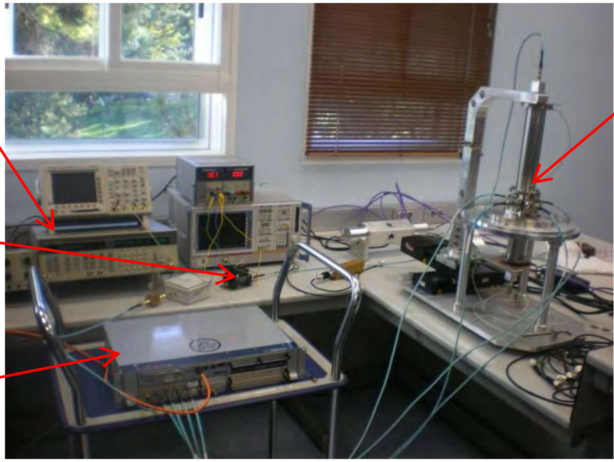
Test bench tests of the pulsed measurements.

Calibration: include precise calibration of log amps, and automatic gain and phase calibration of four channels -> improvement of the absolute accuracy of electronics.

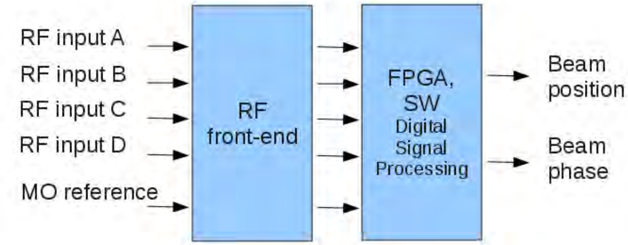
Final prototype tests.

Libera SPH measurements

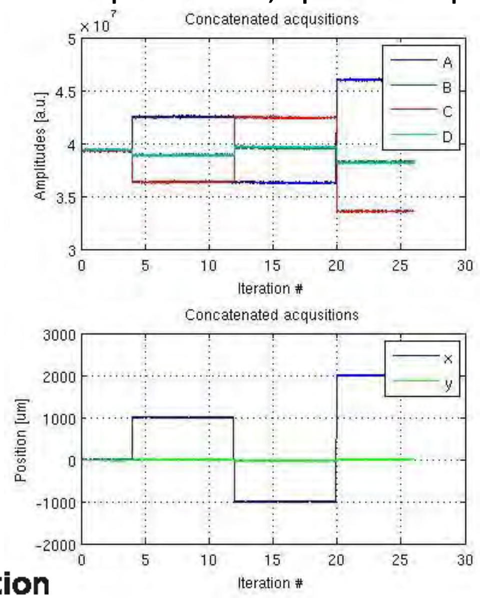
M. Znidarcic et al., DIPAC 2011



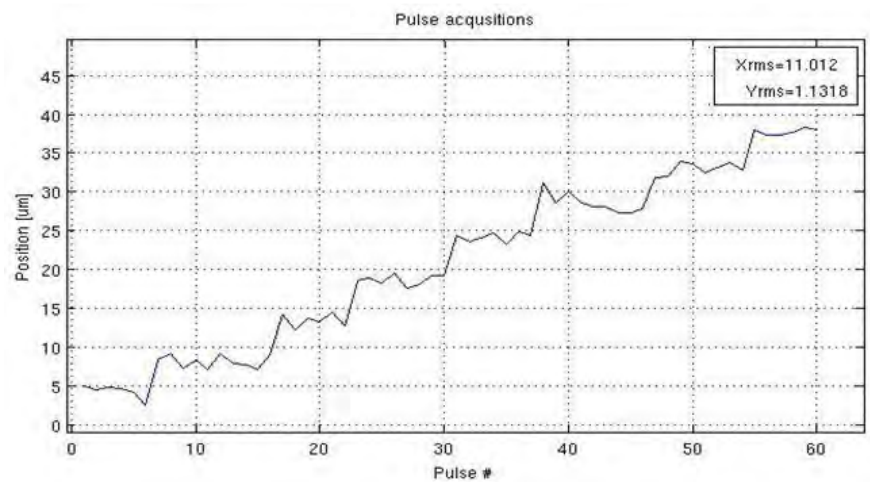
- Libera SPH was tested for first time with a real pickup in the CIEMAT wire test bench using the proto CBPM
- Digital electronics based on undersampling scheme
- Measurements of CW and pulsed bunch-like signals
- Good position and phase resolution



Wire movement measurement. Concatenated results for the displacements over a larger scale (X = +1 mm, -1 mm, +2 mm; Y = 0 mm). Four amplitudes and X, Y positions are plotted.



Wire movement – by 5 um steps in X-direction. Seven steps are seen in position measurement



Instrumentation Technologies

Outline

- IFMIF and LIPAC
- BPM's requirements @ LIPAC
- Pickups design
- Test bench
- Electronics measurements
- **Conclusions & Next steps**

Conclusions

Electromagnetic pickups are not "ideal" instruments for low beta beams but are essential for LIPAC commissioning and operation.

Signal is degratated due to the low-velocity but we have shown signal from BPM's is convenient for LIPAC operation

Capacitive pickups will be used in the MEBT to insert the pickups inside the magnet while keeping their aperture as small as possible

Buttons are chosen as the main candidate inside the SRF. Reliable LHC buttons are used and has been integrated in the solenoid package. Measurement at 350 MHz might be needed due to RF leakage from the sc cavities

Shortcut striplines will be used in the diagnostics plate for the TOF measurement. Detail simulation of striplines vs buttons needs to be carried out.

Responses at 5 MeV of the DBPM's & HBPM's are to be analyzed with the final transport line design for the RFQ commissioning.

A wire test bench has been constructed and tested for characterization of all the LIPAC BPM's.

ESS-Bilbao based on log-amps for position measurement and IQ demodulation for phase measurement of the sum signal acquisition electronics has been designed, manufactured and characterized in the test bench. A demo unit of Libera SPH was also tested.

Prototypes of all the BPM's are being constructed and will be fully characterized this year.

Thanks to…

The ESS-Bilbao team D. Belver, L. Muguira,

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And of course, thanks to all the LIPAC EU-HT

…and for your attention!!

QUESTIONS?

Particularities of low-β beams

Current "densitiy" in A/m for.,..

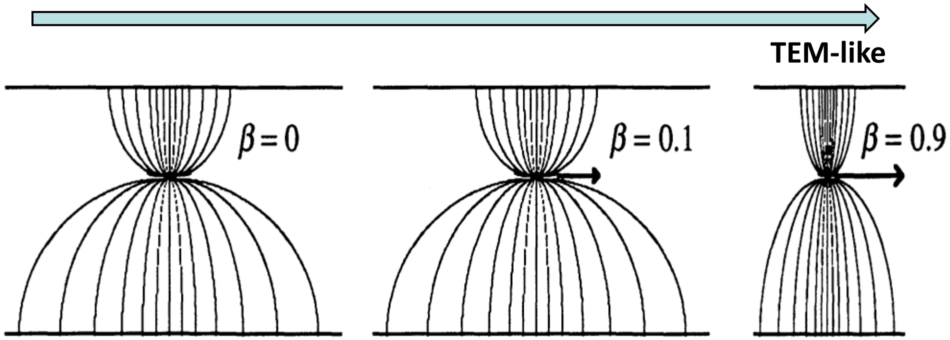
β=1

$$i_w(b,\alpha,t) = \frac{-I_b(t)}{2\pi b}\left[1 + 2\sum_{m=1}^{\infty}\left(\frac{r}{b}\right)^n \cos\left[m(\alpha-\theta)\right]\right] = \frac{-I_b(t)}{2\pi b}\left[\frac{b^2 - r^2}{b^2 + r^2 - 2br\cos(\alpha-\theta)}\right]$$

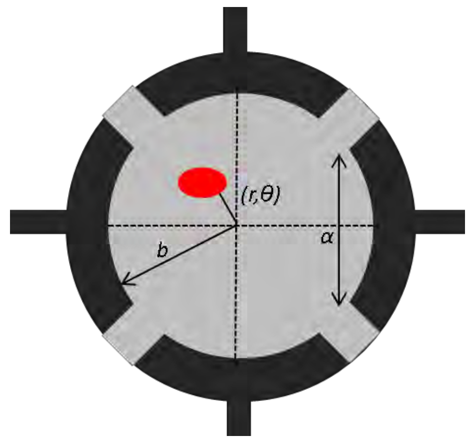
$$i_w(\omega,r,\alpha,\theta) = \frac{A_n\langle I_b\rangle}{\sqrt{2\pi b}}\left[1 + 2\sum_{m=1}^{\infty}\left(\frac{r}{b}\right)^n \cos\left[m(\alpha-\theta)\right]\right]$$

$$E_{\perp,lab}(t) = \gamma \cdot E_{\perp,rest}(t)$$

↑γ => ↓E



$$\sigma_t = \frac{b}{\sqrt{2}\,\gamma\beta c}$$



Any β

$$i_w(\omega,r,\alpha,\theta) = \frac{A_n\langle I_b\rangle}{\sqrt{2\pi b}}\left[\frac{I_0(gr)}{I_0(gb)} + 2\sum_{m=1}^{\infty}\frac{I_m(gr)}{I_m(gb)}\cos\left[m(\alpha-\theta)\right]\right]$$

$$g(\omega) = \frac{\omega}{\beta\gamma c}$$

Equivalent expressions for $g\sim0$

IFMIF LIPAc

Space charge and diffuse beams

High current are dominated by the space charge of the beams. Obviously, high current beams are bigger than low current ones, tending to more diffuse beams.

According to the approximations given in ***Comparison of beam-position transfer functions using circular beam-position monitors*** **(Gilpatrick, PAC97),** the sensitivity change can be noticed if the sum of the beam rms transverse width σ and the beam offset $(\bar{x}, \bar{y})$ is greater than 65% of the electrode radius b.

For example, for a BPM of 150 mm aperture that means the rms width should be greater than 50 mm for this effect to be noticeable. For a 10 mm beam radius, the maximum offset that can accepted is then 40 mm

Total image current in an electrode created by a diffuse beam

$$I_T = \sum_{n=-3\sigma}^{+3\sigma} \sum_{m=-3\sigma}^{+3\sigma} \hat{I}_T a_n b_m e^{\frac{-(x_n^2-\bar{x}^2)}{2\sigma^2}} e^{\frac{-(y_n^2-\bar{y}^2)}{2\sigma^2}}$$