Measuring Radiofrequency Multipoles in the LHC Crab Cavities

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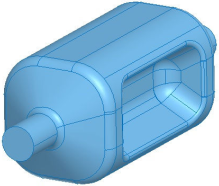
Third Joint HiLumi-LARP Annual Meeting 2013

Daresbury, November 2013

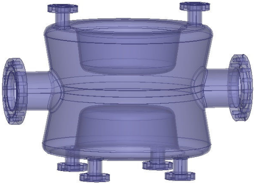
LHC Crab Cavities under Consideration

RF dipole



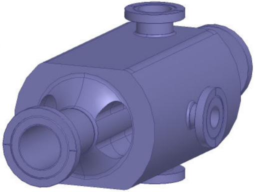
Courtesy of
Z. Li, J. Delayen *et al.*
ODU/SLAC

Double $\frac{1}{4}$-wave



I. Ben-Zvi *et al.*
BNL

4 rod



G. Bull, B. Hall
UK

Non-axial symmetry

Higher order multipolar components of the main deflecting mode

RF-kicks influencing the beam dynamics

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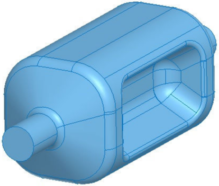

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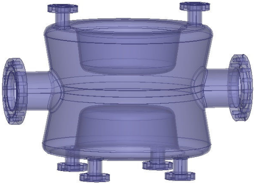

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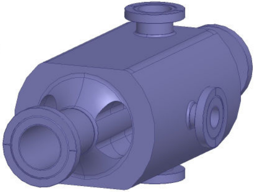

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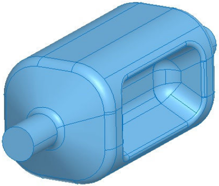

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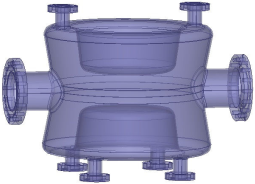

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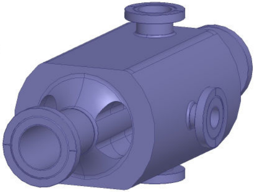

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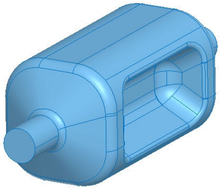

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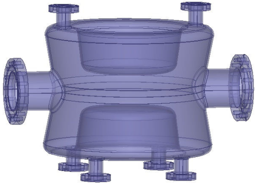

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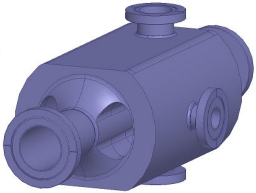

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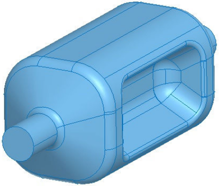

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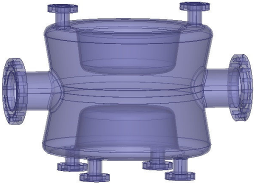

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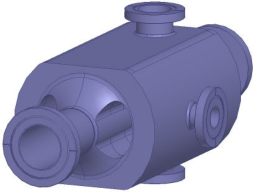

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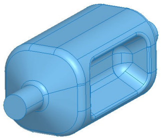
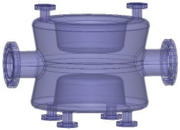
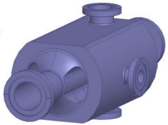
Motivation and Objectives

Latest geometries







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- Study of the **multipolar error** on the **latest cavities**.
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- **Experimental verification** of the RF multipolar components, by means of **bead-pull measurements**.

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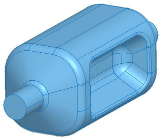

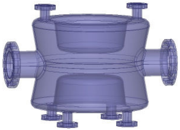

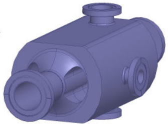

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Outline

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RF Multipole Concept

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similar to

Static Multipole treatment in the Magnet Community

Fields in the aperture of accelerator magnets

- Fourier coefficients,
- field harmonics, or
- multipole coefficients.

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Magnetic Multipoles

Fourier expansion of the radial field components:

$$B_r(r_0,\phi) = \sum_{n=1}^{\infty} [B_n(r_0)\sin n\phi + A_n(r_0)\cos n\phi] \quad \text{being} \quad A_n(r_0) = \frac{1}{\pi}\int_0^{2\pi} B_r(r_0,\phi)\cos n\phi$$

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Magnetic field distribution (*skew positive*)

Dipole ($n = 1$) Quadrupole ($n = 2$) Sextupole ($n = 3$)

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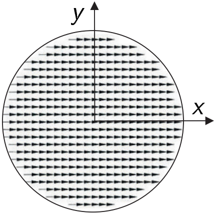
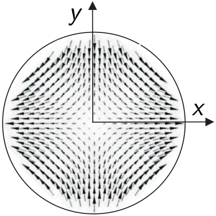
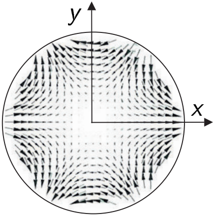


Dipole ($n = 1$)



Quadrupole ($n = 2$)



Sextupole ($n = 3$)

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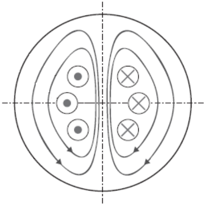


Main deflecting mode (TM_{110} mode) of an axially symmetric cavity:

- Only dipolar variation ($n = 1$)

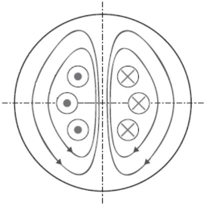
As long as the cavity is far from axial symmetry...

- All the remaining multipolar components ($n > 1$) might be present!
- Not only the dipolar kick, but also higher order kicks.

Presence of higher-order RF multipolar kicks

Beam dynamics perturbations

RF Multipoles



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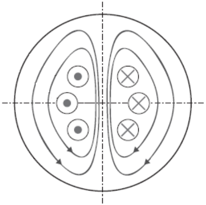

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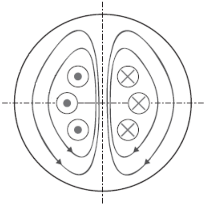

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Presence of higher-order RF multipolar kicks → **Beam dynamics perturbations**

Studies on Multipolar RF Quicks

Non-Linearity of Deflecting Field in LHC crab-cavities

A.Grudiev, CERN, BE-RF

15.11.2011

LHC-CC11, 14-15.11.2011, CERN

Proceedings of IPAC2012, New Orleans, Louisiana, USA TUPPR027

STUDY OF MULTIPOLAR RF KICKS FROM THE MAIN DEFLECTING MODE IN COMPACT CRAB CAVITIES FOR LHC*

J. Barranco García, R. Calaga, R. De Maria, M. Giovannozzi, A. Grudiev, R. Tomás
CERN, Geneva, Switzerland

Abstract

A crab cavity (CC) system is under design in the framework of the High Luminosity LHC project. Due to

where Z_0 is vacuum impedance, u_z the unit vector in Z direction, $E_{kick} = E_{\perp} \cdot e^{j\omega z/c}$; $H_{kick} = H_{\perp} \cdot e^{j\omega z/c}$ are the electric and magnetic fields in the particle frame,

Mesh Definition and Simulation Setup

Lorentz Force

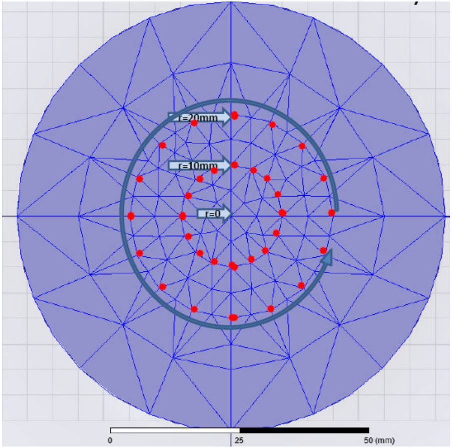
$$\Delta p_\perp(r,\phi) = \frac{q}{c}\int_0^L \left[E_\perp + v_z \times B_\perp\right] \mathrm{d}z$$

Panofsky-Wenzel

$$\Delta p_\perp(r,\phi) = \frac{jq}{\omega}\int_0^L \nabla_\perp E_{acc}(r,\phi,z)\,\mathrm{d}z$$

$$B_\perp^{(n)} = \frac{1}{qc}F_\perp^{(n)} = \frac{nj}{\omega}E_{acc}^{(n)} \qquad [Tm/m^n]$$

$$b_n = \int_0^L B_\perp^{(n)}\,\mathrm{d}z \in \mathbb{C} \qquad [Tm/m^{n-1}]$$



A. Grudiev

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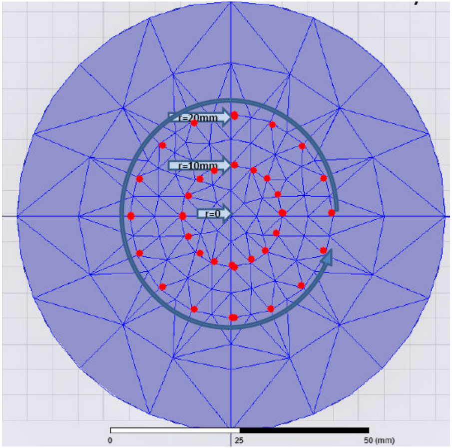

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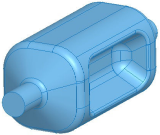
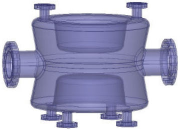
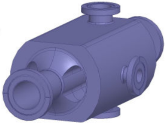
Multipolar Kicks for the Latest Geometries

2012 updated geometries



* No couplers yet





$V_x = 10$ MV	RF Dipole		$\frac{1}{4}$-wave		4-rod	
	$\Re(b_2)$	$\Im(b_2)$	$\Re(b_3)$	$\Im(b_3)$	$\Re(b_4)$	$\Im(b_4)$
$b_2[mTm/m]$	0	0	0	0	0	0
$b_3[mTm/m^2]$	4500	0	1100	0	1160	0
$b_4[mTm/m^3]$	0	0	0	0	0	0

Outline

Examination of Electromagnetic Fields (i)

Slater Perturbation Theorem (∗)

$$\omega^2 = \omega_o^2 \left[1 + k \frac{\int_{\Delta V} (\mu_0 \mathbf{H}^2 - \varepsilon_0 \mathbf{E}^2) \, \mathrm{d}\Delta V}{\int_V (\mu_0 \mathbf{H}^2 + \varepsilon_0 \mathbf{E}^2) \, \mathrm{d}V} \right] \Rightarrow \frac{\Delta\omega}{\omega_o} = \frac{\Delta U}{U}$$

- A perturbation of the cavity volume by a small amount ΔV will cause an unbalance of the electric and magnetic stored energies.
- The resonant frequency will shift to restore this unbalance.
- If the perturbation is small, this frequency shift is proportional to the original amount of energy stored in the perturber volume.

Since U is proportional to $\vec{E}^2$ or $\vec{H}^2$, this theorem offers a way to measure the fields in the cavity.

(∗) *Microwave Measurements*, Ginzton.

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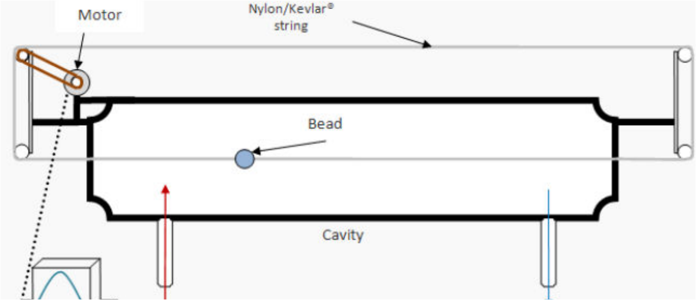
Examination of Electromagnetic Fields (ii)

Bead-Pulling Measurement

- It exploits the Slater Perturbation Theorem.
- Pulling a perturbing object through the cavity while monitoring the the cavity resonant frequency.



Source: Michal Jarosz, "Bead-Pull Measurements", CERN project report.

Measuring RF Multipolar Components

Preliminar considerations

Customarily used to measure the on-axis $\vec{E}$ field in accelerating cavities.

Our requirements

- We are interested in the higher order components.
- Need to carry out off-axis measurements.
- Rotational degree of freedom needed.

What about accuracy?

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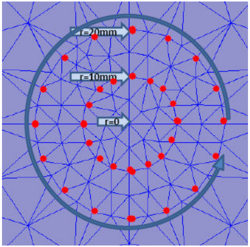

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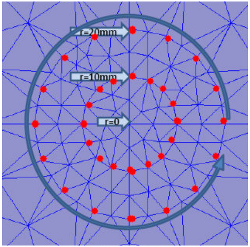
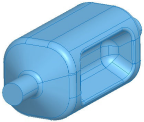


What about accuracy?

Fourier-Decomposed Field Components of E_{acc}

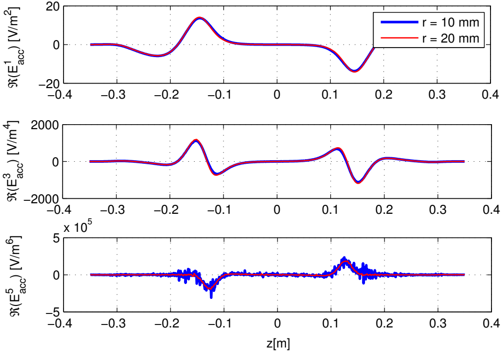
Example: RF-dipole cavity



$$E_{acc}(r,\phi,z) = \sum_{n=0}^{\infty} E_{acc}^{(n)} r^n \cos n\phi$$

$\Re e\,[E_{acc}^{(n)}]$ for a transverse kick of 1 V

On crest - Deflecting



$E_{acc}^{(1)} r^1 \sim 10^{-1}$ V/m

at $r = 10$ mm

$E_{acc}^{(3)} r^3 \sim 10^{-3}$ V/m

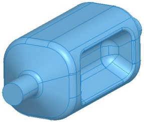
at $r = 10$ mm

$E_{acc}^{(5)} r^5 \sim 10^{-5}$ V/m

at $r = 10$ mm

Fourier-Decomposed Field Components of E_{acc}

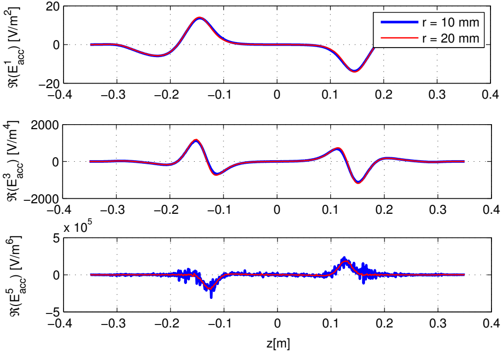
Example: RF-dipole cavity



$$E_{acc}(r,\phi,z) = \sum_{n=0}^{\infty} E_{acc}^{(n)} r^n \cos n\phi$$

$\Re e\,[E_{acc}^{(n)}]$ for a transverse kick of 1 V

On crest - Deflecting



$E_{acc}^{(1)} r^1 \sim 10^{-1}$ V/m

at $r = 10$ mm

$E_{acc}^{(3)} r^3 \sim 10^{-3}$ V/m

at $r = 10$ mm

$E_{acc}^{(5)} r^5 \sim 10^{-5}$ V/m

at $r = 10$ mm

Higher-order effects. Measurable quantities

❶ Non-linearity of the longitudinal voltage

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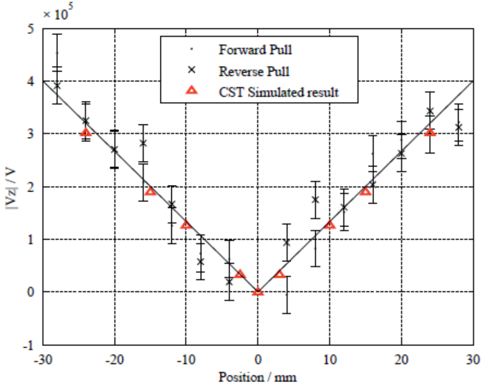
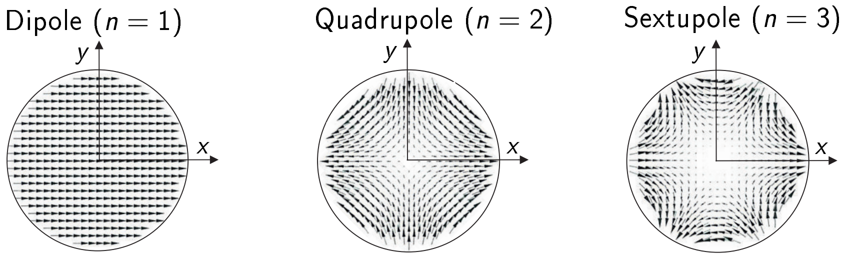


(∗) B. Hall, *2nd Joint HiLumi LHC-LARP Annual Meeting*.

Higher-order effects. Measurable quantities

❷ Non-uniformity of the transverse voltage

Electric field distribution



Higher-order effects. Measurable quantities

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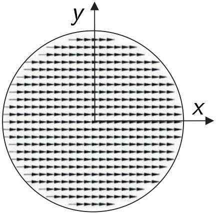
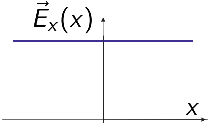
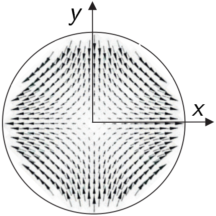
Electric field distribution

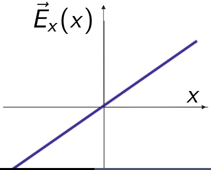
Dipole $(n = 1)$



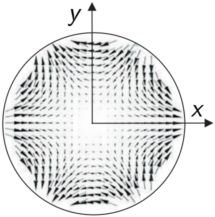


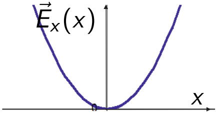
Quadrupole $(n = 2)$





Sextupole $(n = 3)$

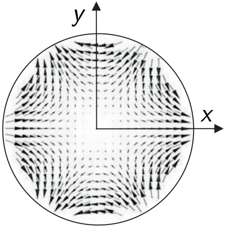




Higher-order effects. Measurable quantities

❸ Non-zero $\vec{E}$-field vertical component

Transverse electric field distribution
for the sextupolar component



Higher-order effects. Measurable quantities

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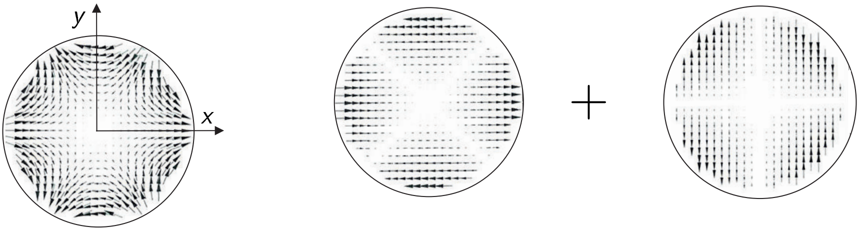

Bead-Pull Test Bench

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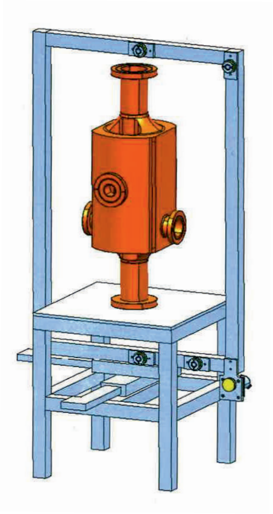
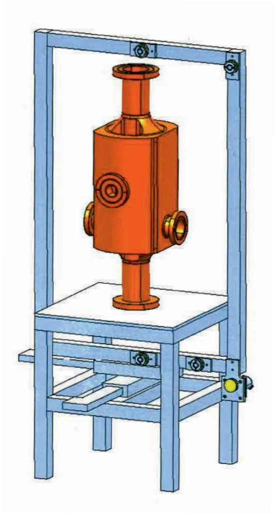
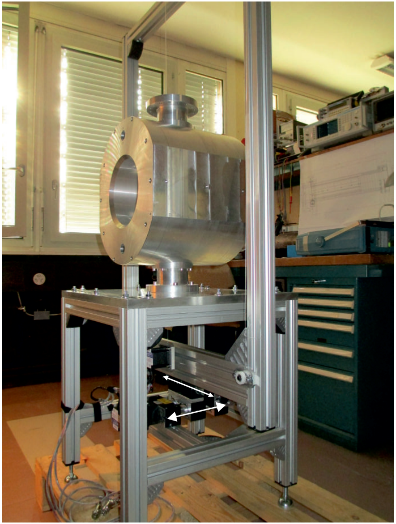


E. Montesinos, A. Boucherie

Bead-Pull Test Bench



E. Montesinos, A. Boucherie



Outline

Summary and conclusions

- Three different cavities (RF dipole, 1/4-wave and 4-rod) have been studied for the **higher-order multipole** viewpoint.
- In order to have **experimental evidence** of this higher-order effects, **precise** and **accurate** measurements are needed.
- A **bead-pull** setup has been built for the purpose.
- Measurements will follow.

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Get curious - take part!

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Measuring Radiofrequency Multipoles in the LHC Crab Cavities

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Third Joint HiLumi-LARP Annual Meeting 2013

Daresbury, November 2013