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MEASUREMENT OF MAGNETIC AXIS IN ACCELERATOR MAGNETS: CRITICAL COMPARISON OF METHODS AND INSTRUMENTS

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Measurement of magnetic axis in accelerator magnets: critical comparison of methods and instruments

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Abstract: *We review 19 measurement systems for the magnetic axis of accelerator magnets, used to align machine components. First, we provide some background information and we describe briefly the instruments and methods used for the magnetic and the geometric measurements. For all systems we give then a performance summary in terms of magnet parameters and measurement uncertainties. The dataset is analyzed statistically to identify the parameter with the most influence on the total uncertainty, which is magnet length. Finally we derive scaling laws relating uncertainties to magnet's parameters, and we discuss the relative performance of the various methods.*

Keywords: *magnetic measurements, multipole superconducting accelerator magnets, magnetic axis, harmonic coils, Hall sensors, stretched wire, Large Hadron Collider, optical survey.*

I. INTRODUCTION

In this paper, we analyze existing methods and instruments to measure the magnetic alignment of multipole magnets for particle accelerators. We consider mostly quadrupole magnets, which have the essential role of keeping the beam focused; however, methods and results are very similar to those for higher-order multipoles. The quantity of interest is essentially the magnetic axis, i.e. the locus where the field is null. On the basis of the extensive experience acquired at CERN, we compare characteristics and experimental results of the instruments used for Large Hadron Collider (LHC) magnets to those used in other contemporary machines.

Modern medium to large scale accelerators include dozens to hundreds of quadrupoles, up to several meters long, with apertures usually up to 200 mm and field strengths up to about 10 T in the case of superconducting technology. To function correctly, all these magnets must be aligned to a tolerance that can range from a few millimetres down to a few micrometers, in the most critical cases [1]. Alignment requirements are normally expressed in terms of the average offset of the magnetic axis w.r.t. the reference closed beam orbit, which must be smaller than a given tolerance RMS. All magnets are referred to a common geodetic network, which allows installation and monitoring of the relative and absolute position of all machine components. While average magnetic properties are the only important parameter for the beam (at least in the case of short magnets compared to betatron wavelengths), a detailed knowledge of the local axis is often useful to establish a correlation with other measured quantities and to assess the construction quality of the assembly.

As specific needs vary greatly, it is clearly not possible to rank the methods uniquely; our goal is rather to identify the components and techniques that perform best in each region of the measurement parameter space. Based on this snapshot of the current state of the art, we also aim at pointing out the main limitations and sources of uncertainty of these systems, in order to suggest possible directions for improvement.

II. PRINCIPLE OF AXIS MEASUREMENTS

The measurement of the magnetic axis is generally a two-step process, often referred to as "fiducialisation", involving a) the detection of the field null in a local reference system by means of some kind of magnetic sensor, and b) the transfer of the axis coordinates to an external reference system rigidly attached to the magnet, materialised by a set of geometric references or fiducials (see a schematic representation in Fig. 1, referred to the case of harmonic coil measurements). The fiducials are typically some kind of optical target, e.g. Taylor-Hobson spheres with prism or retro-reflectors for laser tracker measurements, or simple marks in case theodolites are used. Fiducials must be accessible for measurements both during the tests and after installation in the machine, which may represent a penalizing constraint. This is especially the case for superconducting magnets, where fiducials must be placed on the cryostat that fully encloses the magnet.

Most accelerator laboratories develop their own alignment measurement systems, which are normally a mixture of commercial and custom-built components, highly tuned to their specific requirements. These will include in general:

- a magnetic sensor (see Section III) with its conditioning electronics and acquisition system;
- a mechanical system used to scan the target field volume, carrying the sensor plus some suitable geometrical references and one or more angular references (e.g. optical encoder, tilt sensor);
- a computer-controlled positioning system;

- a 2D or 3D position measurement system (see Section IV) able to relate the references on the probe to a set of fiducials on the magnet, possibly via a network of additional fixed external points. The measurement can be directly provided, all or in part, by the probe positioning system.

The end result consists of the combination of the magnetic and position measurements. The accuracy that can be obtained is a function of the accuracy of individual components and of the size, field strength and multipole order of the magnet to be measured.

For superconducting magnets, the choice must be made whether to carry out the measurements at cryogenic or room temperature (RT). Room conditions give easiest access to the magnet bore and allow inexpensive testing, although results must be extrapolated somehow to the final working conditions taking thermal contractions into account. Cryogenic tests provide directly the wanted result and allow in general more accurate magnetic measurement at very high fields, but on the other hand are much more expensive and may pose serious problems for the survey, due to restricted access and potential thermal gradients that may silently disrupt optical measurements in the bore. In the end, as we shall see later, the choice between the two alternatives is not at all obvious.

III. MAGNETIC SENSORS

The following types of magnetic field sensors and subsystems have been analysed in this work:

1. Colloidal Cell: used essentially only at Brookhaven National Laboratory, this system is able to image digitally the pattern of rotation of polarization of a light beam passing through a ferrofluidic colloidal solution immersed in the field. Although the axis, obtained by best-fitting the field lines to the pattern, may have sub-pixel accuracy, the system is only viable at high gradients.
2. Harmonic Coils: in this classical method, with widespread applications, the field harmonic coefficients are obtained from the Fourier analysis of the signal picked up by a rotating rectangular coil. The offset of the axis of the N^{th} order component (i.e. the main field) w.r.t. the rotation axis is computed from the measured amplitude of the component of order N-1, which is assumed to be generated by the so-called feed-down effect [1]. While generally the magnet is excited in DC and the flux is integrated as the coil rotates, it is possible to enhance RT sensitivity exciting in AC and picking up the signal with fixed coils at different discrete azimuthal positions.
3. Stretched Wire: this method, which is also relatively common, makes use of a single conducting wire stretched through the magnet and moved by precision translation stages at both ends, which are short circuited by a fixed wire. An integrator measures the induced loop voltage and the axis is obtained by iterating horizontal and vertical sweeps until symmetric start and end points are found, giving zero integrated flux.

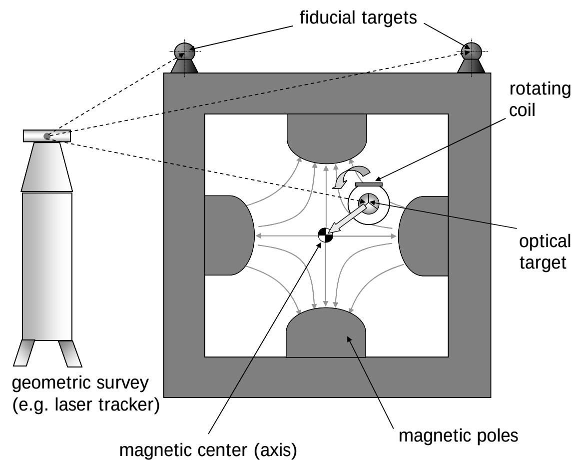

Fig. 1 –Magnetic axis measurement in a quadrupole magnet with harmonic coil method. Axis position is obtained in a frame centered on the coil's rotation axis, then is transferred to magnet fiducials via geometric survey.

4. Pulsed Wire: variation of the Stretched Wire technique which allows to find the field null by setting up with an ultra-short current pulse a travelling transversal wave, detected by optical sensors at the extremities. The amplitude of the wave is proportional to the offset between the wire and the axis, while the timing carries information on the longitudinal coordinate.
5. Vibrating Wire: further evolution of the stretched wire method, in which transversal vibrations are continuously excited at the resonance frequencies of the wire, providing exceptional sensitivity.
6. Hall plates: knowing that an ideal Hall plate will give zero output if placed symmetrically on the axis of a quadrupole field, these sensors have been recently successfully employed by means of precise calibration in a suitable double-pointed permanent magnet setup.

IV. SURVEY SYSTEMS

These are the types of survey systems considered:

1. Theodolite: this classic system, which works on arbitrarily wide ranges, is based on a telescope to carry out precise angle measurements between lines-of-sight, from which 3D point position can be inferred by triangulation.
2. Laser with PSD/CCD: Position Sensing Detectors are assemblies of two or four photodiodes, attached to the object being measured and illuminated by a reference laser beam. The output signal difference between the photodiodes can be used to derive 1D or 2D position information with micrometer accuracy over a range of few millimeters. A similar technique replaces the PSD

Accelerator			Magnet									Instrumentation		Uncertainty			Ref.
Institute	Machine	L [m]	Type	Technology	Lm [m]	Aperture [mm]	I [A]	dB/dr [T/m]	B_{max} [T]	T [K]	Moves	Magnetic	Survey	Axis to sensor [μm]	Sensor to ref. [μm]	Total [μm]	
BNL	**RHIC**	3862	quad	superconducting	1.13	80	5000	71.00	5.7	4.5	no	Colloidal Cell	Theodolite	40	25	47	[2]
BNL	**RHIC**	3862	quad	superconducting	1.13	80	10	0.14	0.01	300	no	Harmonic Coil	Theodolite	25	25	35	[2]
BNL	**SASE**	-	undulator	permanent	4.00	6	-	-	0.8	300	no	Pulsed Wire	Interferometer	10	8	13	[3]
KEK	**B-factory**	3016	quad	resistive	0.40	110	500	10.20	1.12	300	yes	Harmonic Coil	Laser Tracker	15	5	16	[4]
SLAC	**LCLS**	3000	quad	resistive	0.05	12	n.a.	15.00	0.18	300	no	Hall Sensor	CMM	8	1	8	[5]
SLAC	**LCLS**	3000	undulator	permanent	3.40	12	-	-	1.3	300	no	Hall Sensor	CMM	8	15	17	[6]
SLAC	**LCLS**	3000	quad	resistive	0.15	12	n.a.	12.00	0.14	300	yes	Vibrating Wire	CMM	18	10	21	[7]
JASRI	**SPring-8**	1436	quad	resistive	0.64	85	n.a.	17.40	1.48	300	yes	Harmonic Coil	Laser + CCD	2	10	10	[8]
SLAC	**FFTB**	3200	quad	resistive	0.46	23	220	83.00	1.91	300	no	Vibrating Wire	CMM + Micrometer	4	15	15	[9]
MIT-Bates	**SHR**	190	quad	resistive	0.28	35		0.50	0.02	300	no	Harmonic Coil	Theodolite	*26*	*43*	51	[10]
FNAL	**LHC**	26660	quad	superconducting	8.00	63	11850	215.00	13.55	4.5	no	Stretched Wire	Laser Tracker	33	50	60	[11]
FNAL	**LHC**	26660	quad	superconducting	8.00	63	2	0.04	0.00	300	no	Stretched Wire	Laser Tracker	33	50	60	[11]
CERN	**LHC**	26660	quad	superconducting	8.00	40	11850	223.00	8.92	1.9	no	Stretched Wire	Laser Tracker	5	80	80	[12]
CERN	**LHC**	26660	quad	superconducting	8.00	50	2	0.04	0.00	300	no	Stretched Wire	Laser Tracker	20	80	82	[13]
CERN	**LHC**	26660	quad	superconducting	8.00	50	0.5	0.01	0.00	300	no	AC Harmonic Coil	Laser Tracker	51	80	95	[14]
Cornell	**CESR**	768	quad	superconducting	7.50	67	n.a.	13.00	0.87	n.a.	no	Vibrating Wire	Laser Tracker	10	51	52	[15]
Cornell	**CESR**	768	solenoid	superconducting	0.30	200	n.a.	-	0.008	300	no	Vibrating Wire	Laser Tracker	10	25	27	[16]
CNRS/CEA	**SOLEIL**	354	quad	resistive	0.46	66	n.a.	23.00	1.52	300	yes	Harmonic Coil	(mech. tol.)	*5*	*30*	30	[17]
ELETTRA	**SR**	259	quad	resistive	0.49	75	n.a.	20.60	1.55	300	yes	Harmonic Coil	Telescope	*5*	*25*	25	[18]
CERN	**LEP**	26660	quad	resistive	1.55	59	n.a.	9.70	0.57	300	yes	Harmonic Coil	Laser + PSD	20	50	54	[19]

Table 1 – Main parameters and uncertainty of magnetic axis measurements in major contemporary accelerators.

with a CCD camera sensor, which provides the position of the beam directly in terms of pixel intensity levels.

3. Laser Tracker: this instrument is based on a laser beam shot via a 2-axis servo-controlled mirror at a suitable retro-reflecting optical target (typically a prism or a corner cube), which sends it back along exactly the same optical path. The system measures the 3D coordinates of the targets in a polar coordinate system by means of an interferometer for the radial distance, plus two precision optical encoders sensing the azimuth and elevation of the mirror. This system, which is very convenient to use, represents a compromise between accuracy and measurement range.
4. Straightness Interferometer: this system makes use of two or three independent interferometers, working simultaneously along perpendicular directions, to get extreme precision on 2D or 3D readings (limited by the visibility of the targets).
5. Coordinate Measuring Machine (CMM): mechanical instrument based on a measuring head moving on two or three perpendicular high-precision guides. This instruments guarantees extremely good accuracy, however it is limited by the overall size and the ability to access the aperture.
6. Mechanical Tolerance: in one instance the geometry has not been surveyed at all, relying instead on the mechanical tolerances of the assembly including the magnet and the sensor (in such a case, viable only with small magnets, one might say that survey has been performed in the mechanical workshop once and for all).

V. Overview of Contemporary Axis Measurements

The magnetic axis of multipole magnets has been located in many different ways and with different devices during the years. The list given here includes some of the methods used in the major accelerators worldwide during the last two decades or so. The collection is by no means exhaustive, although we believe that it gives a fair representation of the current state-of-the-art in the field. Parameters and performance figures have been taken from the published literature, and we give for each project the appropriate references where more details can be found. An effort has been made towards homogenization of the reported metrics, to ensure that the performance of different systems can be compared consistently. However, published results often depend on both the instrument characteristics as much as on those of the magnets being tested, and disentangling the two contributions may be difficult even for the specialist.

Table 1 lists the main relevant data found in the literature for 19 measurement systems used in 11 different accelerators. The parameters include:

- the size L of the machine (length of the ring);
- the type of the magnet: mostly quadrupoles but also one solenoid and two undulators (special magnets generating a dipole field with alternating direction, used to wiggle the trajectory of charged particles to force the emission of synchrotron radiation);
- the technology used, i.e. superconducting, resistive (traditional copper coils) or permanent-magnet;
- the length L_m of the magnet being measured;
- the aperture a, i.e. the maximum distance (or diameter) between the coils or the poles which is accessible to the magnetic sensor;
- the test current;
- the test field gradient ∇B (for quadrupoles);
- the peak field in the aperture $B_{\max}$ (for quadrupoles, this corresponds to the field at the outer diameter);

- the test temperature of the magnet, which for superconducting magnets will be typically at 4.5 K, i.e. the boiling point of Helium at atmospeheric pressure (with the exception of LHC magnets, operating in superfluid Helium at 1.9 K). Note that in these cases, a so-called anticryostat is usually installed in the aperture so as to allow access at ambient conditions.
- the possibility to move the magnet on the test bench;
- the type of instruments used for the magnetic sensing and optical survey, according to the lists given above;
- the estimated uncertainty of the magnetic axis measurement u_m w.r.t. the magnetic sensor, and of the sensor position w.r.t. the fiducial (reference) coordinate system u_s;
- the total measurement uncertainty u_{TOT}, obtained as the quadratic average of the two uncertainties above.

The uncertainty linked specifically to electronic components such as integrators, voltmeters or ADCs has not been included in the present analysis; however, based on our own experience at CERN, it is felt that this contribution is generally much less important. the In general, the uncertainties reported here have to be interpreted in a loose sense as the best-scenario standard deviation over repeated measurements of the same object. A rigorous assessment of the absolute accuracy, involving systematic comparisons with a reference instrument, has not been carried out in most of the published cases (also for the good reason that such a reference does not exist as an established standard) and has therefore been ignored here. In three cases, all involving harmonic coil setups, only the total uncertainty and not the two separate contributions were quoted in the literature. The values reported in Table 1 (in italics) represent our best guess, based on a linear regression of harmonic coil uncertainty vs. peak magnetic field.

VI. COMPARATIVE ANALYSIS AND SCALING LAWS

A. Scaling law for the total uncertainty

To assess the strength of possible overall trends, first of all we have chosen to plot total uncertainty as a function of magnet length, accelerator length and magnet aperture (Fig. 2, 3 and 4 respectively). The size of the machine may conceivably influence results via factors that cannot be quantified a priori (besides a trivial correlation between large magnets in a large ring), like e.g. environmental conditions during the measurement. In fact, while for certain small-scale project the use of conditioned environment is possible and very often enforced, for large scale accelerators (e.g. LHC) this is not always possible, given the number and the rate of magnets to be measured, typical of industrial projects.

The plots suggest a definite tendency towards increasing uncertainty with magnet and accelerator size, while on the other hand no clear trend can be detected as a function of magnet aperture. To confirm quantitatively this impression a 5% significance level Pareto analysis has been performed, providing the following t-values:

- Size L: t=3.0
- Magnet length L_m: t=2.3
- Magnet aperture a: t=1.0

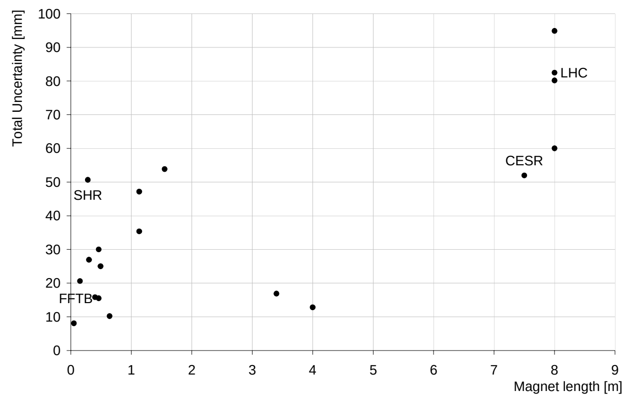

Fig 2 – Total estimated uncertainty of axis measurements vs. magnet length (data from Table 1)

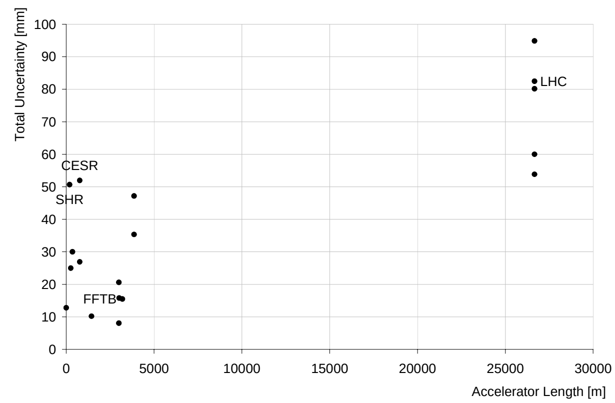

Fig 3 – Total estimated uncertainty of axis measurements vs. accelerator length (data from Table 1)

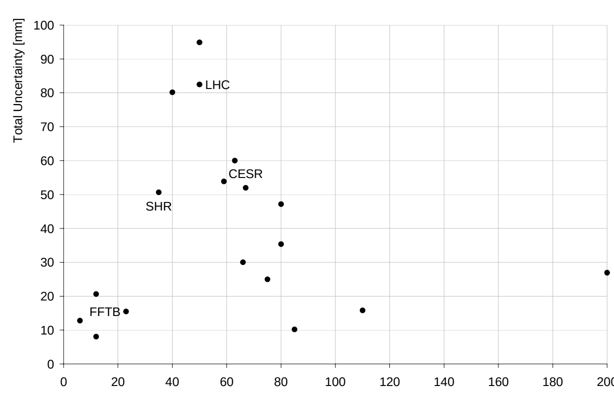

Fig 4 – Total estimated uncertainty of axis measurements vs. magnet aperture (data from Table 1)

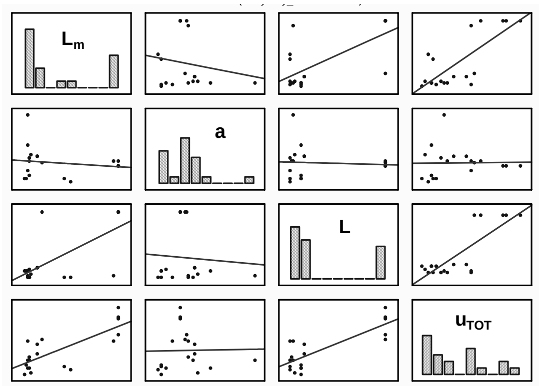

Fig 5 – Correlation matrix scatterplot with the bivariate linear regressions of all combinations of the variables magnet size, aperture, machine length and total uncertainty. The four histograms of the respective distributions are shown on the diagonal.

The total uncertainty u_{TOT} appears to be strongly correlated to magnet length, less so to accelerator size, and not at all to magnet aperture, as further confirmed by the correlation matrix scatterplot shown in Fig. 5. These results can be summarized in the following multivariate linear regression, which provides a tentative scaling law:

$$u_{TOT} = u_0 + \frac{\partial u}{\partial L} L + \frac{\partial u}{\partial L_m} L_m + \frac{\partial u}{\partial a} a \qquad (1)$$

where:

- u_0=14.7 µm
- $\partial u/\partial L$=1.3 ± 0.4 µm/km
- $\partial u/\partial L_m$=3.3 ± 1.5 µm/m
- $\partial u/\partial a$=0.1 ± 0.1 µm/mm

The intercept u_0 may be thought of as an average of all constant contributions, including e.g. electronic noise and mechanical tolerances. The low value of $\partial u/\partial a$ may be ascribed to the fact that large apertures are often associated by design to a lower field, the benefit of wide access being therefore compensated by lower magnetic accuracy.

B. Magnetic and survey uncertainty

The contributions of magnetic sensor and geometric survey to the total accuracy are summarized in Fig. 6 and 7 respectively, where they have been grouped by instrument type. On the basis of the collected results, we find that on average the geometric survey contributes almost twice as much as the magnetic measurement to the total uncertainty. This may be seen as a reflection of the current industry trends going towards ever higher magnetic fields, thus easing the job of the magnetic sensors, but more penalizing geometries, with long magnets and narrow apertures. While an absolute ranking of the methods is not possible, as the results depend upon the parameters of the magnet being measured, the following considerations can be made:

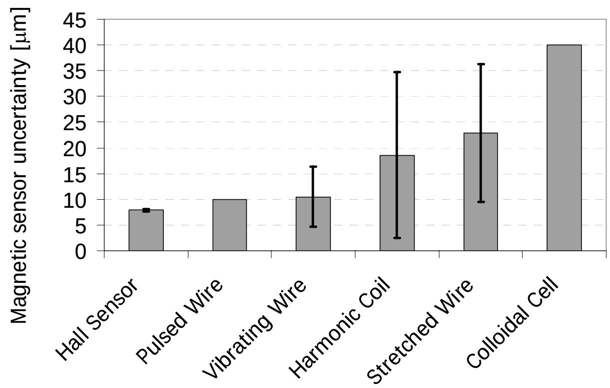

Fig 6 – Summary of magnetic sensor uncertainties. The error bars represent observed value ranges, where applicable.

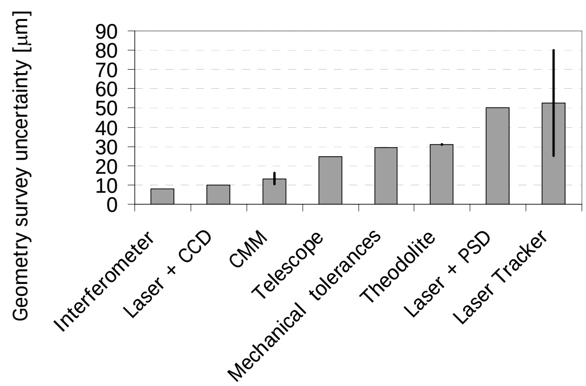

Fig 7 – Summary of geometric survey uncertainties. The error bars represent observed value ranges, where applicable.

- well-established magnetic measurement techniques such as the harmonic coil or the stretched wire, which on average seem to give mediocre performance, attain in some cases exceptionally low uncertainties in the micrometer range (note that to get any better than this is neither required by the current generation of machines, nor physically meaningful unless operation in a strictly controlled environment is envisaged).
- when mechanical alignment means are adopted (movable girder or CMM), the survey accuracy is sensibly improved and the error budget is limited by the magnetic technique. On the other hand, when the size of the magnet enforces the choice of a purely optical survey, the total accuracy is adversely affected.

To gain further insight, we attempted to parameterize the two sources of uncertainty with the following scaling laws:

a) magnetic: $u_m \propto a^{-2}\nabla B^{-1} \propto a^{-1}B_{\max}^{-1}$ (magnetic gradient measurements being facilitated by larger fields and wider access)
b) survey: $u_s \propto L_m^2$ (on the assumption that survey errors due, for instance, to optical refraction scale with the square of the distance)

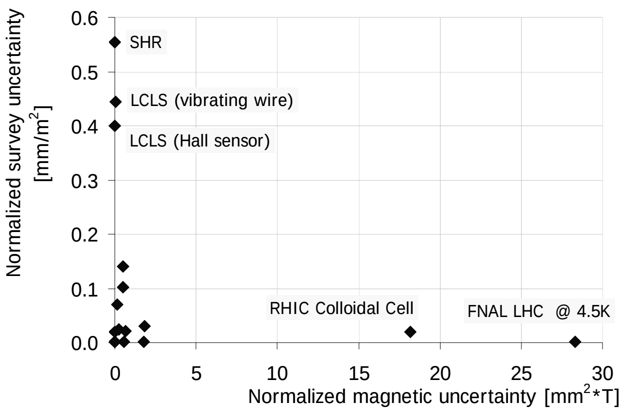

Fig 8 – Normalized survey and magnetic uncertainties.

Fig. 8 represents the uncertainties of all measurement methods considered for quadrupoles in the plane of the normalized variables ($u_m a B_{\max}$, u_s/L_m^2). Here, methods that are good intrinsically (i.e. independently of the parameters of the particular magnet being measured) should be as close as possible to the origin on both axes, and indeed this is what we generally observe with a few exceptions:

- systems with normalized survey uncertainty ≥ 0.4 mm/m^2 (SHR and LCLS quadrupoles); in these three cases the magnet is extremely short (less than 300 m), so it is reasonable to expect that the scaling w.r.t. L_m^2 breaks down.
- systems with normalized magnetic uncertainty ≥ 15 mm^{2}T (RHIC and LHC quadrupoles); in these two cases a large uncertainty is associated with an extremely large magnetic gradient at cryogenic temperatures, contradicting assumption a) above.

VII. Conclusions

In this work we have considered an impressive array of techniques for the measurement of magnetic axis, capable of providing results with uncertainties well below one tenth of a millimetre, which are in all cases compatible with the requirements of the respective accelerators. Our review points out some of the parameters that most affect the result, such as the magnet length, and some of those that (perhaps surprisingly) do not, such as the aperture and the field gradient. In most cases the accuracy of the survey represents the limiting factor and it is clear that traditional mechanical systems retain a strong advantage, despite the flexibility and convenience of optical methods. Even though it is impossible to single out a method as the "best", we plan in the future to widen our sample and to refine our scaling laws with the aim to identify the zones of parameter space where any given technique may be more appropriate or more promising.

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