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LEIR Closed Orbit Measurement system

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Abstract
In the Low Energy Ion Ring (LEIR) continuous (every 10 ms) tracking of the closed orbit is necessary during the acceleration and on request. To do so parts of the existing hardware, mainly the pick-ups (PUs) and cables, from LEAR have been re-used while other parts like the head amplifiers and the acquisition system has been re-designed. This note describes the hardware and software developed for the closed orbit measurement system as well as measurement results. The commissioning of LEIR started in September 2005 and is now close to nominal operation.

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1. Introduction

The LEIR nominal cycle (Figure 1) has a length of 3.6 s and accumulates 4 multi turn injections on the flat bottom. Every injected beam is electron cooled and moved to a “stack orbit”. After the 4 injections the beam is bunched, accelerated and extracted. The orbits are measured and stored every 10 ms except cycle’s boundaries.

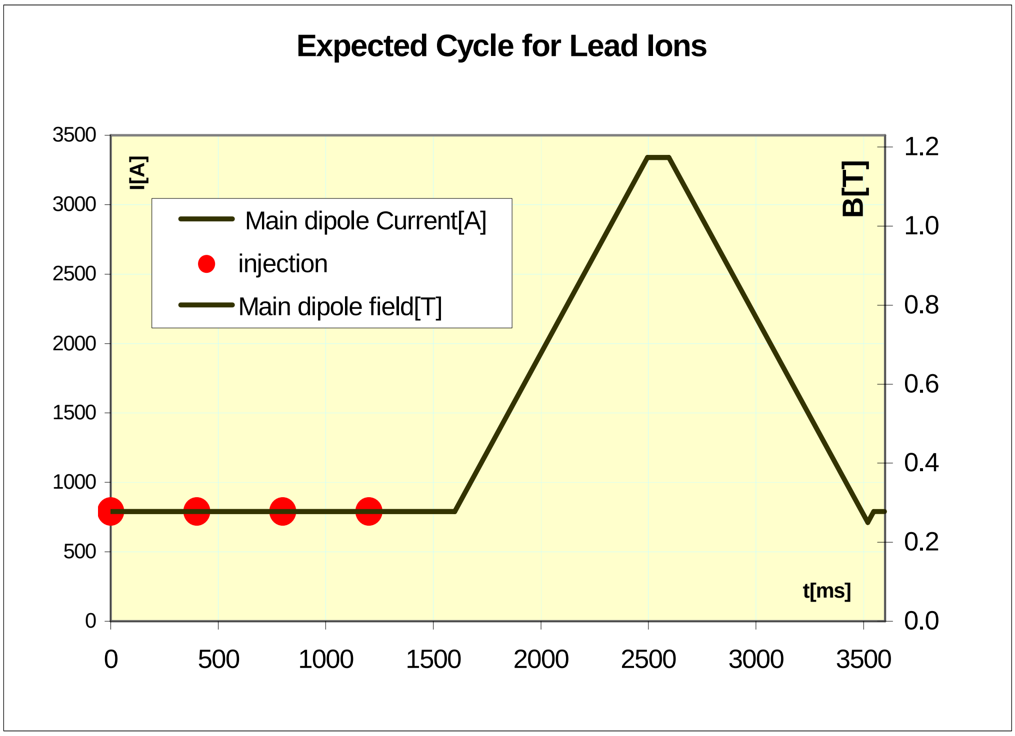

Figure 1: LEIR cycle

In LEAR 16 horizontal and 16 vertical PU were installed plus 2 horizontal and vertical PUs in the electron cooler. In LEIR 2 PUs for the new electron cooler have been constructed and 14 of the existing ring PUs are re-used. The 2 (H+V) electron cooler PUs included in the orbit measurement for the ions are also used to measure the trajectory of the electrons. Two different types of PUs are installed in the ring. 16 PUs are installed inside the bending magnets and consist of 4 metalized, ceramic rectangular plates, on which diagonal cuts have been made, in order to form shoebox type PUs. Eight combined horizontal and vertical cylindrical PUs are installed in the 4 straight sections and from which 2 are installed inside the electron cooler. They consist of metalized ceramic tubes on which semi-sinusoidal cuts have been made on the inside. The characteristics of the PUs are resumed in Table 1.

Cylindrical PU diameter [mm]	180/140
Shoebox PU Inner Dimensions [mm}	160*42.5
Electrical Length [mm]	40
Capacitance per electrode[pF]	~500
Differential sensitivity [V/mm]	$11.4*10^{-15}*N*B_f$

Table 1: PUs parameters

Where N is the number of charges and B_f is the bunching factor.

2. Requirements

The requirements for the orbit measurement system and some of the main beam parameters are summarised in Table 2 and in Table 3 correspondingly.

Max. displacement [mm]	±90
Position resolution @ 10^8 Ch. [mm]	1
Position resolution @ 10^9 Ch. [mm]	0.1
Absolute precision at centre [mm]	0.3
Relative precision	1%
Vacuum [Torr]	$3*10^{-12}$
Bake out temperature [ºC]	300

Table 2: Requirements

LEIR circumference [m]	78
Intensity [Nb. of Ch.]	10^8-$2*10^{11}$
Bunch lengths [ns]	100-700
Relativistic beta	0.095-0.612
Nb of bunches	2
Revolution frequency [MHz]	0.36-2.4

Table 3: Beam parameters

3. Analogue electronics

The layout of the orbit measurement system is shown in Figure 2. It consists of head amplifiers, differential transmission to the control room and reception amplifiers with three single ended outputs. One of these outputs is used by the analogue normalizer which is described later.

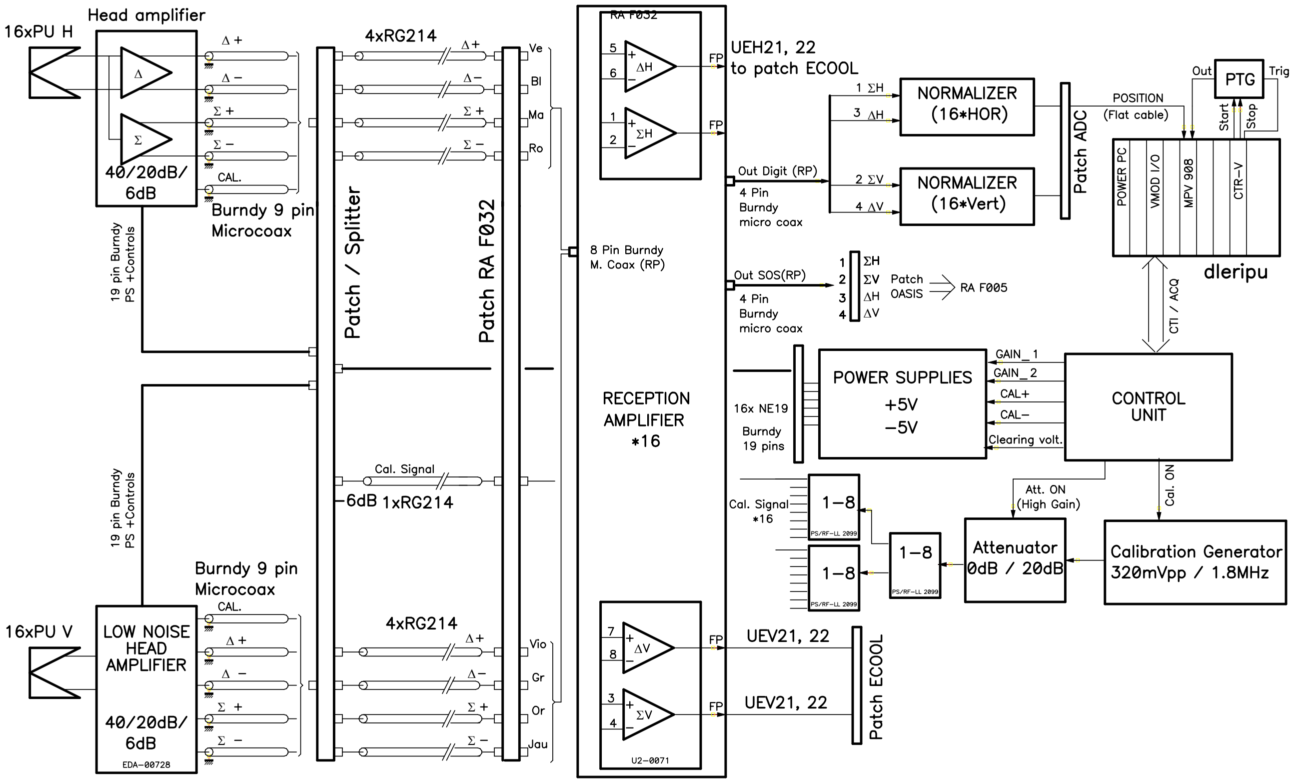

Figure 2: Closed orbit block diagram

3.1. *Head amplifier*

The specifications of the analogue electronics is mainly determined by the head amplifier whose performance is resumed in Table 4. The head amplifier, which actively generates Δ and Σ–signals from the electrode signals, has 3 different gains in order to cover the high intensity range.

Gains [dB]	10 / 30 / 50
Bandwidth [MHz]	0.003-30
Max. Output voltage [V]	2
Input / Output impedance [□]	1M / 50
Equivalent input noise [$nV/\sqrt{Hz}$]	1
S/N-ratio @ 1mm, 10^8 Ch.	0.4
Resolution 10^8 Ch [mm]	2.5

Table 4: Head amplifier specifications

3.2. *Reception amplifier*

The old LEAR reception amplifiers are re-used for the first run, but will soon be replaced with a newly developed similar module, which has a bigger dynamic range. The purpose of this module is to “receive” the differential PU signals and to distribute them single ended to several users. The performance of the reception amplifiers is resumed in Table 5.

Gain (single ended) [dB]	-6
Bandwidth [MHz]	0.0003-110
CMRR @1MHz [dB]	60
Max. Input / Output voltage [V]	2
Input / Output impedance [□]	50
Nb. of channels, 1□3	4

Table 5: Reception amplifier specifications

3.3. *Analogue normalizer*

The analogue normalizer [1] is based on a principle (Figure 3) where the sigma signal is kept constant and used to control the gain of a common amplifier chain. From the input signals (Δ and Σ) two signals are generated in turn: (Σ+Δ) and (Σ-Δ), which are amplified by the common filter and amplifier stage and peak detected. The two sums and difference signals are always positive as long as the Δ-signal does not exceed the Σ-signal, which is normally never the case. This simplifies the peak detector which can thus be unipolar. The averaged signals from the peak detector are stored in analogue memories and their sum and difference signals are generated. The sum of the signals is proportional to the sigma signal and is used to control the automatic gain control (AGC), in order to keep the sigma signal constant and thereby remove the intensity dependence of the position signal. The difference of the signals on the memory outputs is directly proportional to the beam position. In the normalizer module two AGC loops are used in order to increase the dynamic range. The filter BW and centre frequency are chosen such as to cover the revolution frequency range. This module is a “stand alone” unit which does not require any external signals other than the 2 beam signals.

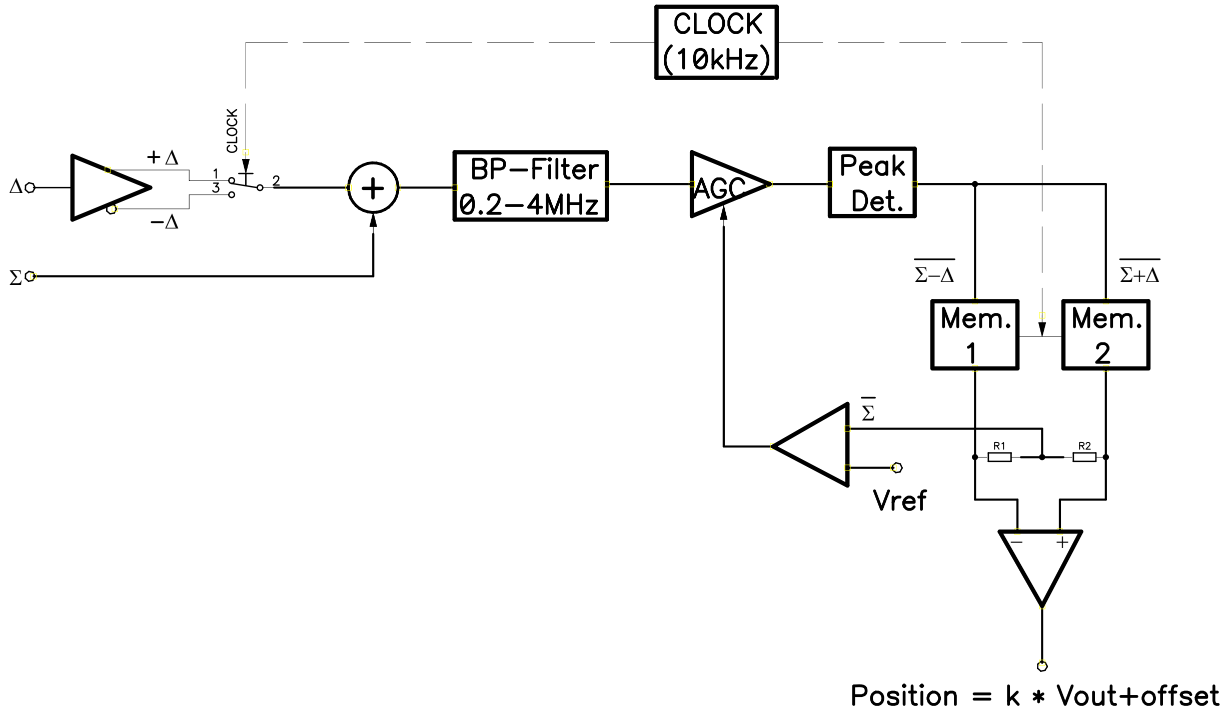

Figure 3: Normalizer block diagram

The performance of the one unit NIM module is summarized in Table 6 below:

Input / output impedance [Ω]	50
Transfer function	$V_{out} = \frac{4*\Delta}{\Sigma}[V]$
-3dB bandwidth [MHz]	0.2-4
Equivalent input noise [nV /$\sqrt{Hz}$]	< 3
Max input voltage [V]	± 1.5
Dynamic range [dB]	54
Response time (no input) [ms]	3
Response time (position change) [ms]	0.3
Linearity [%]	~0.4
Resolution @ 10^8 Ch., injection [mm]	0.3

Table 6: Specifications of the analogue normalizer

The resolution of 0.3 mm quoted in Table 6 is calculated from the resolution quoted in Table 4 (2.5 mm) and which is improved by a factor of ~8.4, due to analogue averaging in the normalizer. This factor is calculated from $\sqrt{\frac{f_{Bunch}}{f_{Clock}}}$; where f_{Bunch} is the minimum bunch frequency and f_{Clock} is the normalizer clock frequency of ~10 kHz. This averaging thus improves at higher revolution frequencies and can be further improved by digital averaging of the normalizer output.

3.4. *OASIS*

As shown on Figure 2 all of the analogue difference and sum signals are connected to OASIS. The cable numbers and corresponding channels in **dleioas1** are shown in Table 7.

Pick up	Cable number	Ch.	Signal	Pick up	Cable number	Ch.	Signal
ER UEHV11	2606264	1	ΣH	**ER UEHV31**	2606744	45	ΣH
	2606265	2	ΣV		2606745	46	ΣV
	2606266	3	ΔH		2606746	47	ΔH
	2606267	4	ΔV		2606747	48	ΔV
ER UEHV12	2606268	5	ΣH	**ER UEHV32**	2606748	49	ΣH
	2606269	6	ΣV		2606749	50	ΣV
	2606270	11	ΔH		2606750	51	ΔH
	2606271	12	ΔV		2606751	52	ΔV
ER UEHV13	2606272	13	ΣH	**ER UEHV33**	2606752	53	ΣH
	2606721	14	ΣV		2606753	54	ΣV
	2606722	15	ΔH		2606754	59	ΔH
	2606723	16	ΔV		2606755	60	ΔV
ER UEHV14	2606724	17	ΣH	**ER UEHV34**	2606756	61	ΣH
	2606725	18	ΣV		2606757	62	ΣV
	2606726	19	ΔH		2606758	63	ΔH
	2606727	20	ΔV		2606759	64	ΔV
ER UEHV21	2606728	21	ΣH	**ER UEHV41**	2606760	65	ΣH
	2606729	22	ΣV		2606761	66	ΣV
	2606730	27	ΔH		2606762	67	ΔH
	2606731	28	ΔV		2606763	68	ΔV
ER UEHV22	2606732	29	ΣH	**ER UEHV42**	2606764	69	ΣH
	2606733	30	ΣV		2606765	70	ΣV
	2606734	31	ΔH		2606766	75	ΔH
	2606735	32	ΔV		2606767	76	ΔV
ER UEHV23	2606736	33	ΣH	**ER UEHV43**	2606768	77	ΣH
	2606737	34	ΣV		2606769	78	ΣV
	2606738	35	ΔH		2606770	79	ΔH
	2606739	36	ΔV		2606771	80	ΔV
ER UEHV24	2606740	37	ΣH	**ER UEHV44**	2606772	22	ΣH
	2606741	38	ΣV		2606773	23	ΣV
	2606742	43	ΔH		2606774	39	ΔH
	2606743	44	ΔV		2607817	55	ΔV

Table 7: OASIS channel allocation

4. Digitization

The normalizer outputs are digitised by a 32 channels multiplexed 12 bits ADC, the MPV908. The ADC data are acquired every 10 ms except cycle's boundaries. The channel allocation and PU correspondence are shown in Table 8.

Device name	MPV908 ch.	Device name	MPV908 ch.
ER.UEH11	1	ER.UEV11	17
ER.UEH12	2	ER.UEV12	18
ER.UEH13	3	ER.UEV13	19
ER.UEH14	4	ER.UEV14	20
ER.UEH21	5	ER.UEV21	21
ER.UEH22	6	ER.UEV22	22
ER.UEH23	7	ER.UEV23	23
ER.UEH24	8	ER.UEV24	24
ER.UEH31	9	ER.UEV31	25
ER.UEH32	10	ER.UEV32	26
ER.UEH33	11	ER.UEV33	27
ER.UEH34	12	ER.UEV34	28
ER.UEH41	13	ER.UEV41	29
ER.UEH42	14	ER.UEV42	30
ER.UEH43	15	ER.UEV43	31
ER.UEH44	16	ER.UEV44	32

Table 8: MPV908 channel allocation

5. Timing and control

The following fast timings needed to trigger the ADC in beam and calibration modes, have been installed in the DSC:

EX.STRIG-RIPU & EX.TRIG-RIPU & EX.ETRIG-RIPU:

This is a 100 Hz ADC conversion pulse train of the bursts of 32 pulses separated by 10 us derived from the c-train.

In order to acquire continuously the data stored in the ADC 2 slow interrupts have been foreseen:

EX.ACQ-RIPU:

This is a 5Hz train derived from the c-train. It is used for retrieving just arrived data to ADC and release of unused ADC memory.

EX.PUB-RIPU:

It comes out once at the end of each cycle (not at each basic period, generated from EX.WCY200-MTG with delay 200).

Via a VMOD-TTL VME module the following **NON-PPM** controls have been foreseen:

- **Gain**: hi (HG), medium (MG) or low (LG). The gain is chosen by the operator according to intensity.
- **Mode**: beam or calibration.
- **Clearing voltage**: ON / OFF.

Signal	Pin	Direction	Function
Port A D0	1	OUTPUT	Low gain CTL
Port A D1	25	OUTPUT	High gain CTL
Port A D2	2	OUTPUT	Cal + CTL
Port A D3	24	OUTPUT	Cal – CTL
Port A D4	3	OUTPUT	Clearing voltage ON CTL
Port A D5	23	OUTPUT	Spare
Port A D6	4	OUTPUT	Spare
Port A D7	22	OUTPUT	Spare
Port B D0	6	INPUT	Low gain ACQ
Port B D1	20	INPUT	High gain ACQ
Port B D2	7	INPUT	Cal + ACQ
Port B D3	19	INPUT	Cal – ACQ
Port B D4	8	INPUT	Clearing voltage ON ACQ
Port B D5	18	INPUT	Beam bunched ACQ
Port B D6	9	INPUT	Local / remote ACQ
Port B D7	17	INPUT	Spare

Table 9: VMOD TTL bit allocation

6. FE-Software and application program

6.1. *FE-Software*

The front-end software reads the digitised values (MPV908) from the normalizer and computes the 32 positions every 10 ms. It is based on BI front end software standard interface for beam position measurements [2] and implemented using FESA [3].

Two modes of operation are foreseen [4]:

- Beam:

  The 32 beam positions are calculated using scaling factors k and offsets measured in the calibration mode:

  $$Pos. = u_f \cdot \left(k \cdot (V_{Norm.} - Cal_0) + offset\right),$$

  where

  u_f is unit factor,
  offset = electrical offset ($\mathbf{a_0}$) + mechanical offset,
  Cal_0 is normalizer output voltage when LEIR Orbit is in calibration zero mode.

- Calibration: A pulse generator is used to simulate the beams:

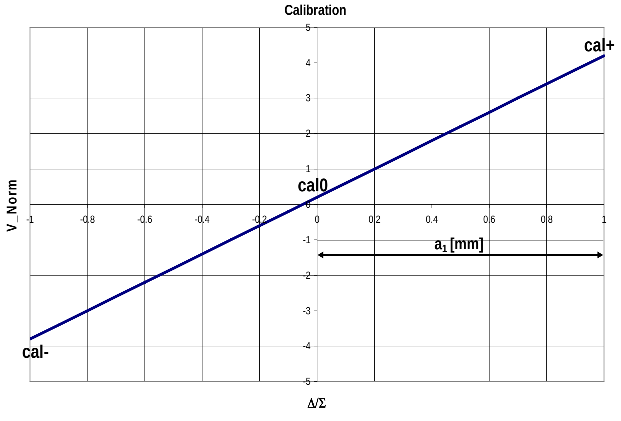

Figure 4: Calibration

– Cal_+: Simulates the maximum positive beam displacement.
– Cal_0: Simulates a centered beam.
– Cal_–: Simulates the maximum negative beam displacement.

The slope of the line, which is determined by the $\Delta_{Gain} / \Sigma_{Gain}$ and the normalizer transfer function, is used to normalise the beam position measurements such that:

$$k = \frac{2 * a_1}{V_{Norm}(cal_+) - V_{Norm}(cal_-)},$$

where $\mathbf{a_1}$ is the PU sensitivity.

Every PU has been measured on a test bench and its coefficients (**a_0** and **a_1**) from a linear fit are known [4]. The calibration is done on request a few times per year.

Additional information about the front-end software can be found in [4] and [5].

7. Results

The beam orbits at injection and ejection (registered on 02.11.2006) are shown in Figure 5.

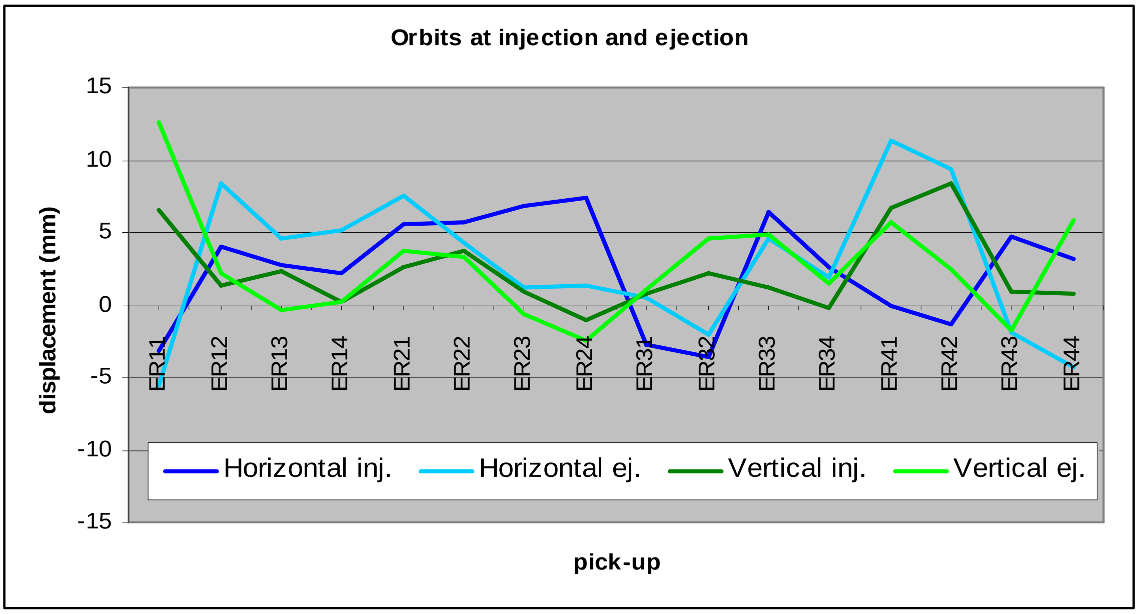

Figure 5: Orbits

To estimate the resolution of the orbit measurement system ~80 measurements were made and the estimated RMS noise is shown in Figure 6 and Figure 7. The measurements are done on consequent cycles and not on a flat top of one cycle, and do thus include the cycle to cycle jitter of the machine. The shown measurements are from a "good day" were the machine was very stable. In the vertical plane it is clearly seen that the smaller aperture pick-ups in the bending magnets (U13, U14, U23, U24, U33, U34, U43, and U44) gives a better resolution. The maximum RMS noise is estimated to ~0.2mm with $3*10^8$ charges.

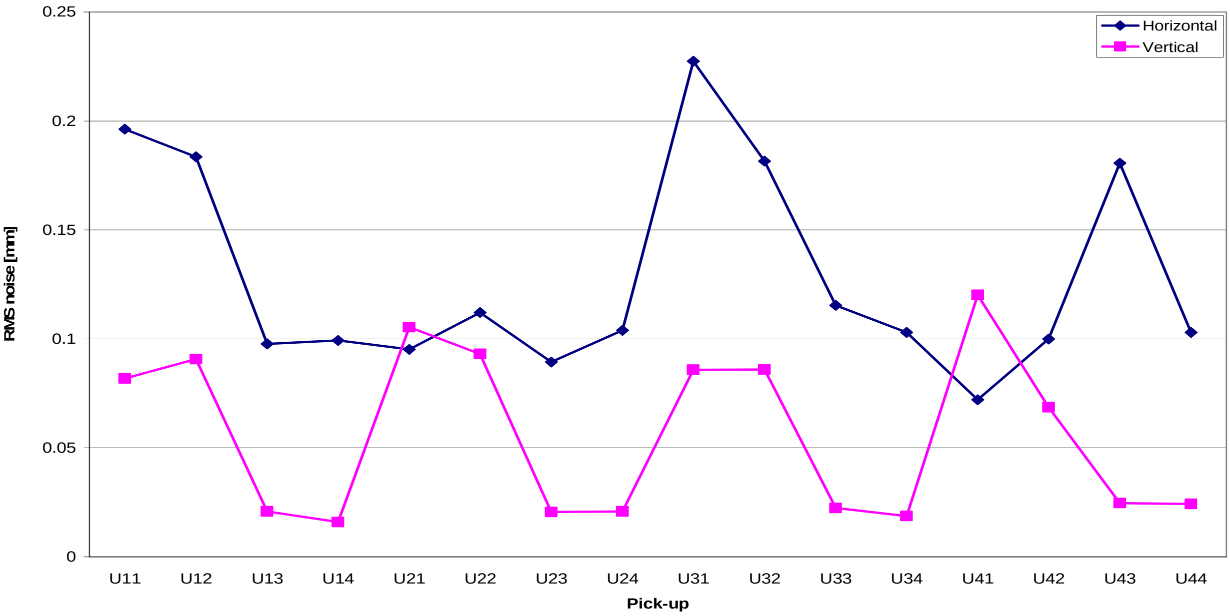

Figure 6: Measurement noise at injection.

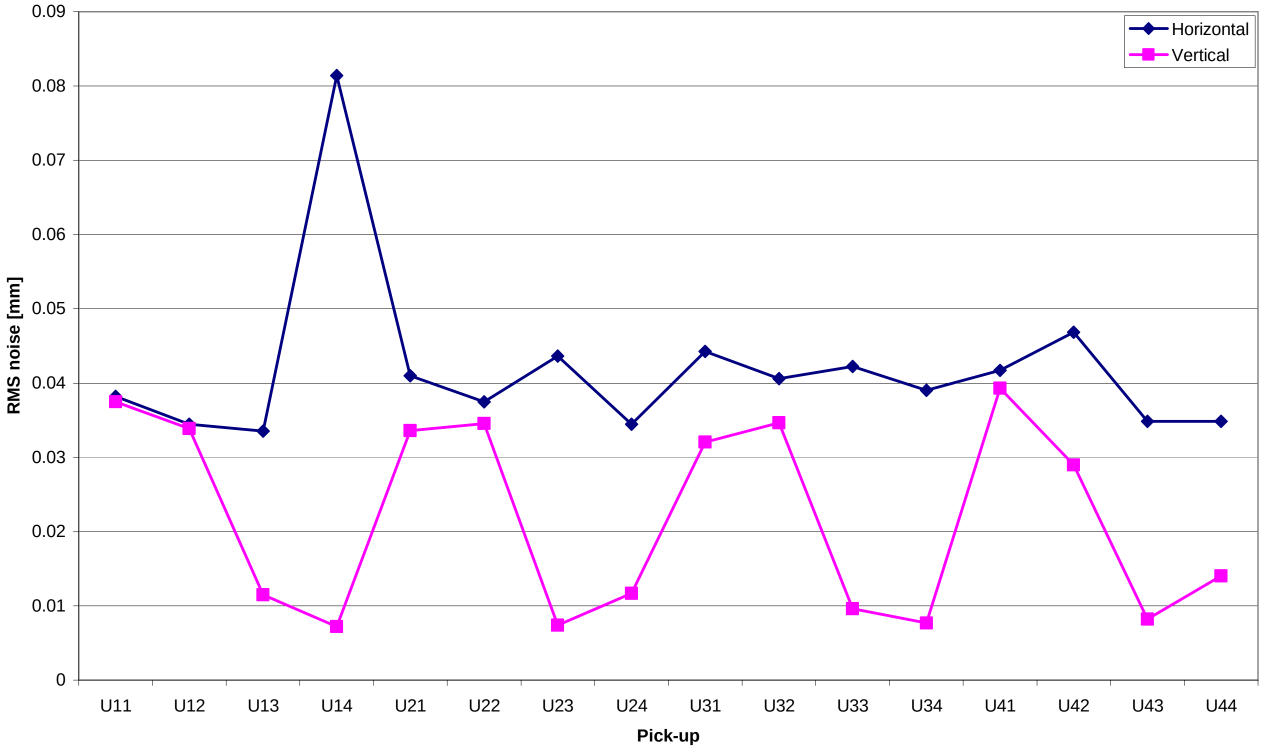

Figure 7: Measurement noise at ejection

8. Conclusion

For the LEIR orbit measurement system parts of the existing hardware, such as PUs, cables and reception amplifiers are re-used. The head amplifiers are newly developed units which have three different gains in order to cover the high intensity range. The front-end software provides orbit(s) on any requested time(s), but is by default measuring every 10ms, except at cycle's boundaries. The system was commissioned with beam in the first run of 2005 was fully operational from the start.

An estimate of the resolution of the orbit measurement system has been done by measuring the fluctuations of the beam positions on different cycles. This was done in a period when the machine was "stable" and is estimated to 0.2mm RMS at $3*10^8$ charges. It was not possible to do consecutive orbit measurements on a flat top of one cycle.

9. References

[1] G. Gelato, M. Magnani, "Improved radial pick-up electronics for use over a wide dynamic range", Rapport MPS/BR/75-8, 1975.

[2] Stephane Bart Pedersen, John Fullerton, Jean-Jacques Gras, Ana Guerrero, Stephen Jackson, Lars Jensen, Peter Karlsson, Danil Korchagin, Arkady Lokhovitskiy, Michael Ludwig, "BI Front End Software Standard Interface for Beam Position Measurements", CERN EDMS Id 630857, 2004.

[3] Front End Software Architecture Web Site, http://project-fesa.web.cern.ch/project-fesa .

[4] Danil Korchagin, Michael Ludwig, Lars Soby, "BI Front End Software Functional Specifications for the LEIR Orbit Measurement System [BPNCO]", CERN EDMS Id 633270, 2005.

[5] Danil Korchagin, Michael Ludwig, "BI Front End Software Interface for the LEIR Orbit Measurement System [BPNCO]", CERN EDMS Id 633270, 2005.