Development of tools for real-time betatron tune measurements at Nuclotron

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VBLHEP, JINR

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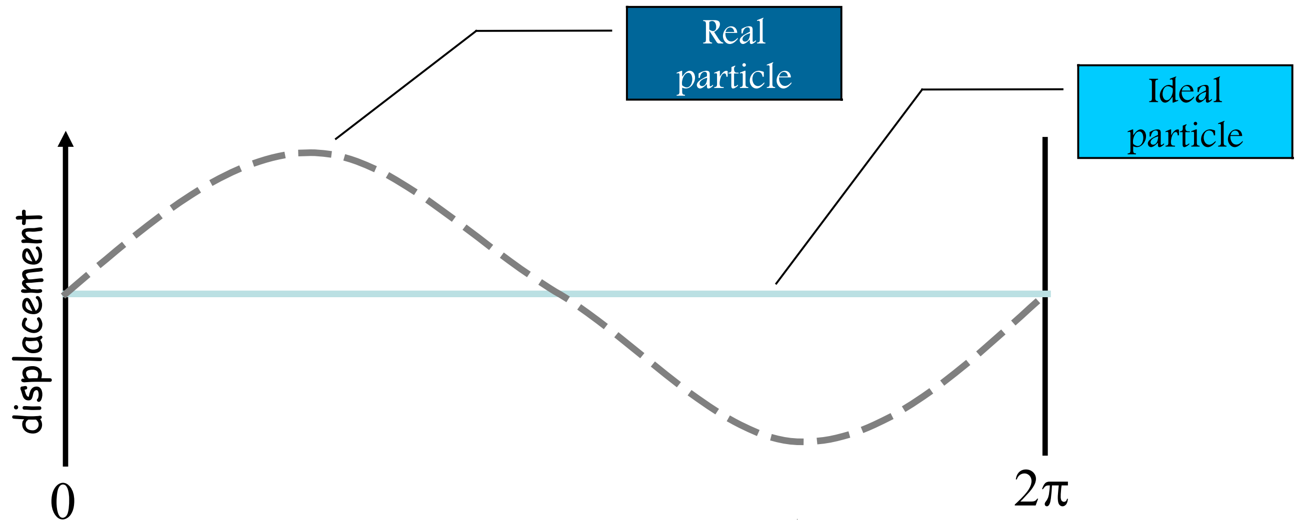
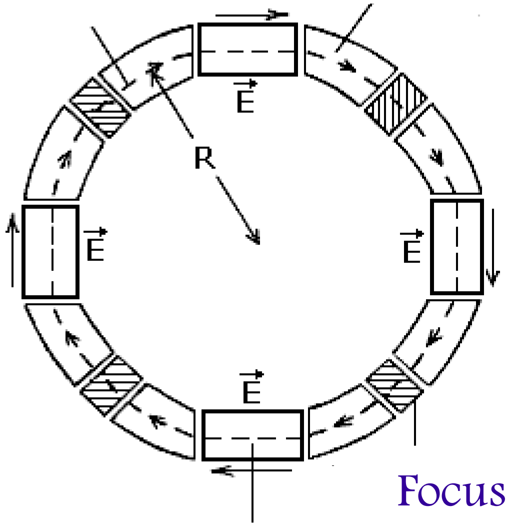
Betatron oscillations

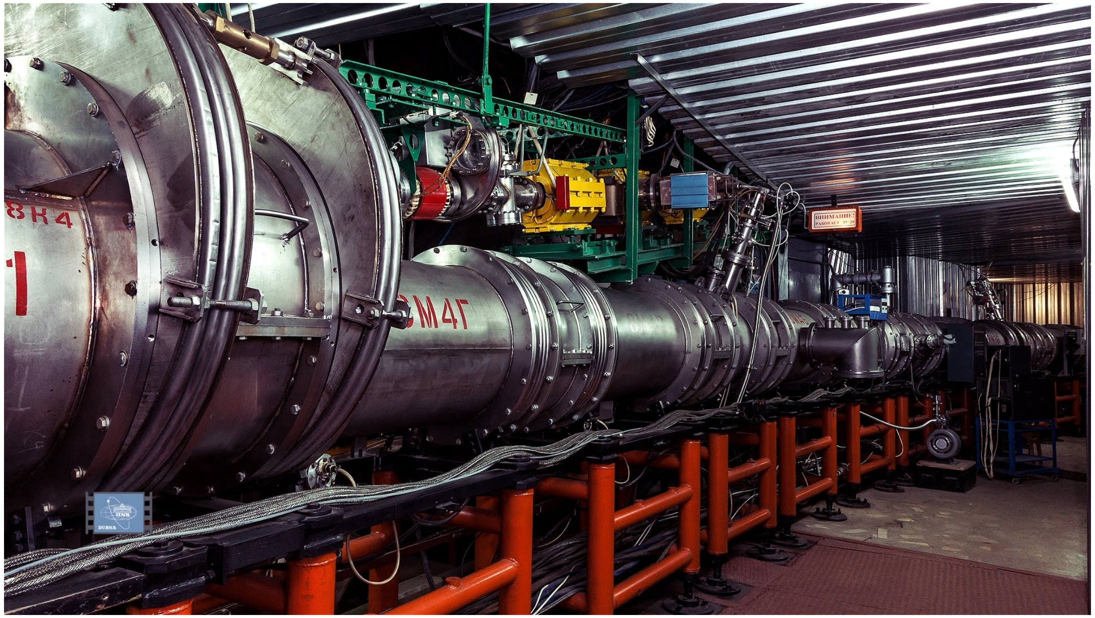


The ideal particle will follow a particular trajectory, which closes on itself after one revolution – the closed orbit. The real particles will perform oscillations around the closed orbit. These transverse oscillations are called Betatron Oscillations, and they exist in both horizontal(X) and vertical(Z) planes. The number of such oscillations per one turn is called Betatron Tunes – Q_x and Q_z .

Synchrotron accelerators

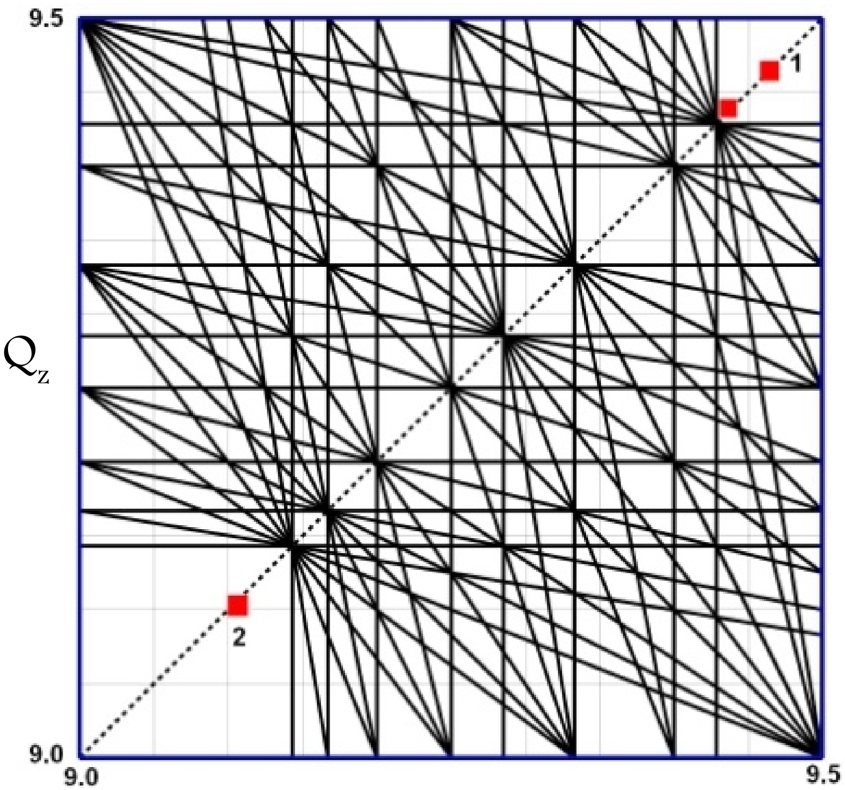
Synchrotron accelerators like Nuclotron and Booster(NICA) have a constant circular orbit (R=const), magnetic field is increasing during acceleration. Beam is accelerated at **RF resonator** section. During acceleration an ion beam is moving through periodic set of ion optic elements (**quadrupole lenses**).





Why it's important to measure Q?

Diagram of resonances (transverse motion) up to 7-th order (calculated for NICA)



Dipole errors lead to integer resonances, quadrupole errors lead to resonances at half-integer Q values, sextupole fields excite resonances at third-integer Q values and so on. Moreover, one has in general a coupling between horizontal and vertical betatron oscillations due to sextupoles or misalignment of magnet, skew quadrupole fields etc.

General resonance condition: $$nQ_x + mQ_z = l$$

(n, m, l – integer numbers; n,m – small).

The **working point** (Q_x,Q_z) has be chosen in a reasonable distance from the resonance lines. Optimizing and controlling the betatron tunes Q_x, Q_z improves the beam lifetime and can reduce beam loss during acceleration. For simplicity, the fractional part of the betatron tunes will also be denoted by Q_x and Q_z.

Q_x, Q_z – betatron tunes (number of betatron oscillation at one turn)

How to measure Q

A common method to measure the fractional part of the betatron tune is to excite transverse beam motion and to detect the transverse beam position over a number of successive turns N.

The fractional part of the betatron tune (Q_x or Q_z) can be calculated as the ratio of the betatron oscillation frequency (excited resonance oscillation) and the particle revolution frequency (can be obtained from Nuclotron RF system):

$$Q = f_\beta / f_{rev}$$

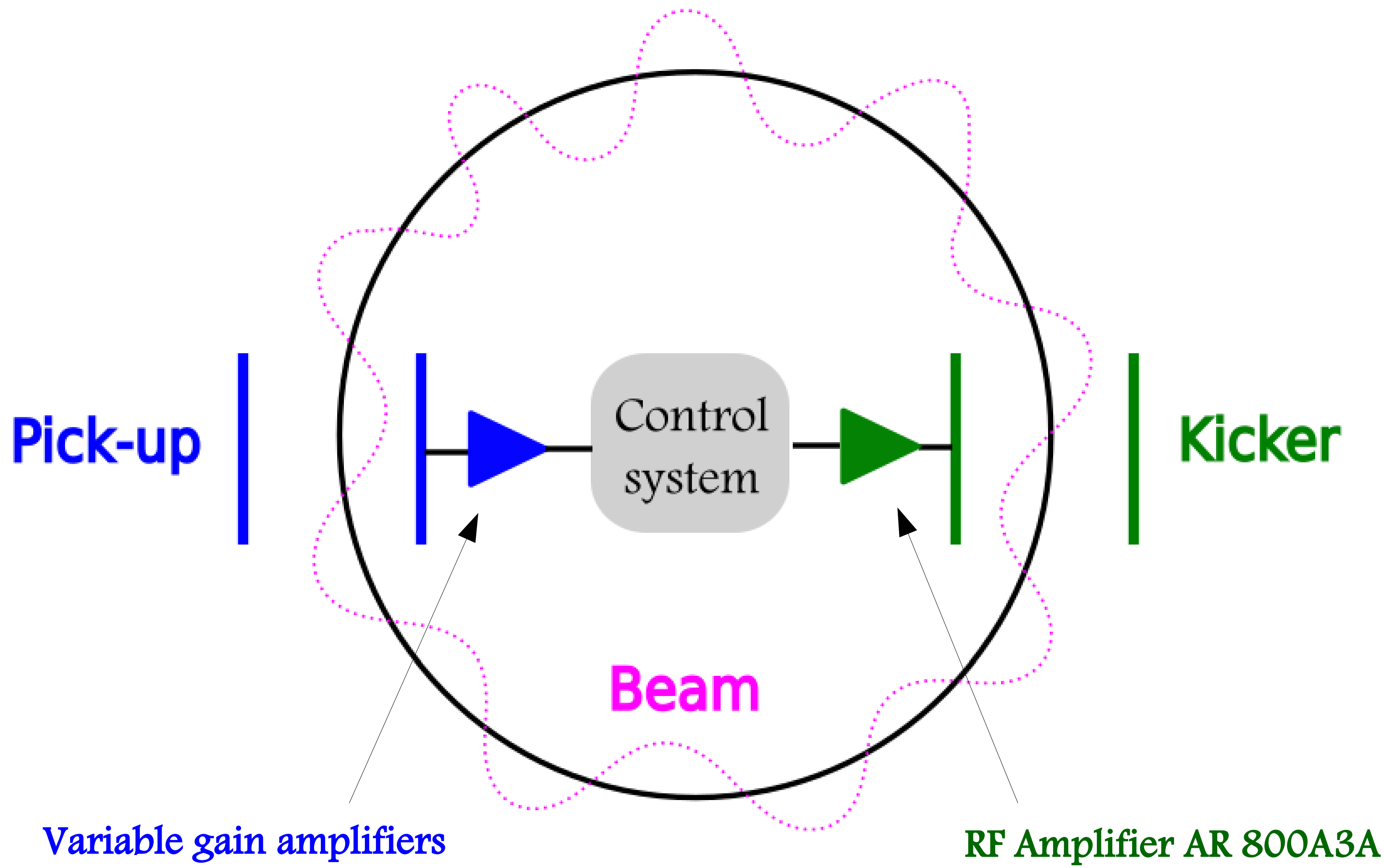
The excitation consists of white noise or a chirp - signal in which the frequency increases ('up-chirp') or decreases ('down-chirp') with time. The power density of the detected signal is computed via a Fast Fourier Transformation (**FFT**), and the betatron tunes are identified as the frequencies with the highest amplitude peak. To obtain a tune value with a resolution of 0.001 or better requires orbit data for about 1000 turns.

The frequency resolution of the FFT is the ratio of sampling rate to the size of the frame (by default 1024):

$$df = f_{samplig} / 1024$$

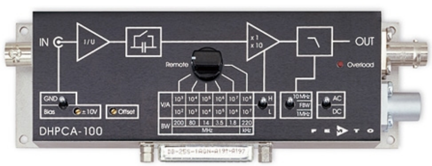
For example, with a sampling frequency of 10 MHz and a frame length of 8192 samples, the frequency resolution is approximately 1.22 kHz. The accuracy of the Fourier analysis can be further improved with data windowing. To effectively eliminate the spectral leekage (effect of spreading the spectrum) the Hamming window function was used because it has a minimal side-lobe level -42 dB.

Measurement system at Nuclotron



Control system

Variable gain amplifiers



FlexRIO
Digitizer
ADC 14 bit
input

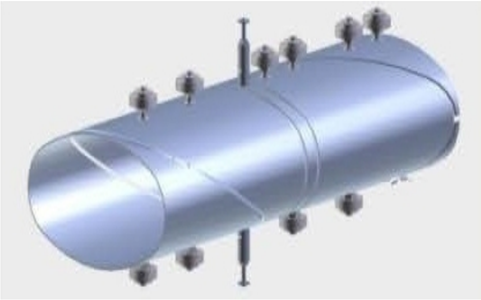
NI PXIe-1082 crate (PXI system)
with modules:

- <u>FlexRIO digitizer (developed at JINR)</u>
- Tegam Model 4040A differential amplifier 2x
- PXI-6733 High-Speed Analog Outputs
- NI PXIe-8135 2.3 GHz Quad-Core PXI Express Controller

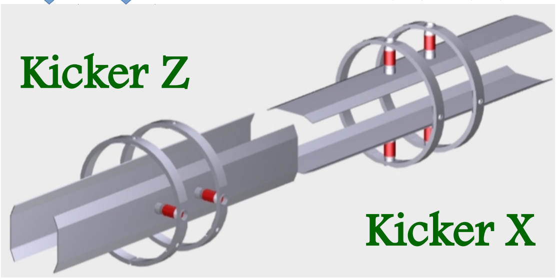
FlexRIO
Digitizer
DAC 16 bit
output

RF Amplifier AR 800A3A

Impedance transformers

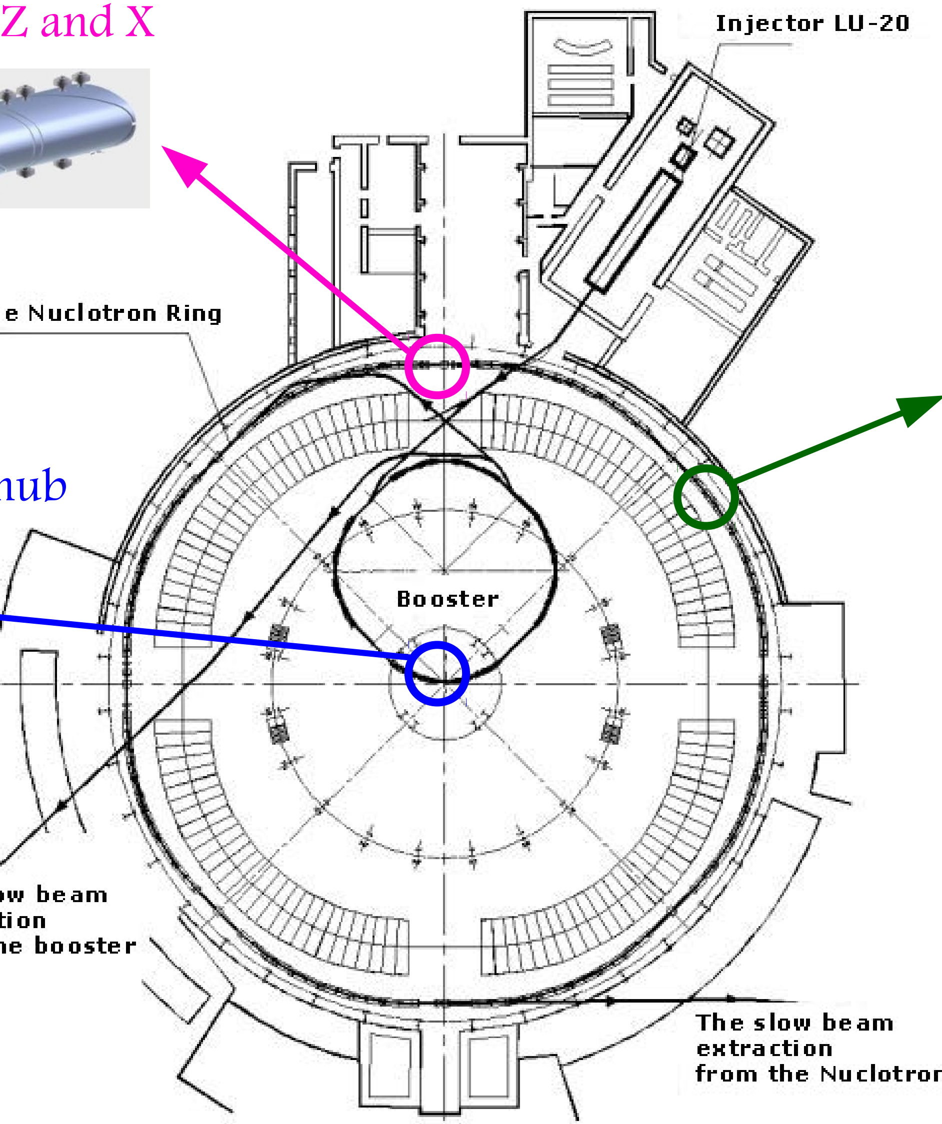


Pick-up electrodes X and Z



Measurement system layout

Pick-up Z and X

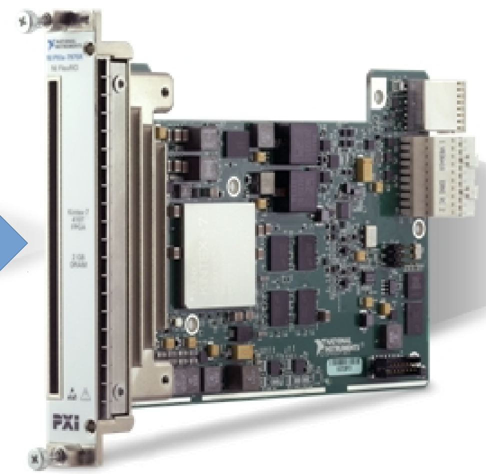


Kicker Z and X

Nuclotron control hub with PXI system

FlexRIO module and PXI system

FlexRIO Adapter Module

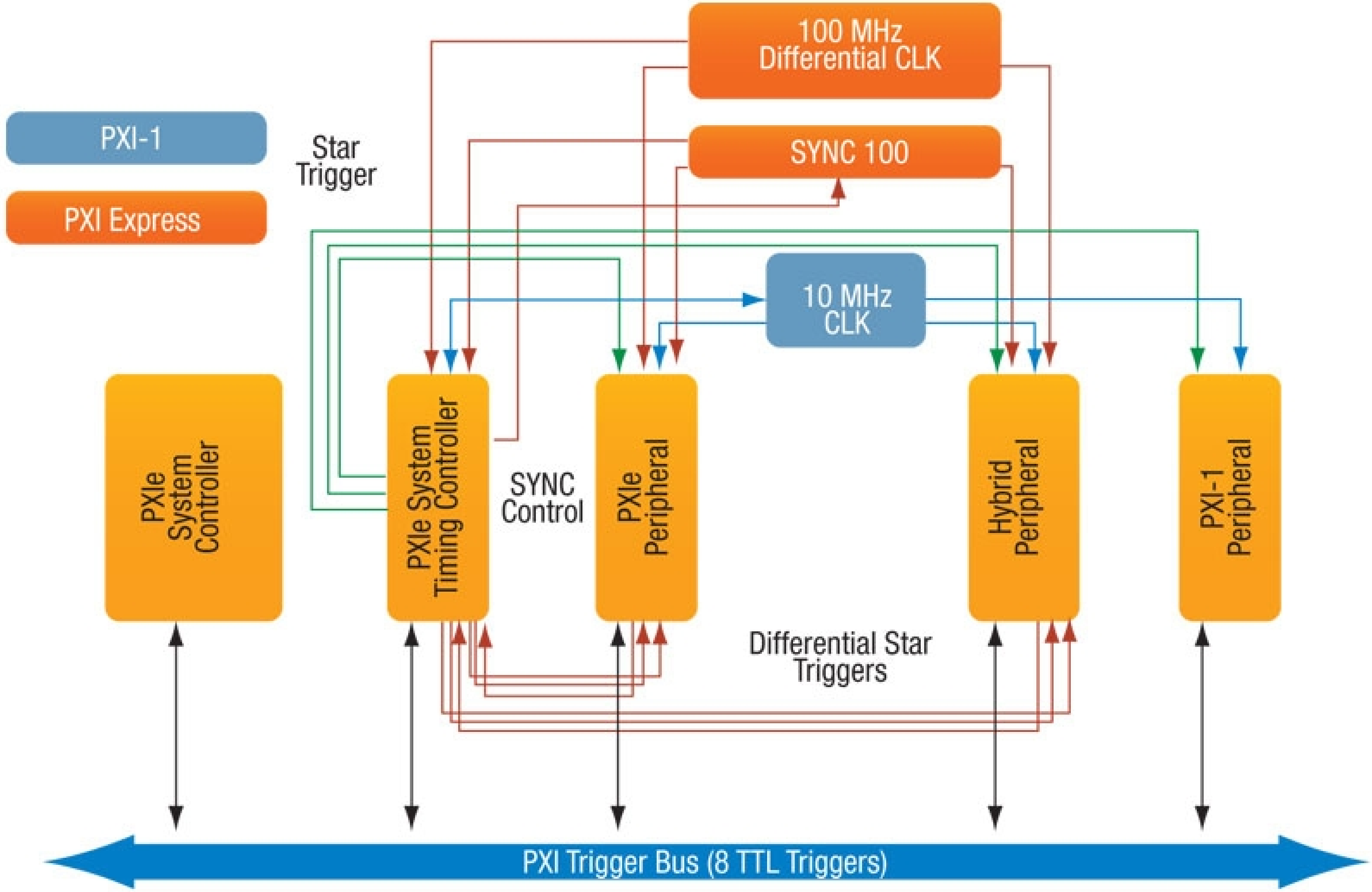


FlexRIO Module

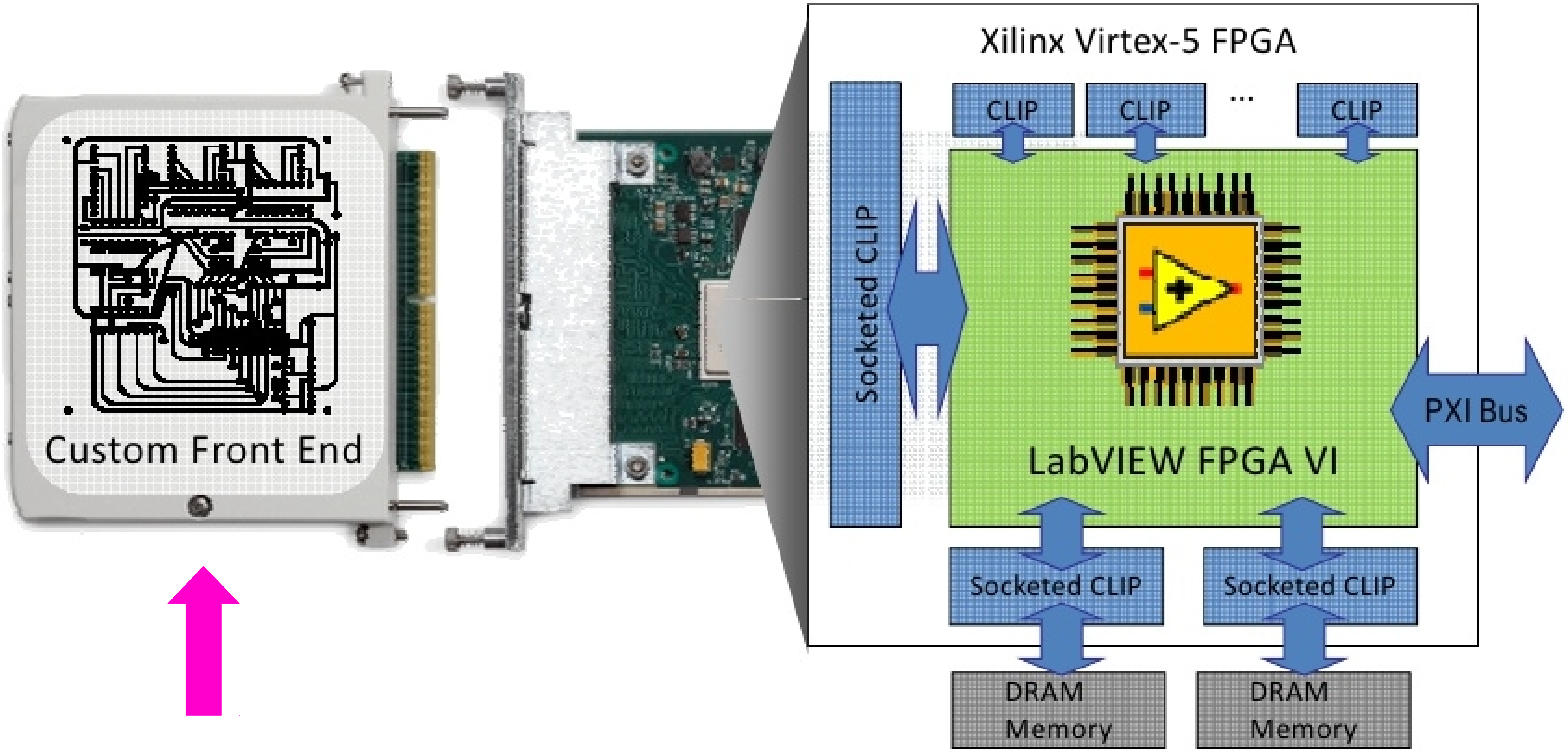
PXI System

Digitizer module, developed at VBLHEP

PXI control bus 100 MHz sync clock



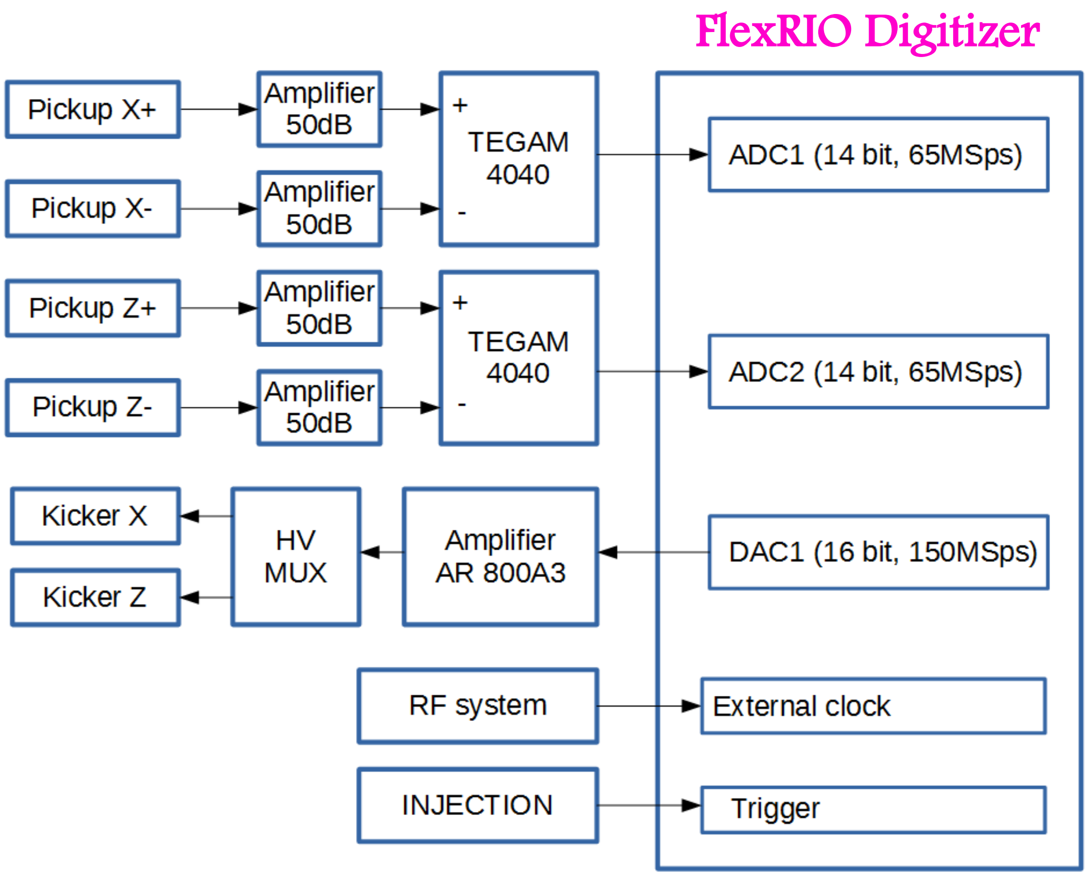
PXI custom module development

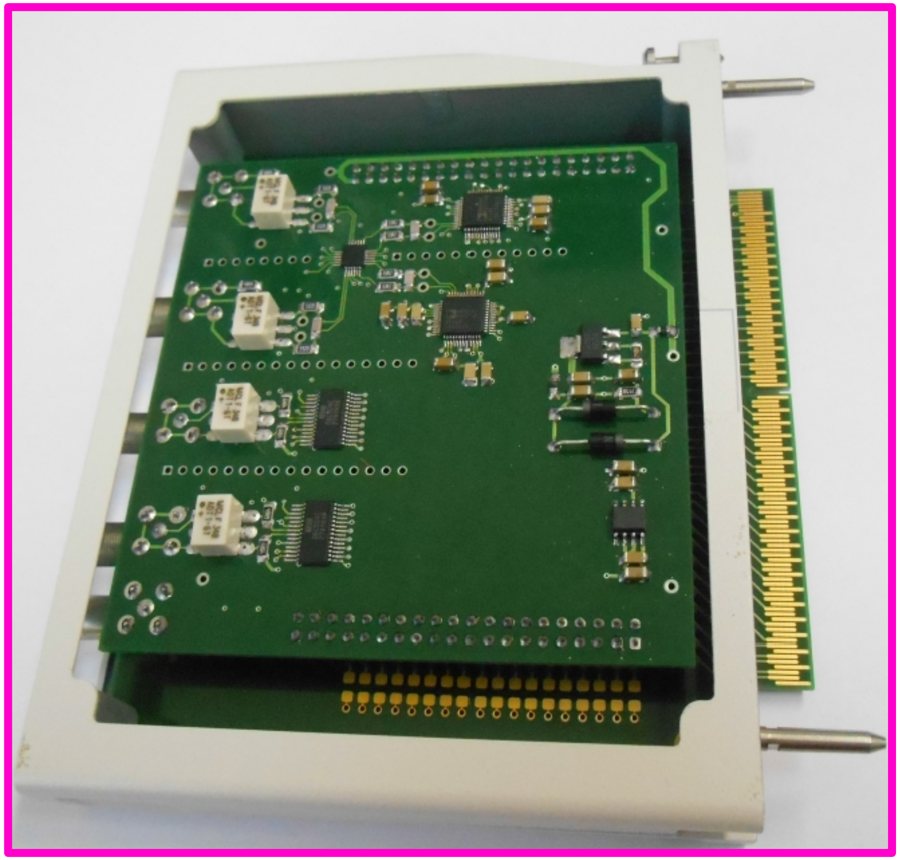


FlexRIO Digitizer module

JINR NI Vendor ID 0xAB66

PXI system: interconnection diagram



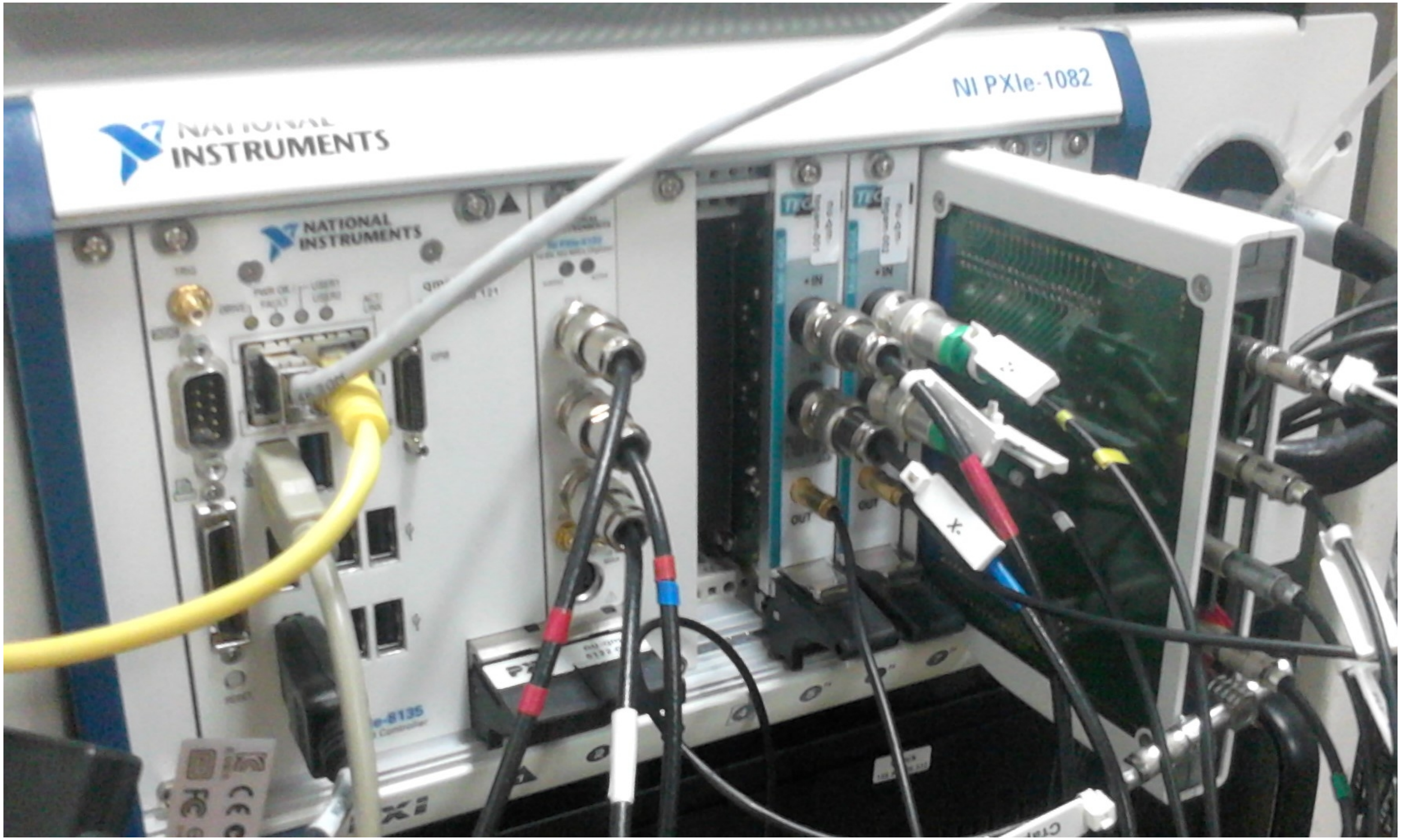


FlexRIO Digitizer

JINR NI Vendor ID 0xAB66

PXI system at Nuclotron control hub

PXI system at Nuclotron control hub



RF amplifier AR 800A3A at Nuclotron control hub

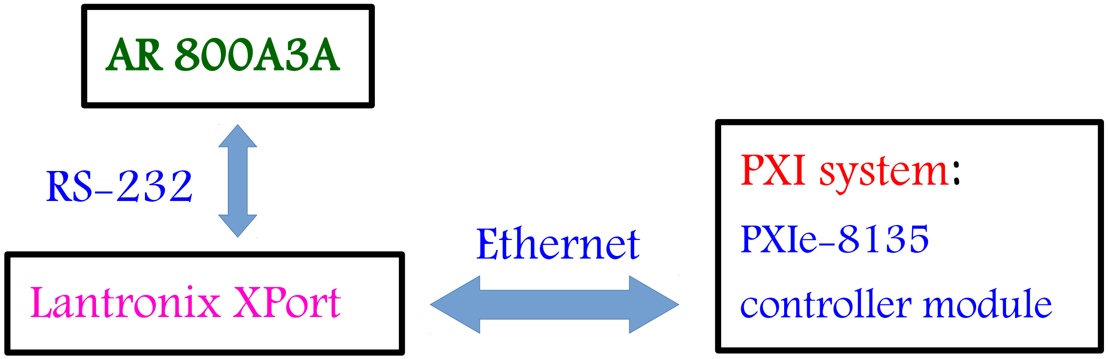
POWER OUTPUT: 700 watts, 10 kHz–2 MHz

INPUT IMPEDANCE : 50 ohms nominal

OUTPUT IMPEDANCE: 25, 50, 100, 150, 200, 400 ohms

MISMATCH TOLERANCE: 100% rated power without foldback up to 6:1 mismatch above which may limit to 400 watts reflected power. Will operate without damage or oscillation with any magnitude and phase of source and load impedance.

REMOTE CONTROL: IEEE-488/**RS-232**/USB, ability to remote control and power an external impedance transformer.



PXI system integration with **TANGO Controls**

Tango client application:
Nuclotron operator interface

Ethernet

PXI Express 1 GB/s

Communication and synchronization with other PXI modules

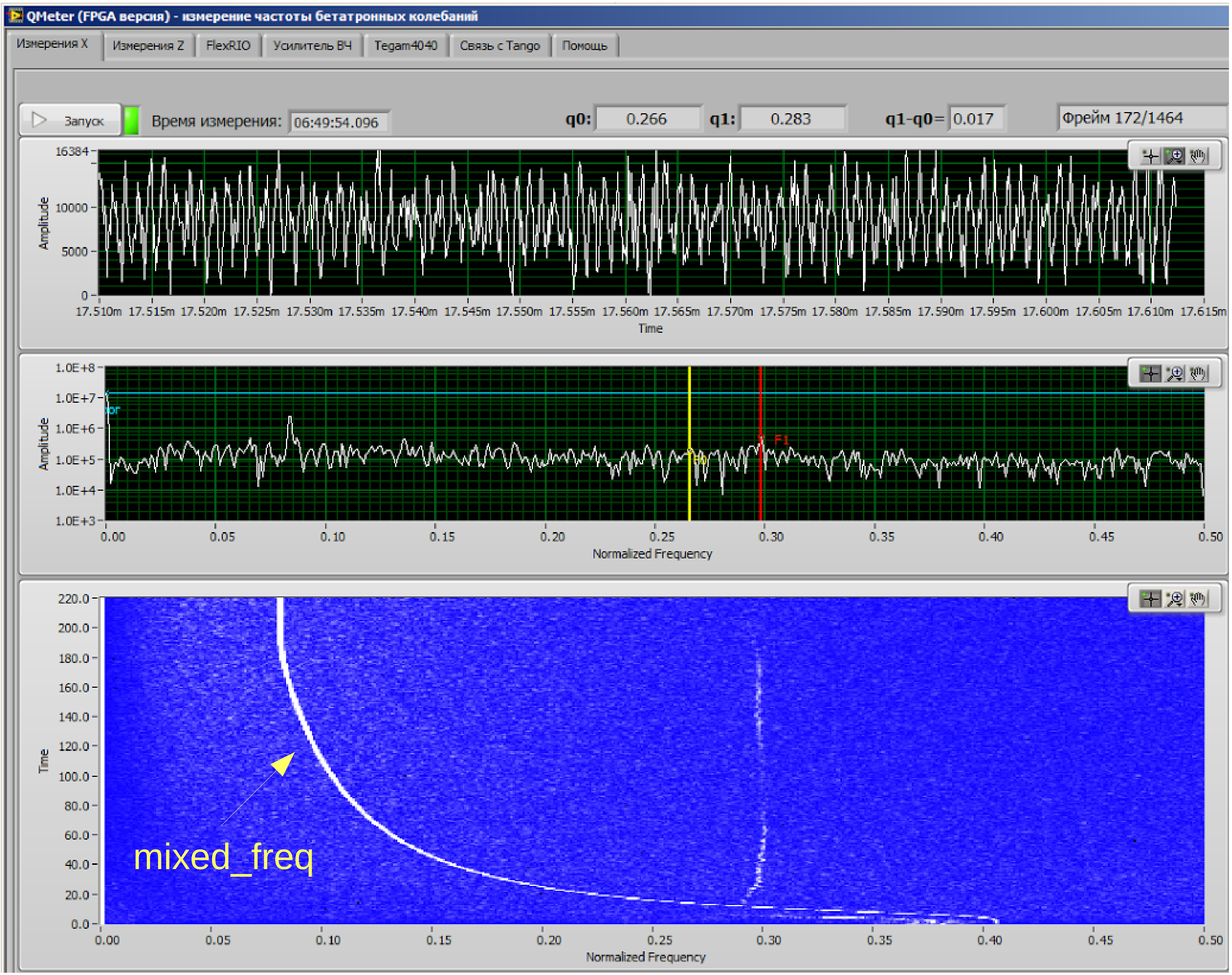
NI PXIe-8135

- 2.3 GHz quad-core Intel Core i7 processor
- 8 GB 1600 MHz DDR3 RAM
- USB, Gigabit Ethernet, RS-232
- Windows OS and drivers already installed

Tango Device Server for FlexRIO Digitizer ***LabView***

Tango Device Server for RF Amplifier AR 800A3a ***Python***

PXI control bus



Nuclotron operator interface:

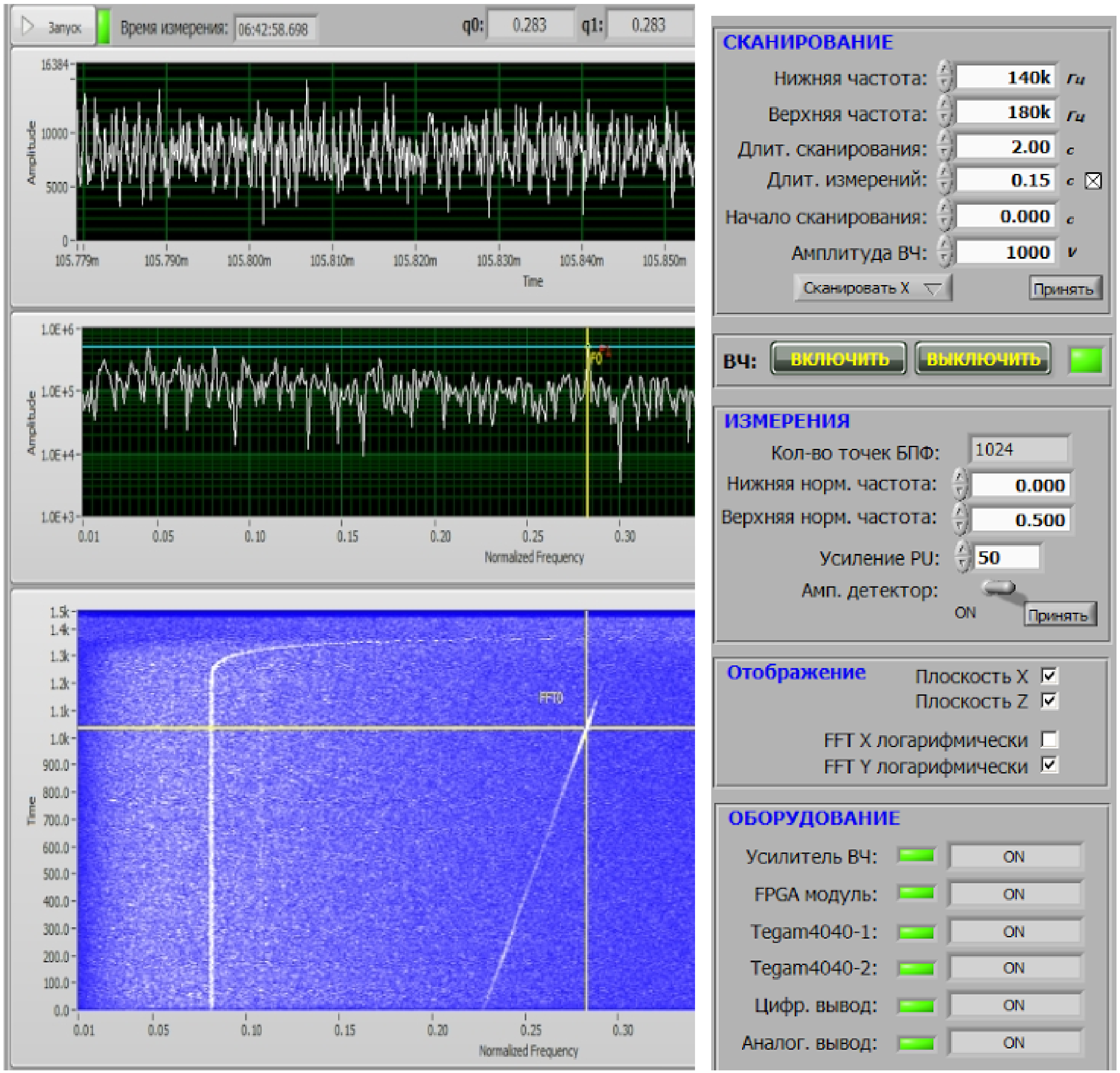
Q_x monitoring during beam acceleration

Chirp mode: excitation frequency increases from 140 to 180 kHz

Input signal mixed with frequency:

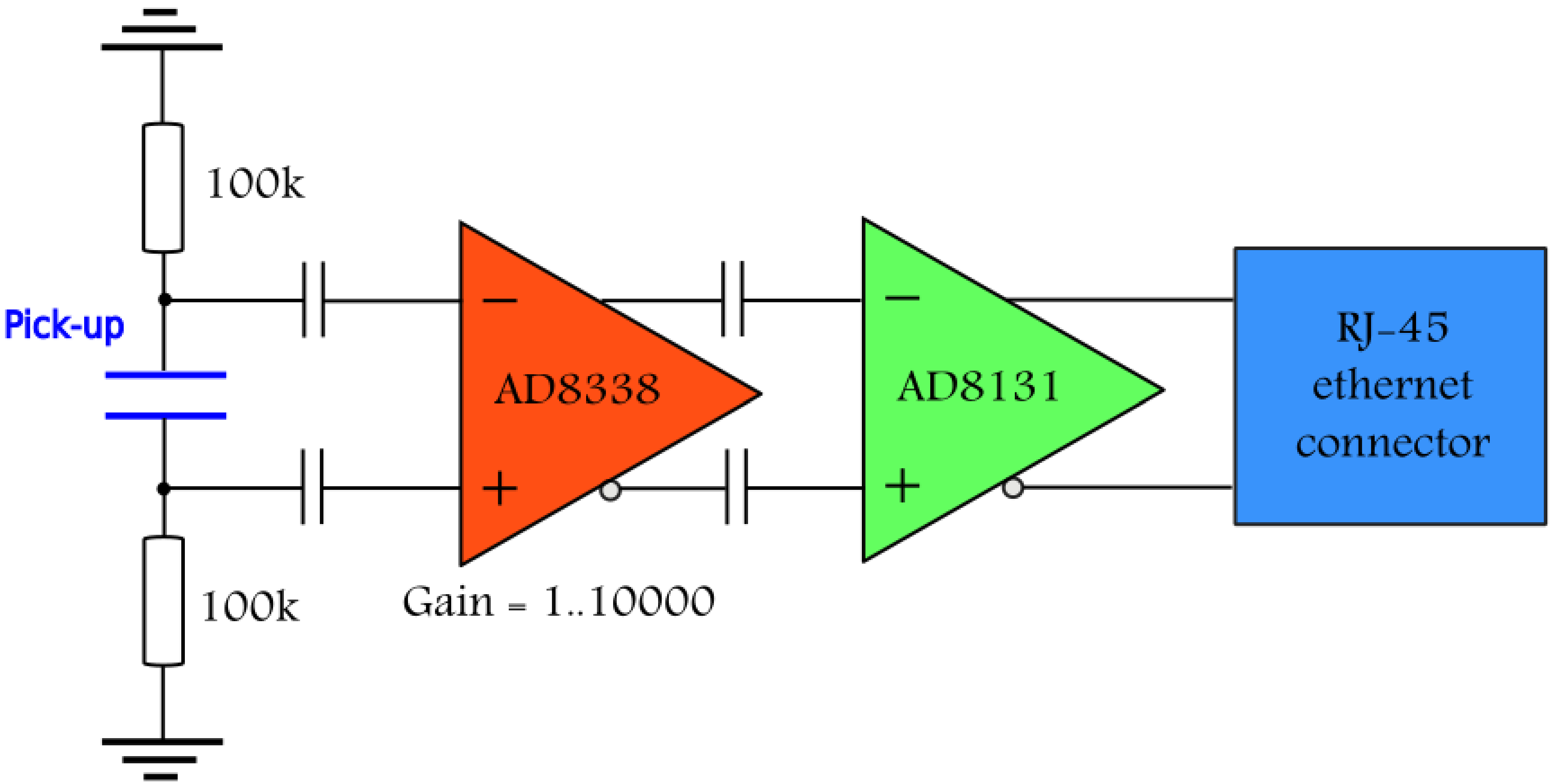
mixed_freq = 50kHz

ADC sampling frequency is proportional to signal from RF system


Запуск
Время измерения: 06:42:58.698
q0: 0.283
q1: 0.283
Amplitude
Time
Normalized Frequency
СКАНИРОВАНИЕ
Нижняя частота: 140k Гц
Верхняя частота: 180k Гц
Длит. сканирования: 2.00 с
Длит. измерений: 0.15 с
Начало сканирования: 0.000 с
Амплитуда ВЧ: 1000 V
Сканировать X
Принять
ВЧ: ВКЛЮЧИТЬ ВЫКЛЮЧИТЬ
ИЗМЕРЕНИЯ
Кол-во точек БПФ: 1024
Нижняя норм. частота: 0.000
Верхняя норм. частота: 0.500
Усиление PU: 50
Амп. детектор:
ON
Принять
Отображение
Плоскость X
Плоскость Z
FFT X логарифмически
FFT Y логарифмически
ОБОРУДОВАНИЕ
Усилитель ВЧ: ON
FPGA модуль: ON
Tegam4040-1: ON
Tegam4040-2: ON
Цифр. вывод: ON
Аналог. вывод: ON

$Q_x = 0.283$

Further improvements: Differential amplifier

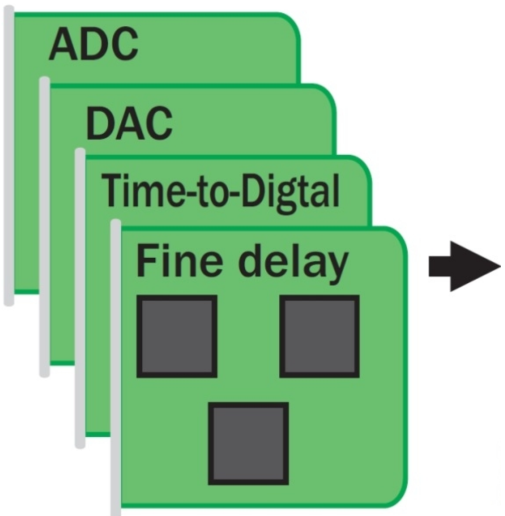


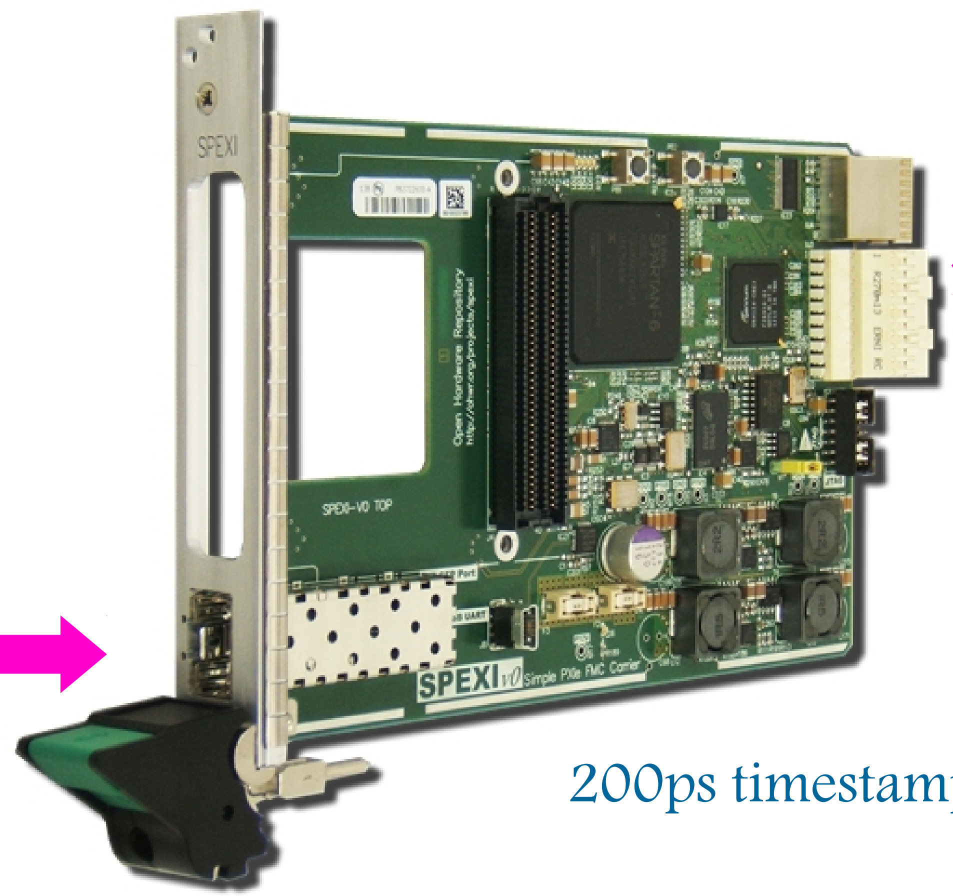
Further improvements: new digitizer module

- Two AD7960, 18-Bit, 5 MSPS PulSAR differential ADC with LVDS interface (250 Mhz clock frequency)
- One DAC904, 14-Bit, 165MSPS DAC
- TDC-GP22, measurement range 500 ns to 4 ms, 90 ps resolution

Digitizer with 14-bit ADC will work at a constant sampling frequency, 40 MHz. A new digitizer with 18-bit ADC will be sampled at frequency, proportional to measured (with Acam TDC) revolution frequency. Simultaneous measurement using two modules can be a test for measurement system – Q values should be the same.

White Rabbit PXI module for synchronization



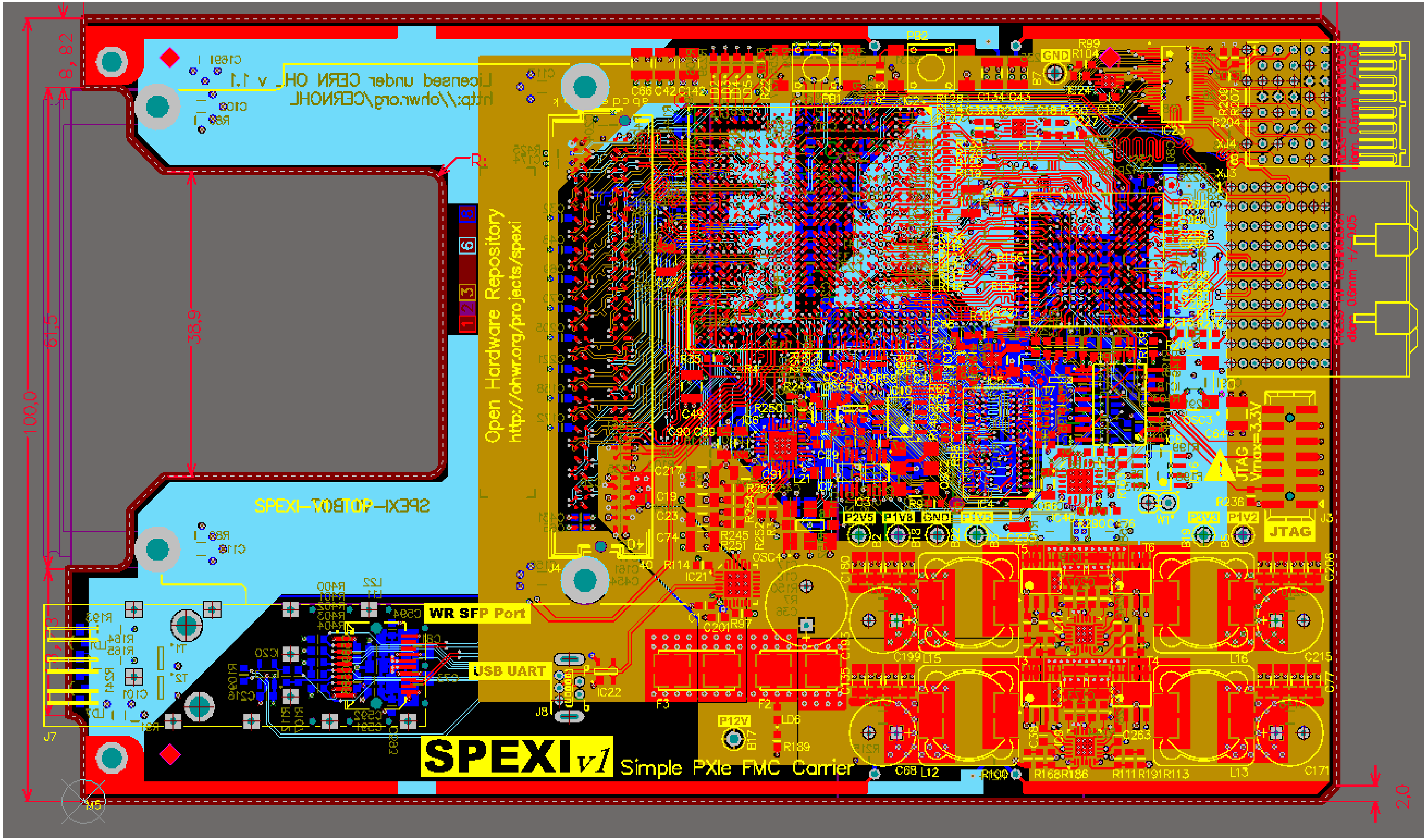


PXI bus
1 GB/s

White Rabbit optic fiber
2.5 Gbps

200ps timestamp accuracy

SPEXI module developed at CERN is Open Hardware. Labview drivers are available for the FMC DEL 1ns 4channel delay and FMC TDC 1ns 5channel TDC mezzanine cards.


Open Hardware Repository
http://ohwr.org/projects/spexi
WR SFP Port
USB UART
JTAG
Vmax=3.3V
SPEXI v1
Simple PXIe FMC Carrier

Thank you