Console Electronics

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ISMRM
21st Annual Meeting & Exhibition
Salt Lake City, Utah, USA
20 – 26 April 2013
"Discovery, Innovation & Application – Advancing MR for Improved Health"

Declaration of Relevant Financial Interests or Relationships

Speaker Name: Katsumi Kose, Ph.D.

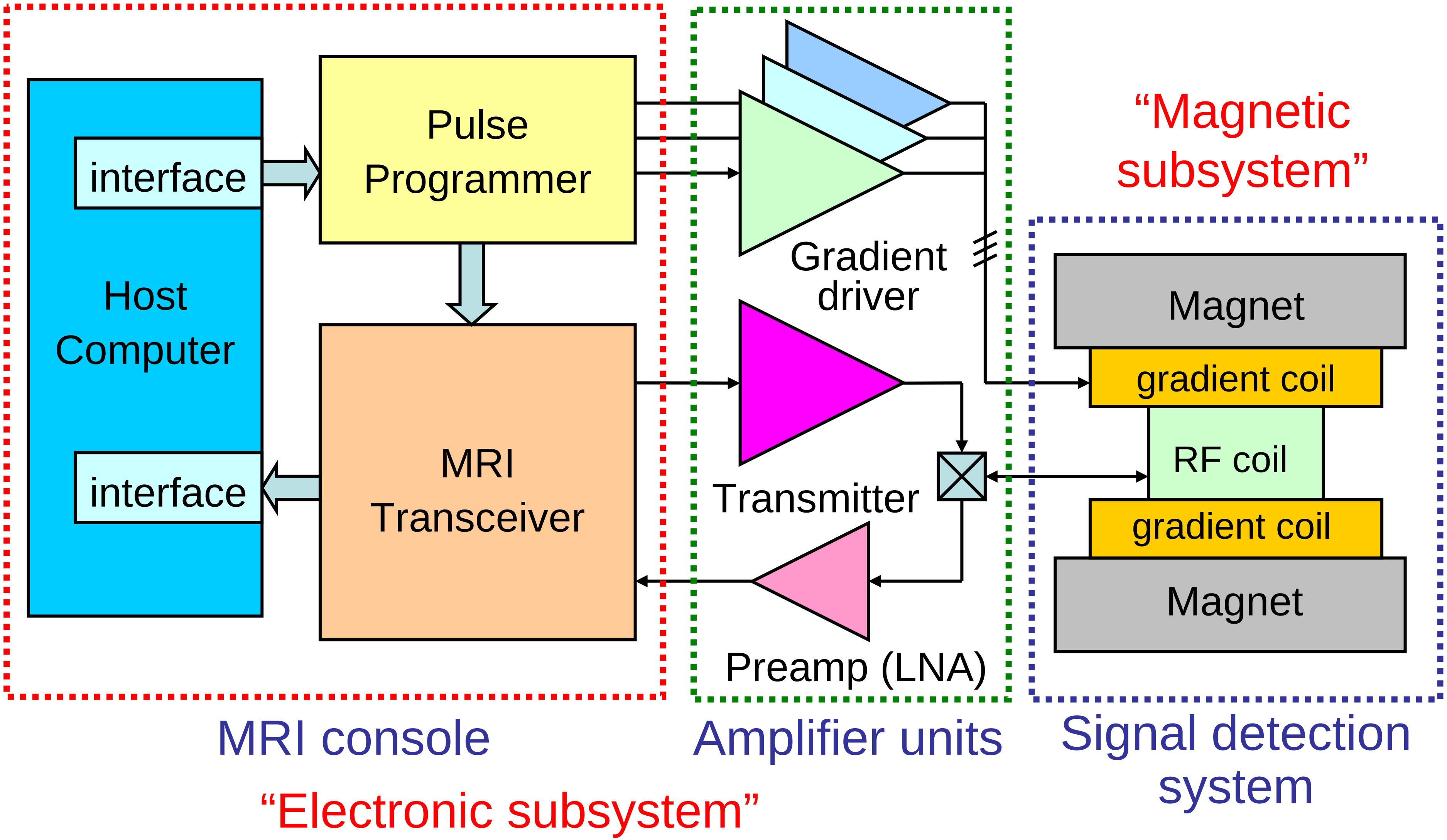
I have the following relevant financial interest or relationship to disclose with regard to the subject matter of this presentation:

Company name: MRTechnology, Tsukuba, Japan
Type of relationship: Advisor

Outline

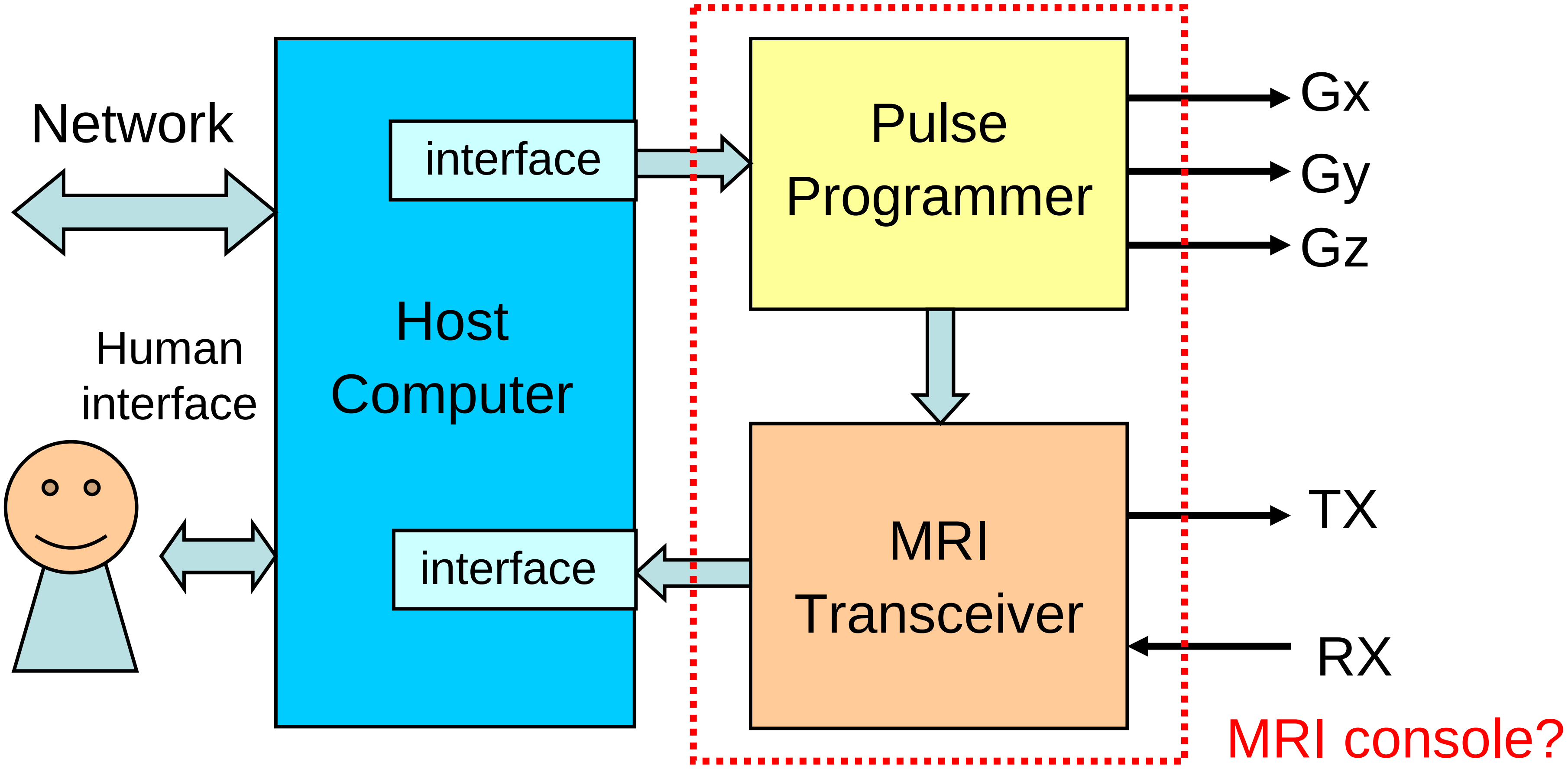
1. What is the MRI Console?
2. Host computer and interface
3. Pulse programmer
4. MRI transceiver
5. Experiments : Analog vs Digital
6. Conclusion

What is the MRI console?



The MRI Console is the **core part** of the MRI electronics.

What is the MRI console?



The MRI console has three main components: the host computer, the pulse programmer, and the MRI transceiver. The pulse programmer and the MRI transceiver are often integrated to a single board or a single unit and called the MRI console.

What is the MRI console?

Various MRI consoles (usually without host computer) are commercially available. However, the detail of these systems are not opened, so I will show the detail structure of the MRI consoles based on **my experience**.

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Host computer

The host computer plays three important roles:

1. Controlling the time-critical pulse programmer
2. Acquiring a large quantity of MR signal data
3. Reconstructing MR images (quickly)

Host computer

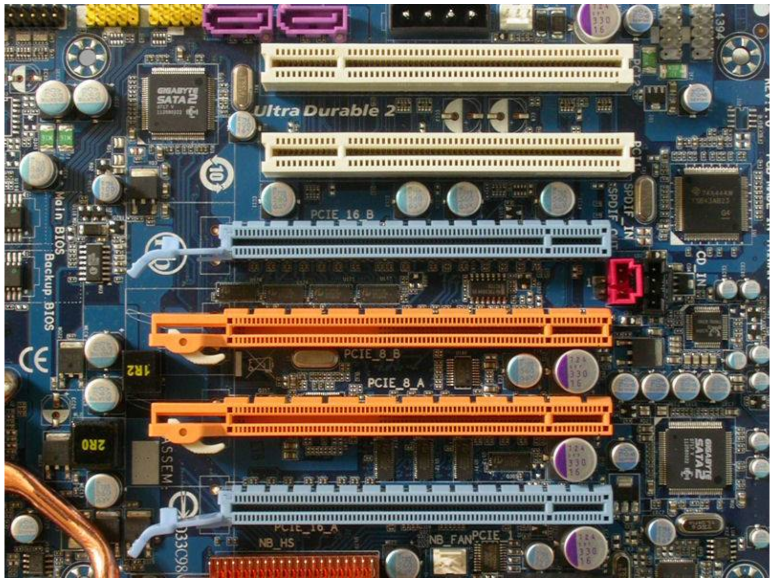
In the early days of MRI development, minicomputers were widely used. Then, workstations replaced the minicomputers.

With the development of high-performance personal computers (PCs), PC hosts are now widely used with Windows, UNIX/Linux, or specialized real-time operating systems.

Minicomputer → Workstation → High-performance PC

Interfacing to the MRI system

Interfacing the host computers to the pulse programmer and the MRI transceiver is a **critical issue**. The choice of either the **internal bus** (PCI/PCIe) or **external interface** (USB, Ethernet, or other high-speed interface) critically affects the architecture and overall performance of the MRI console.



Internal bus: PCI/PCIe

USB

Ethernet

External interface

Interfacing to the MRI system

Internal bus (PCI/PCIe…) interface

Advantages:

Fast data transfer (PCI:133 MB/s, PCIe: 8 GB/s)

No protocol overhead

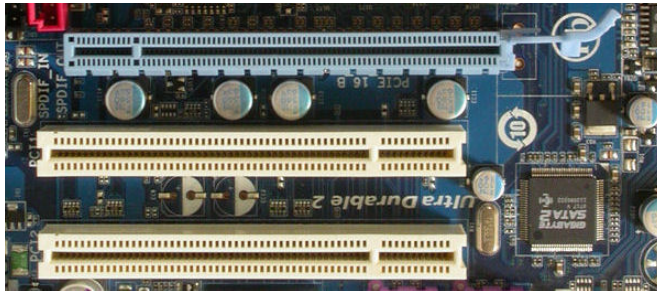
Faster data-transfer than external interface

Disadvantages:

Commercially available boards are limited

Customized device driver is required

Cannot be used with a notebook (or compact) PC



Interfacing to the MRI system

External interface (USB, Ethernet, wireless)

Advantages:

Any computer system can be connected

Customized device driver is not required

Disadvantages:

System overhead is substantial (depends on software!)

Programming flexibility is limited

Slower data-transfer than internal bus (PCI, PCIe) connection

(USB3.0 and Gigabit Ethernet is very fast ….)

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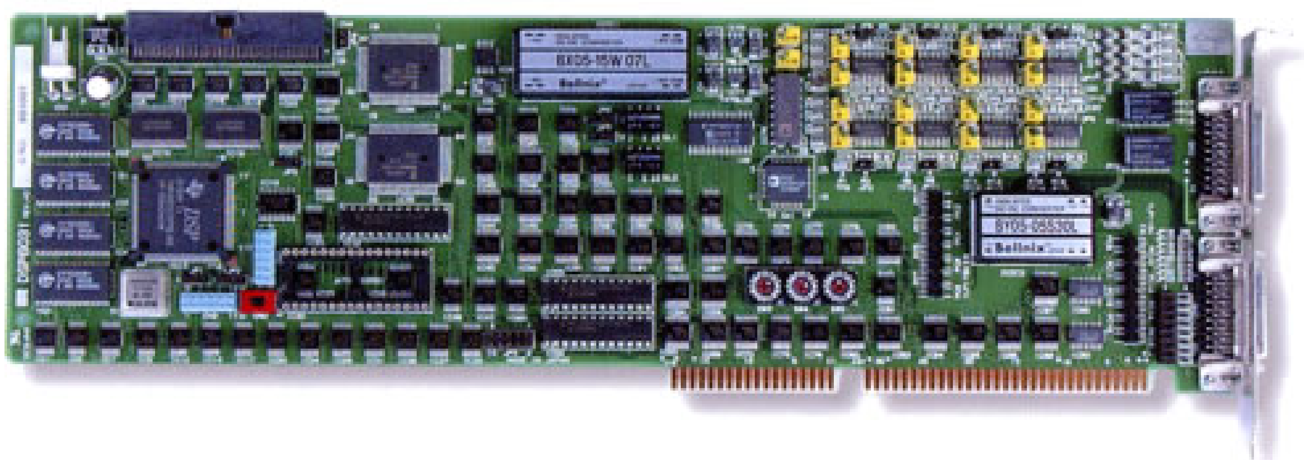
Pulse programmer

The pulse programmer is the core unit of the MRI console. It must output sequences of long control words (64~256 bits : separable) in the time unit of 10 ns – 1 μs with no time jitter, and update them for every repetition time (>1 ms).



Single board MRI pulse programmer (1997)

Pulse programmer

The pulse programmer must supply

→ 3CH gradient waveforms

→ (time-varying) shim currents

→ arbitrary RF pulse shapes in both amplitude and phase

→ transmitter gate pulses

→ data-acquisition triggers or clocks

→ other timing-control signals: 64 ~ 256 bits in total

Single chip MRI pulse programmer (2006)

Pulse programmer

Various approaches to PPG design have been reported by many research groups. They are

1. Microprocessor

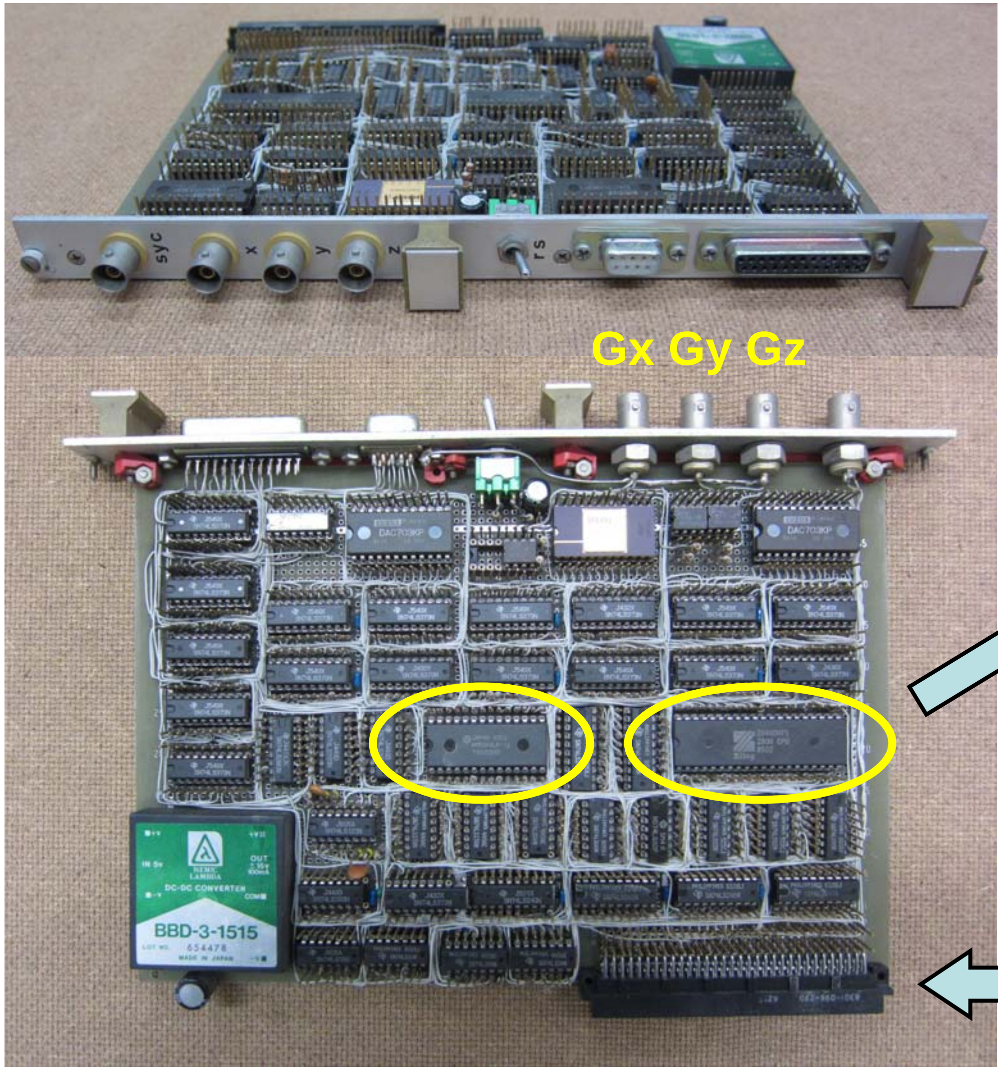
2. DSP (digital signal processor)

3. FPGA (field programmable gate array)

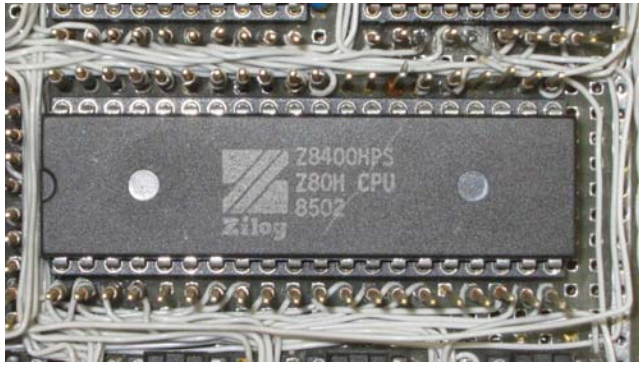
4. PC with a large buffer memory

Pulse programmer (example)

PPG with a Z80 microprocessor (1983, 1986(VME))



Z80 (4MHz clock) with a static memory chip

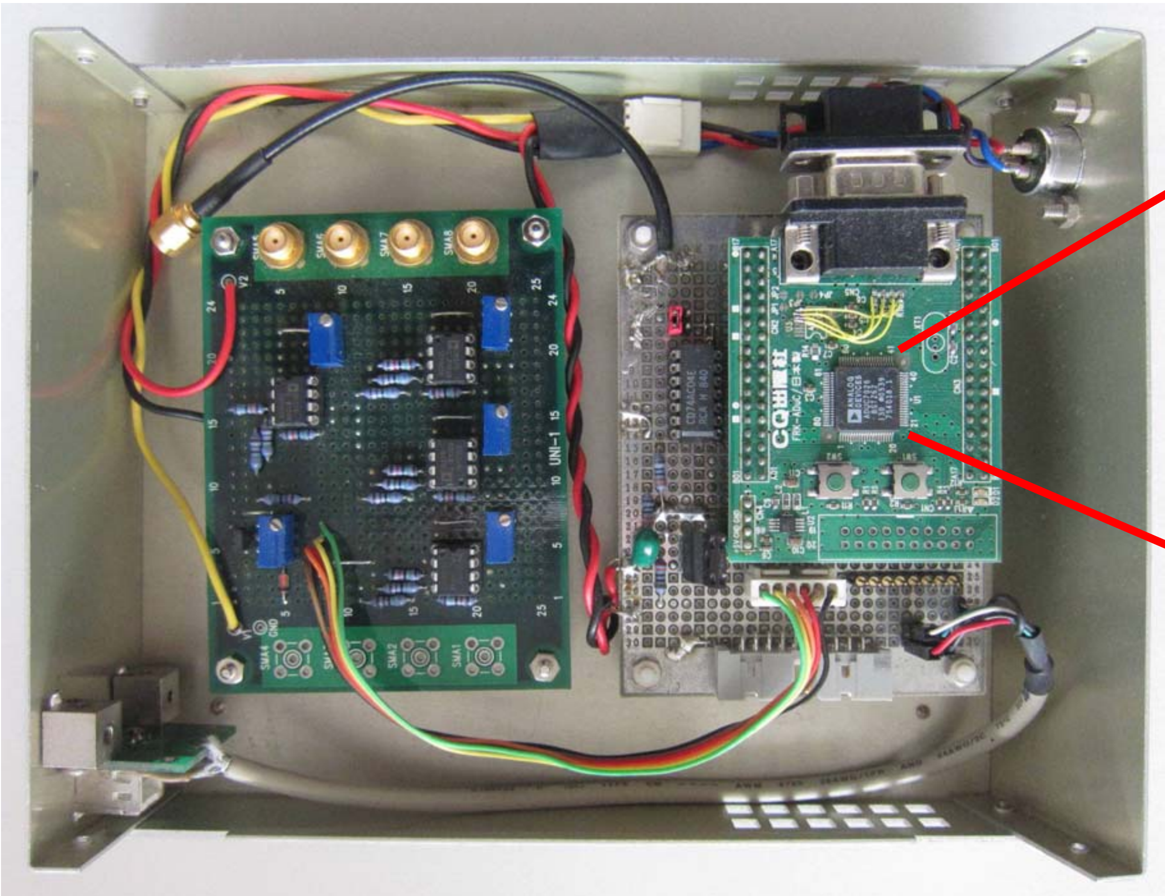


16-bit word can be output every 100 μs, in the unit of 20 μs.

VME bus

Pulse programmer (example)

PPG with an ARM7 microcontroller (2006)



USB

One-chip MRI PPG!

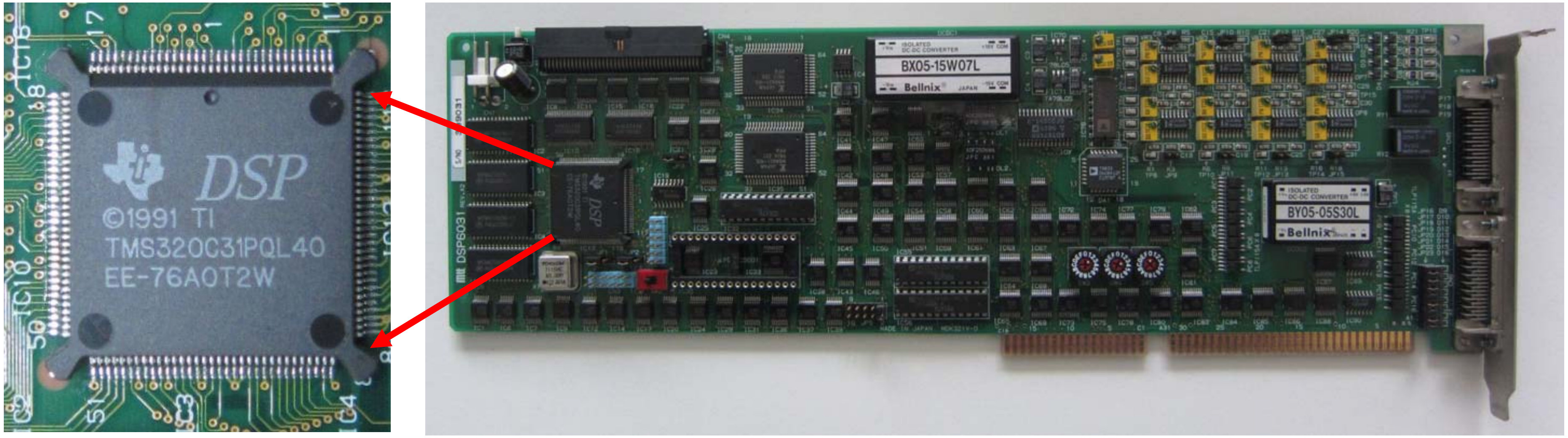
32-bit word can be output every 9 μs, in the unit of 100 ns.

Single-chip pulse programmer for magnetic resonance imaging using a 32-bit microcontroller. S. Handa, T. Domalain, K. Kose, Rev. Sci. Instrum 78, 084705 (2007).

Pulse programmer (example)

DSP (digital signal processor) (1997)

One-board MRI PPG! (commercially available)

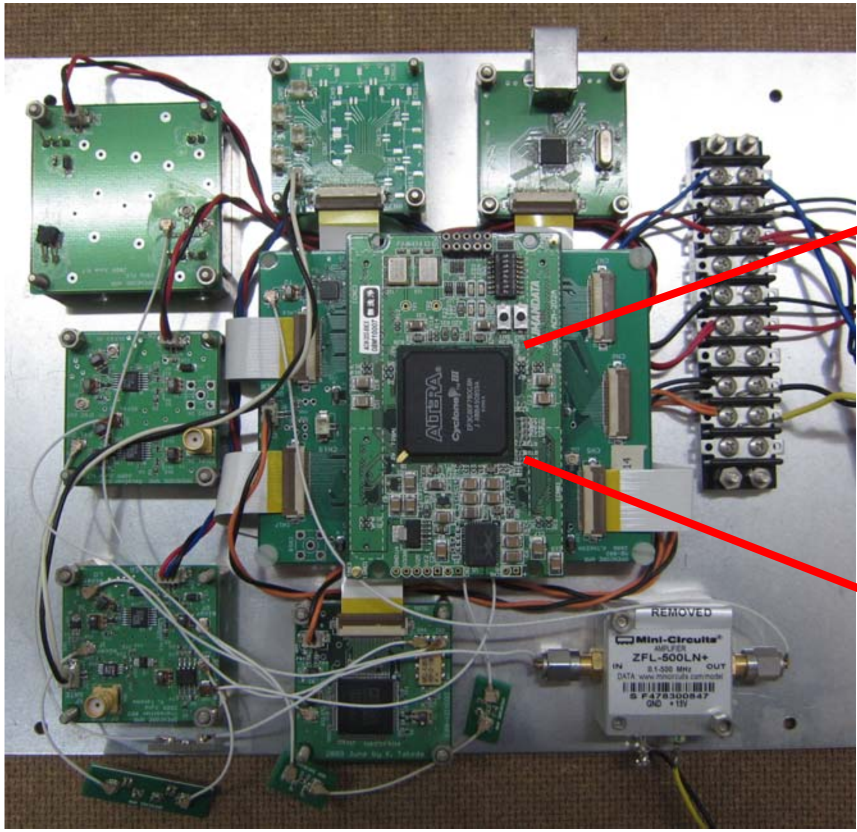


32-bit word can be output every 3.7 μs, in the unit of 100 ns.

Development of a flexible pulse programmer for MRI using a commercial digital signal processor board. K. Kose, T. Haishi,
Spatially Resolved Magnetic Resonance, Edited by P. Blumler,
B. Bluemich, R. Botto, E. Fukushima, WILEY-VCH, 703-709 (1998).

Pulse programmer (example)

FPGA (field programmable gate array) (2007)



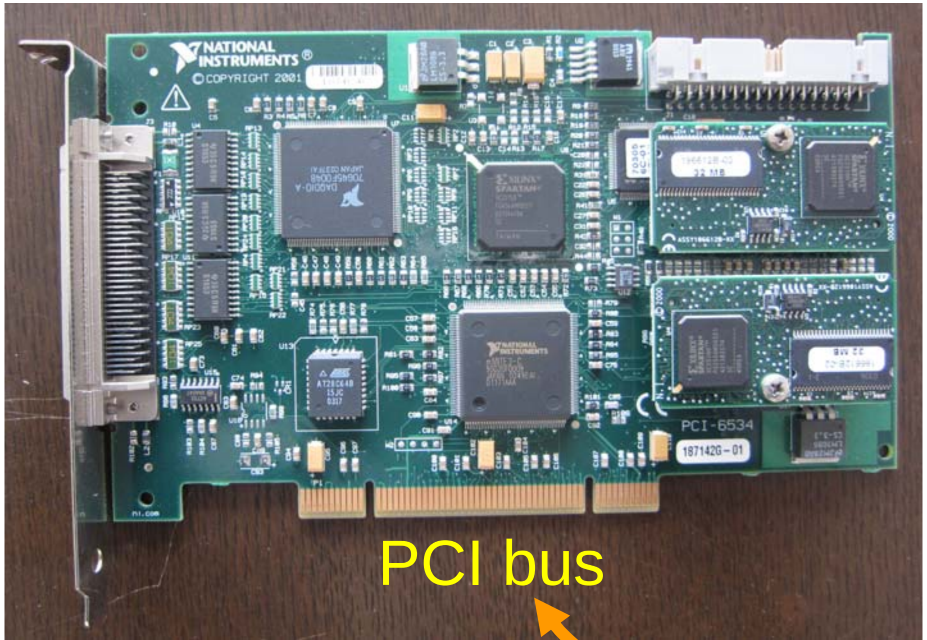
64-bit word can be output in the time unit of 10 ns.

OPENCORE NMR: Open-source core modules for implementing and integrated FPGA-based NMR spectrometer
Kazuyuki Takeda, J. Magn. Reson. 192, 218-229 (2008). **Kyoto University**

Pulse programmer (example)

Windows PC with a large buffer memory (2012)

Digital Transceiver

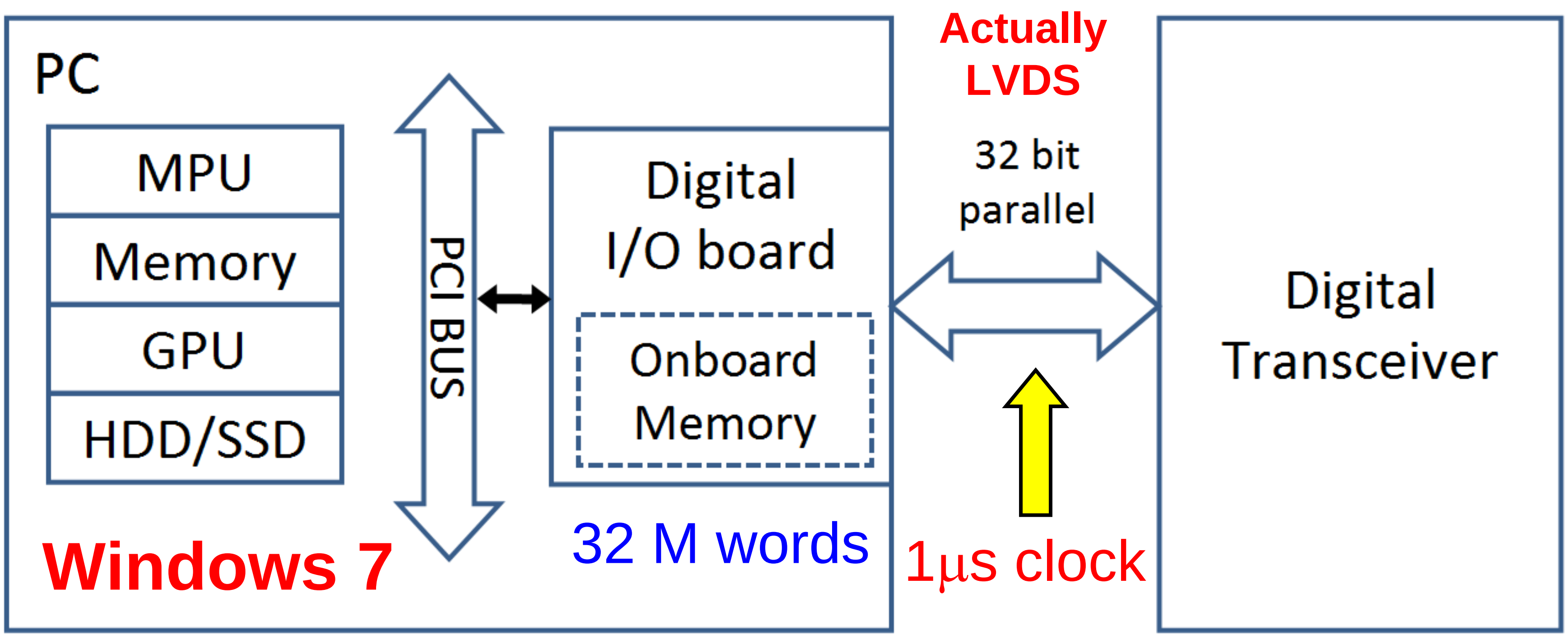


128-bit word can be output every 1 μs, in the unit of 1 μs.

Development of a pulse programmer for magnetic resonance imaging using a personal computer and a high-speed digital input–output board
S. Hashimoto, K. Kose, T. Haishi, Rev. Sci. Instrum 83, 053702 (2012).

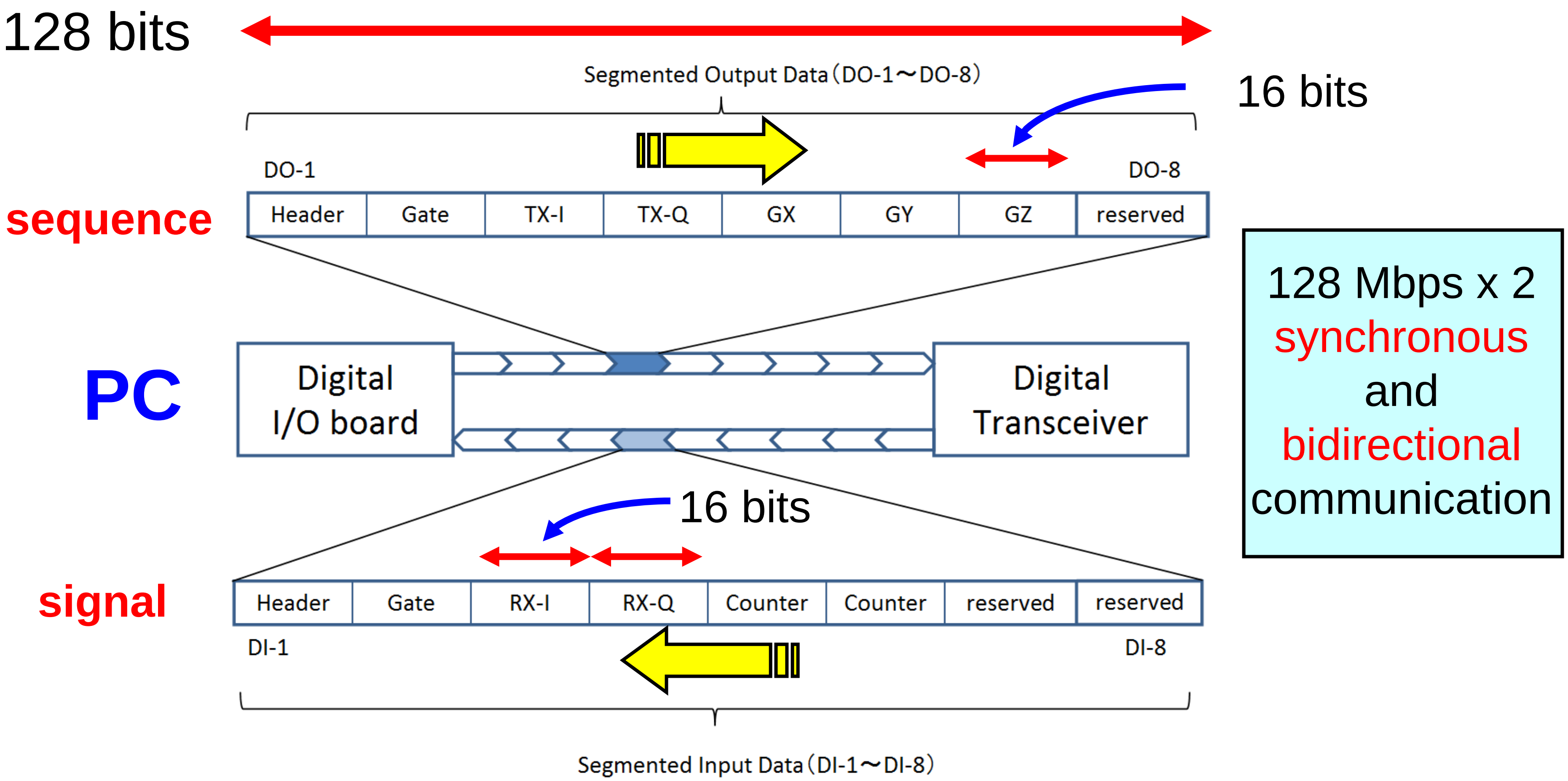
Pulse programmer (example)

PC with a large buffer memory (2012)



Overhead of the Windows 7 operating system is buffered using a large buffer memory (32 M words : buffer for 2 second data for TX/RX), which enables generation of **time-critical** pulse sequences (x Windows updates).

Pulse programmer (example)



The pulse sequence data and MRI signal data are **synchronously** transferred using a 1 MHz clock. At present, **16 bits data** are used for I/Q signal, the **dynamic range** is limited by this word length, which can be easily expanded to 32 bit word.

Pulse programmer (example)

The advantages of the PC pulse programmer are

(1) The host PC and the pulse programmer are integrated into one computer, which simplify the system structure and programming

(2) Low cost PC memory can be used for large pulse sequence data (gradient shape memory)

(3) No special hardware is required except the commercially available I/O board with large buffer memory

The 1 μs time-resolution may limit some solid-state MRI applications or frequency-offset fine phase modulation and so on, but most MRI applications can be implemented.

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MRI Transceiver

The MRI transceivers can be divided into analog and digital transceivers. Analog MRI transceivers were exclusively used in the early MRI systems, and even now, widely used. Because the structure of the analog RF transceiver is simple and relatively easy to understand, we should learn about the analog transceivers before considering the digital transceivers.

Double balanced mixer

Active mixer

FPGA

Analog transceiver (**linear device**)

Digital transceiver (**logic device**)

MRI Transceiver

The major difference between the analog and digital transceivers is the **conversion frequency** used in the AD converter and the DA converter.

For the analog transceiver, the conversion frequency is around the Nyquist frequency of the MRI signal (**up to several 100 kHz**) in the rotating frame.

For the digital transceiver, the conversion frequency is **several tens of MHz**, and modulation and demodulation of the RF signal are performed digitally, or numerically. Then, **phase noise** associated with the signal detection is not present.

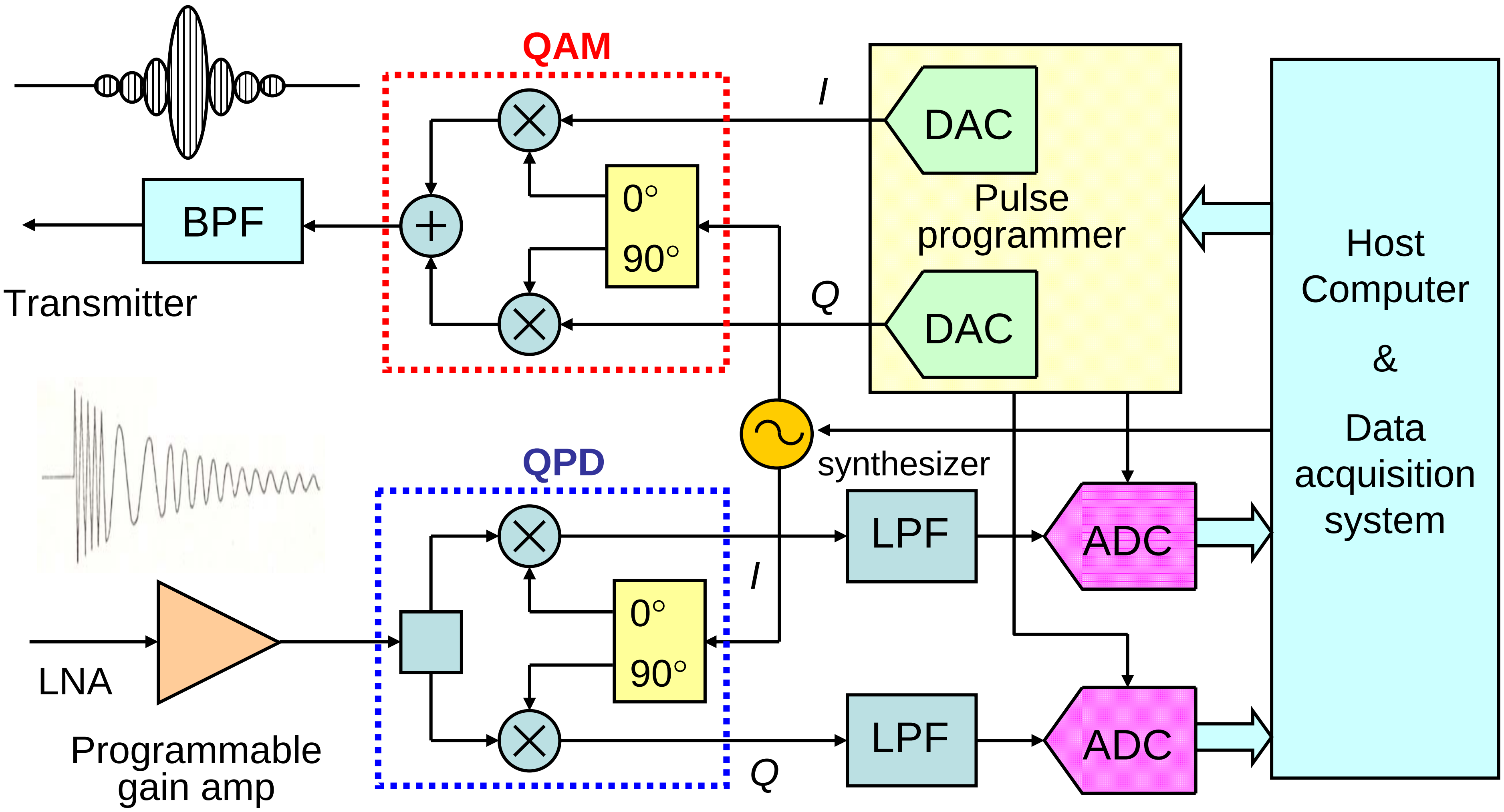
Analog

14 bit 1 MSPS : base band sampling

Digital

16 bit 105 MSPS : IF or RF sampling

Analog transceiver

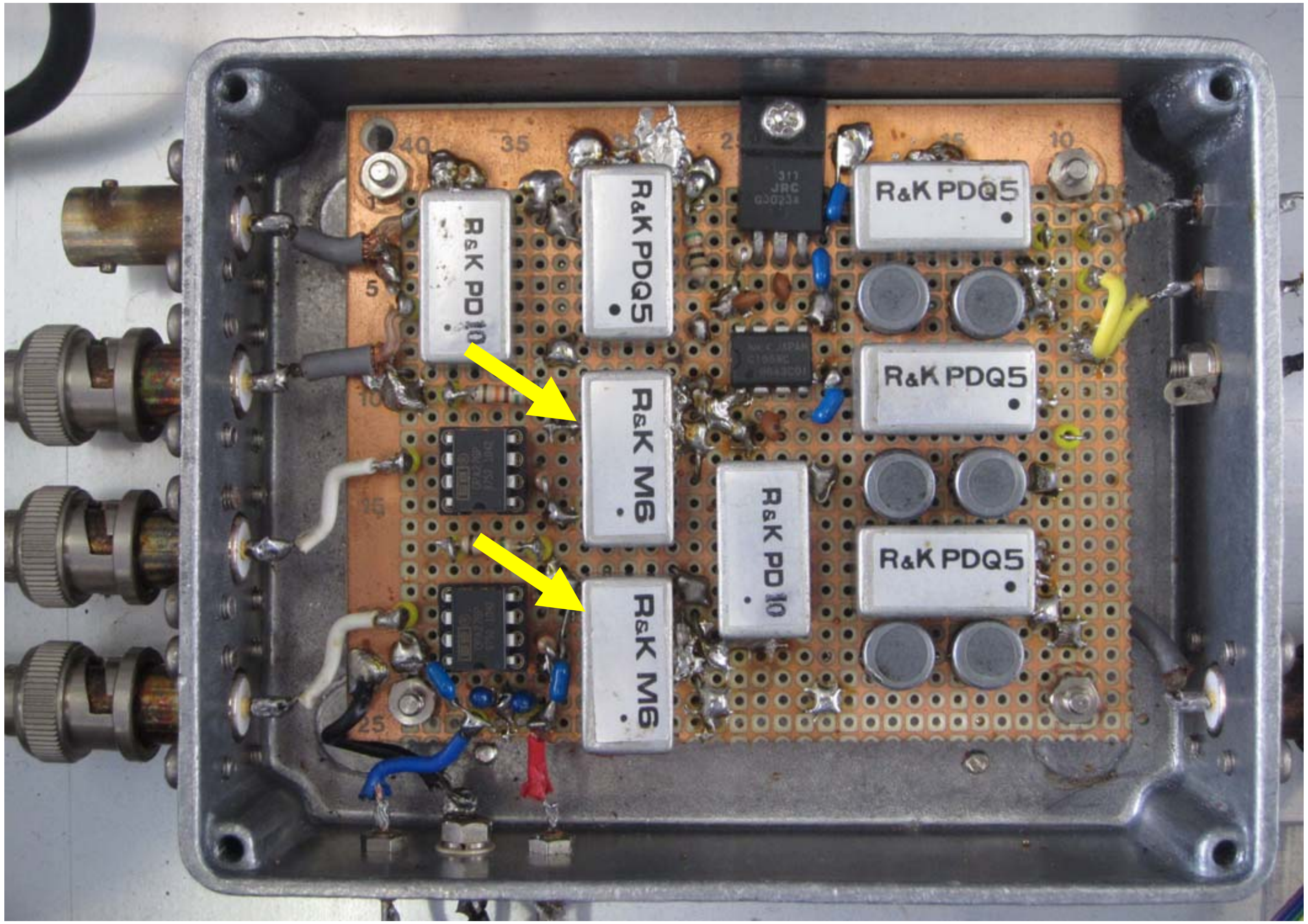


Base band sampling

QAM : Quadrature Amplitude Modulator

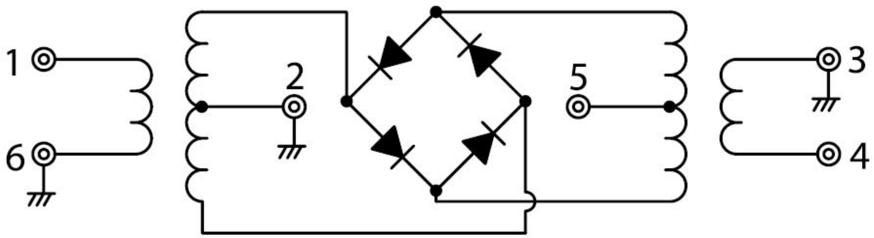
QPD : Quadrature Phase Detector

Analog transceiver

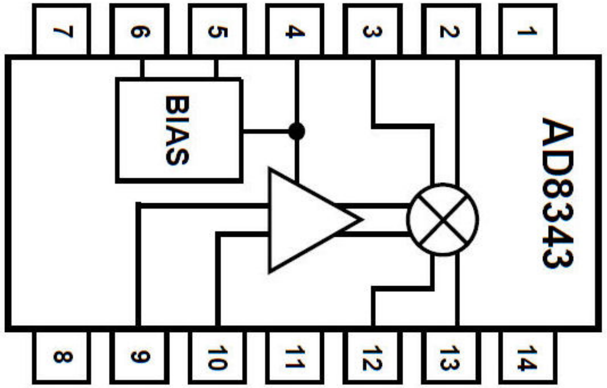


In the early MRI transceivers, **double balanced mixers** (DBM) using Ferrite cores were widely used.

Analog transceiver



Double balanced mixer



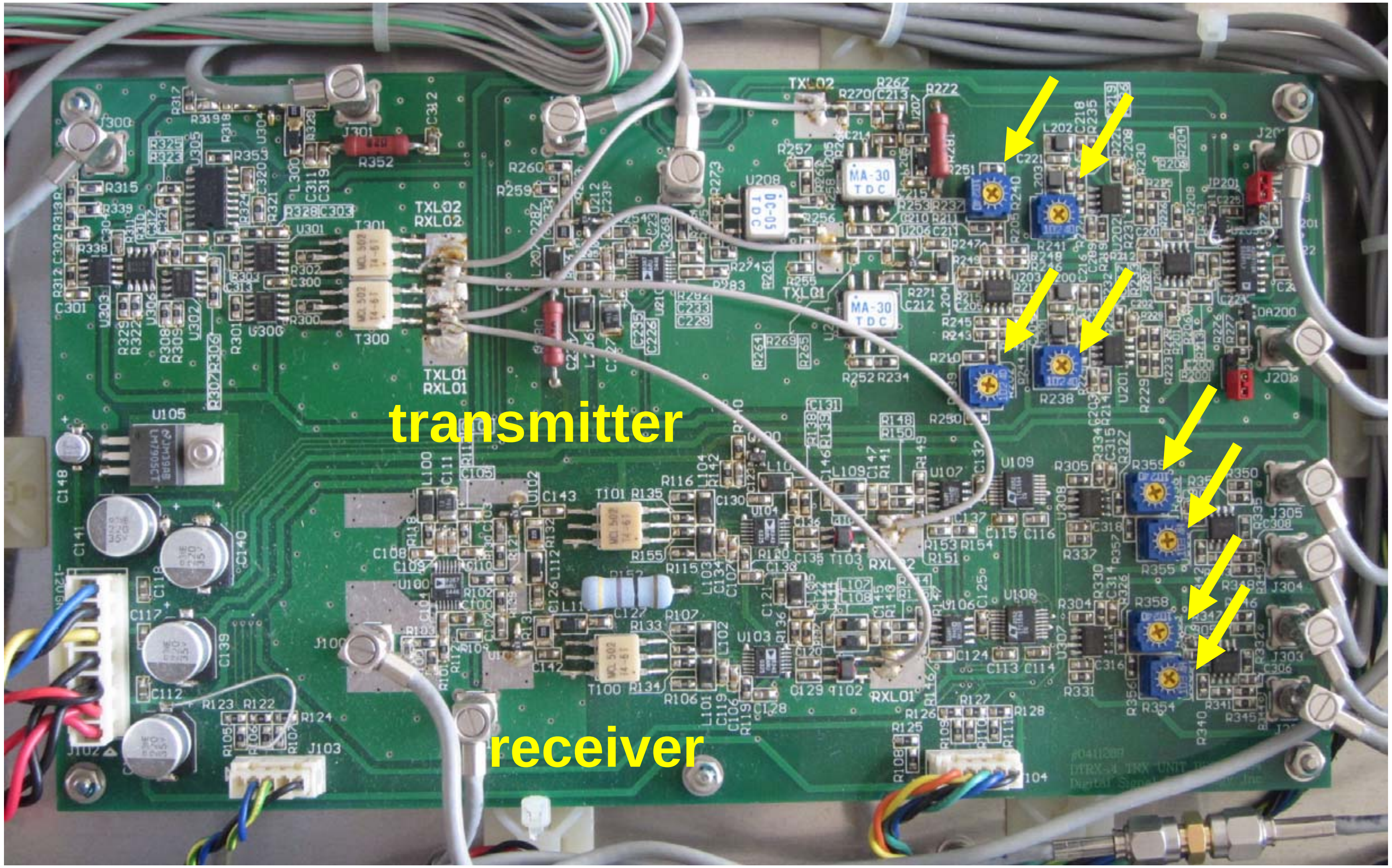
Active mixer

The DBMs were replaced by **active mixers** using semiconductor technology to overcome the insertion loss (~ -7dB).

Analog transceiver

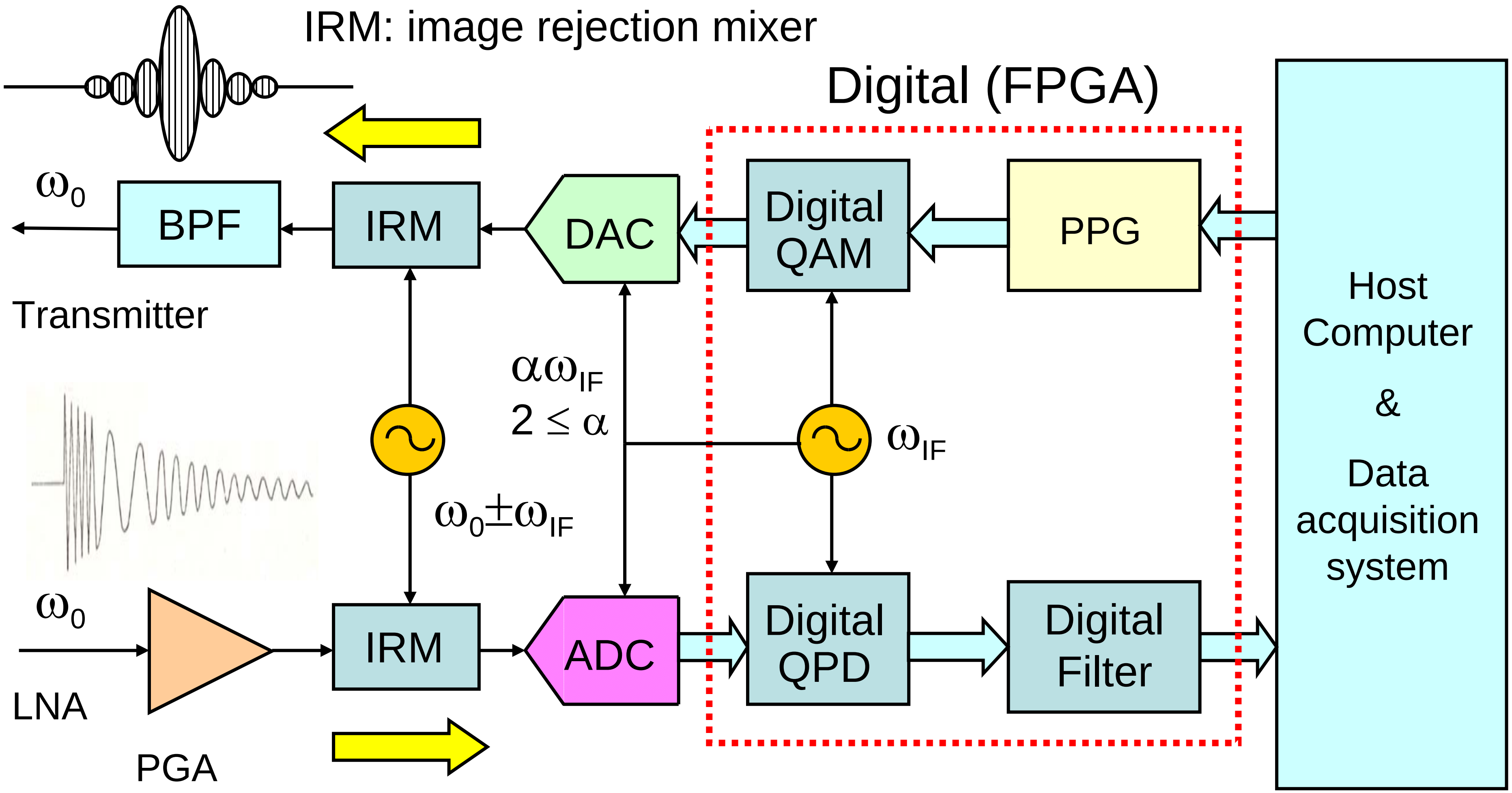
202 MHz **direct conversion** (**no intermediate frequency**) analog transceiver for our 4.74 T superconducting magnet

Analog transceiver



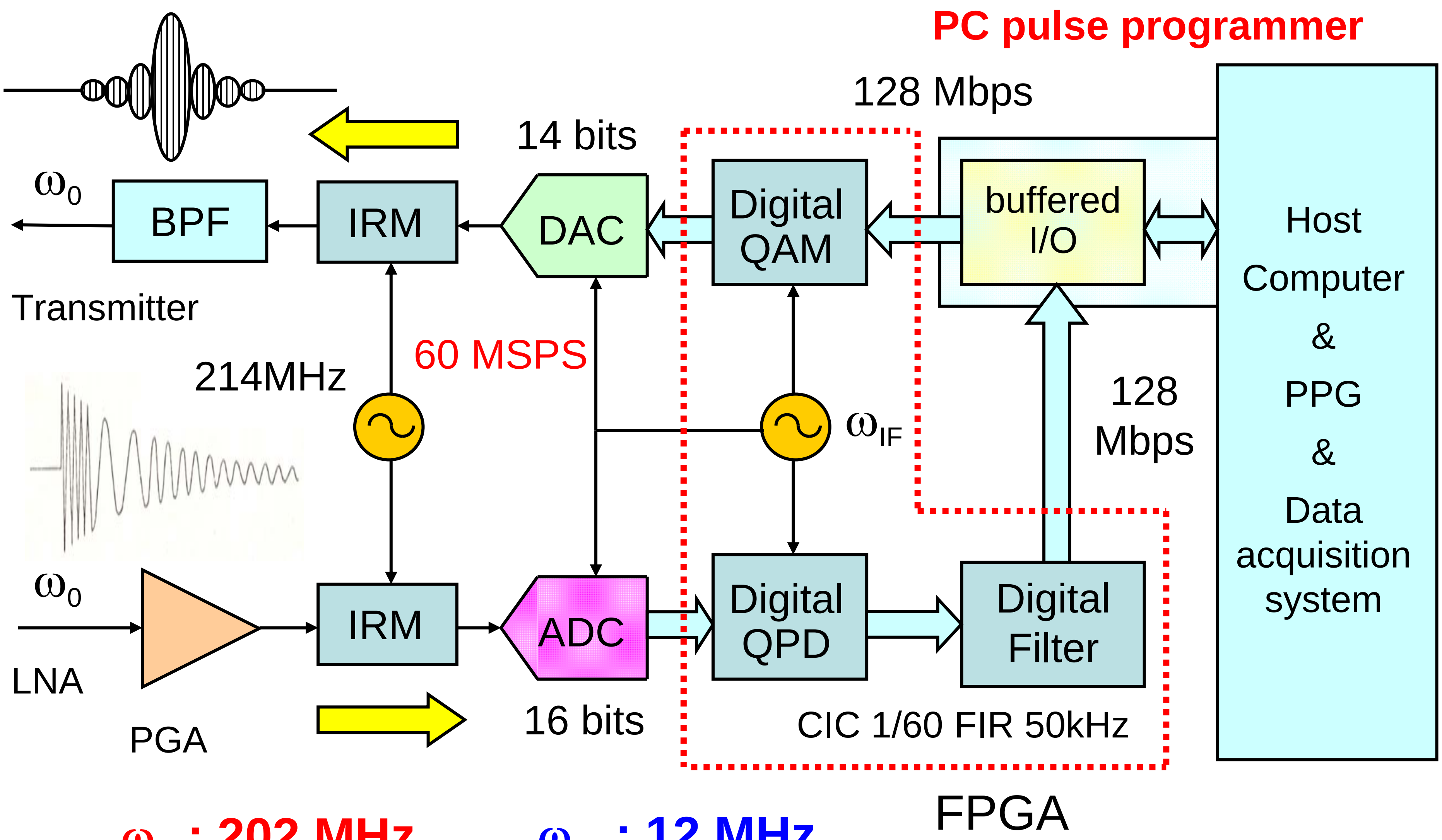
Gain balancing between I/Q channels and DC offset corrections are performed using trimmer resistors. **The trimming** is very time consuming and subject to **temperature drift** or **long term drift**, which can be overcome by **digital transceiver**.

Digital transceiver (general)



ω_0 : Larmor frequency ω_{IF} : intermediate frequency

Digital transceiver for our 202 MHz system

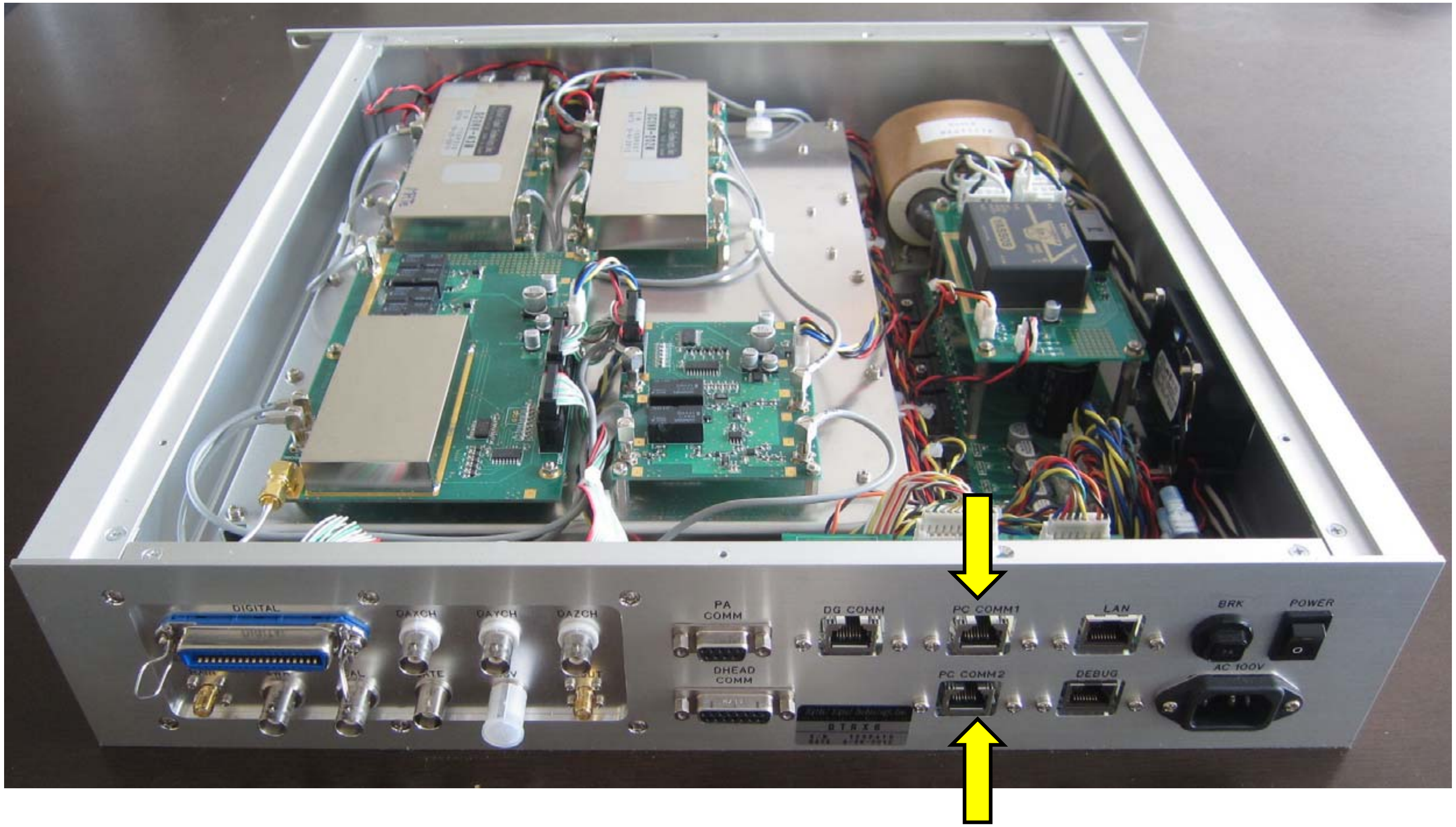


ω_0 : 202 MHz ω_{IF} : 12 MHz

Digital transceiver for our 202 MHz system

Digital transceiver with 12 MHz intermediate frequency (front view)

Digital transceiver for our 202 MHz system

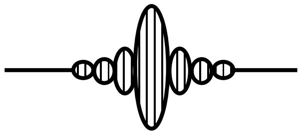


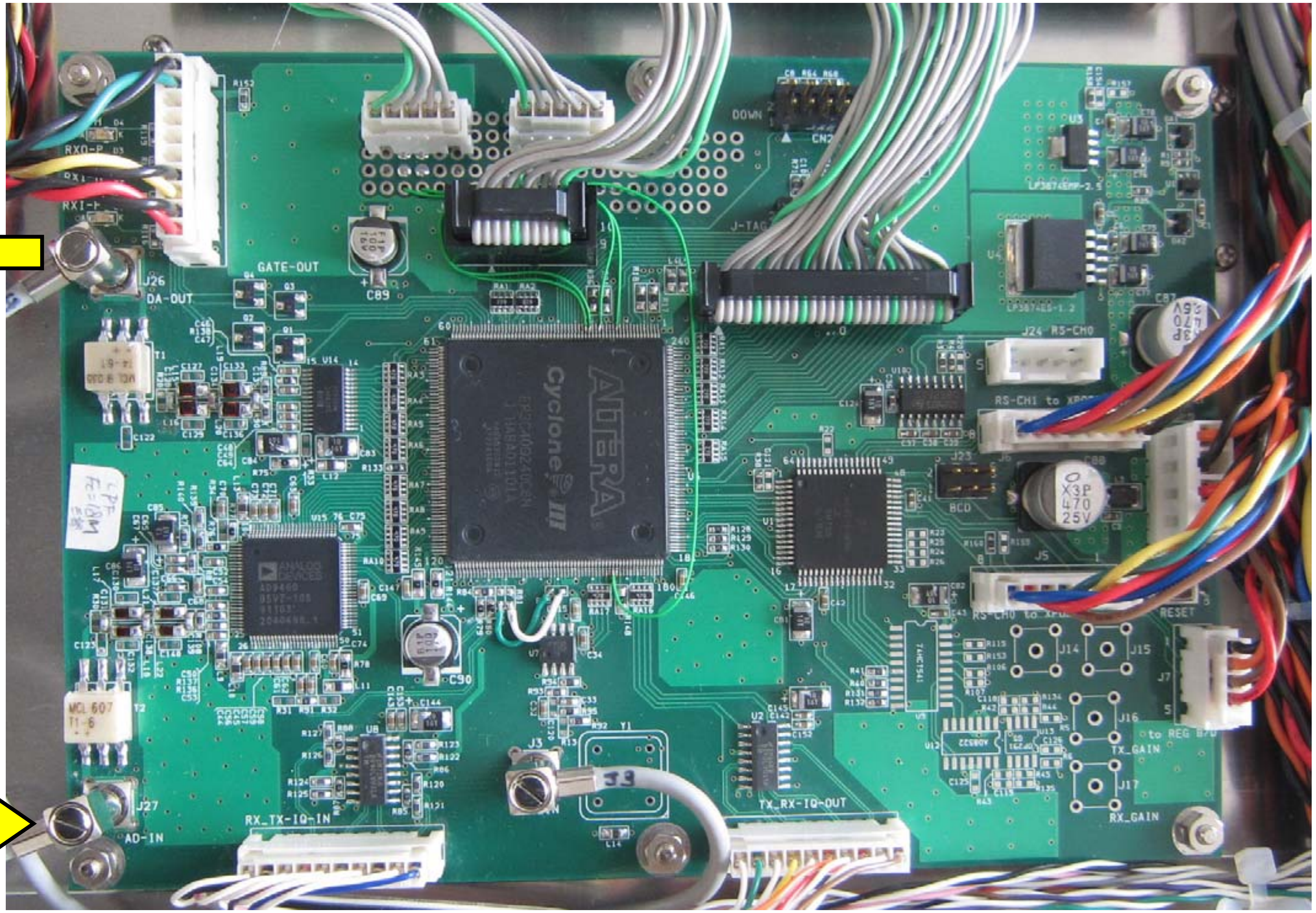
Digital transceiver with 12 MHz intermediate frequency (back view)

Communication with the host PC is performed serially using LVDS technique.

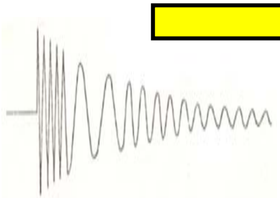
Digital transceiver (main board)

TX : IF





RX: IF



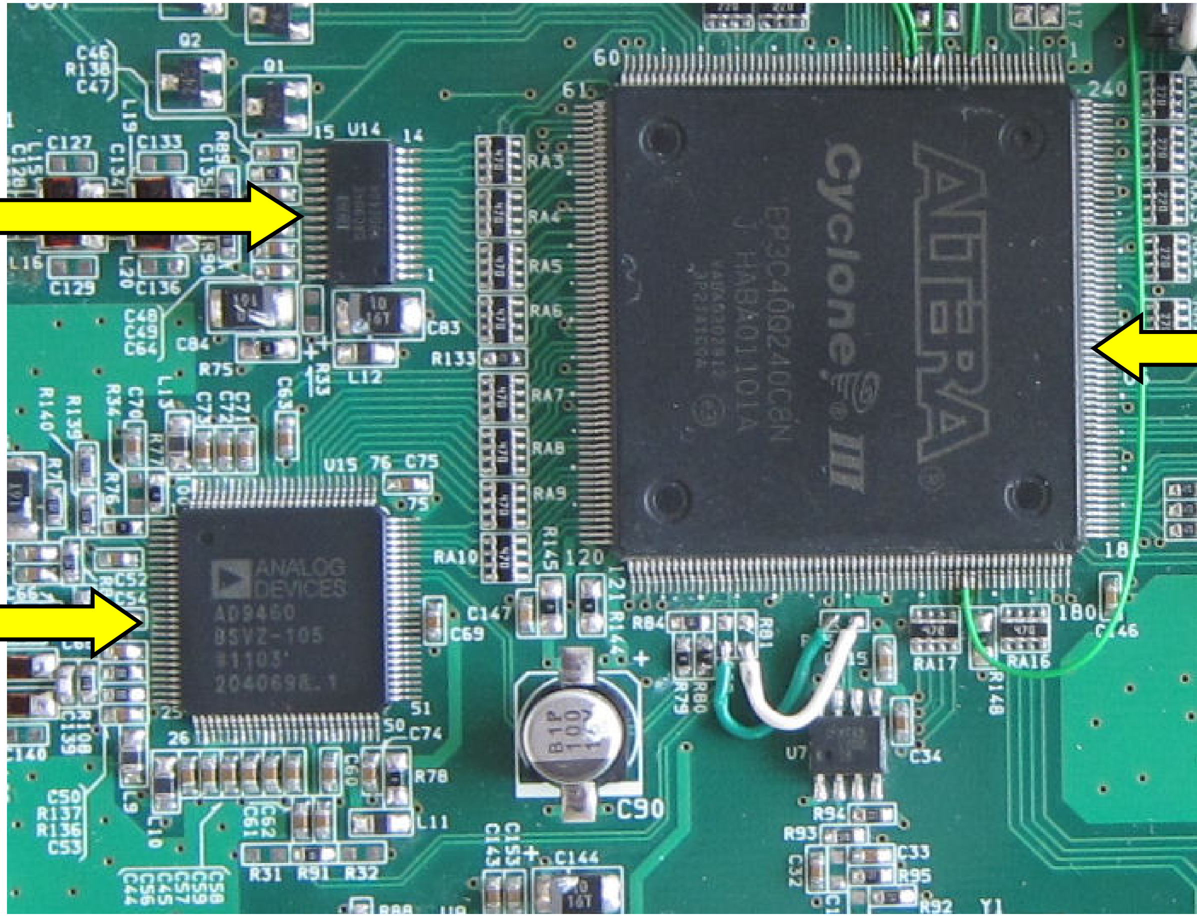
TX input **RX output** : digital (LVDS)

Main digital board of the digital transceiver. **No trimmer!!!**

Digital transceiver (core unit)

DAC
14 bit
60MSPS

ADC
16 bit
60MSPS



FPGA
60 MHz
clock

TCXO

The DA and AD sampling rate is 60 MSPS.
The digital resolution for the DA and AD is 14 and 16 bits.

Advantages of the digital transceiver

The advantages of the digital transceiver over the analog transceiver are:

→ no DC offset (less analog noise)

→ perfect IQ balance (no symmetric ghost)

→ good RF phase reproducibility or stability

→ a wide dynamic range (case dependent!)

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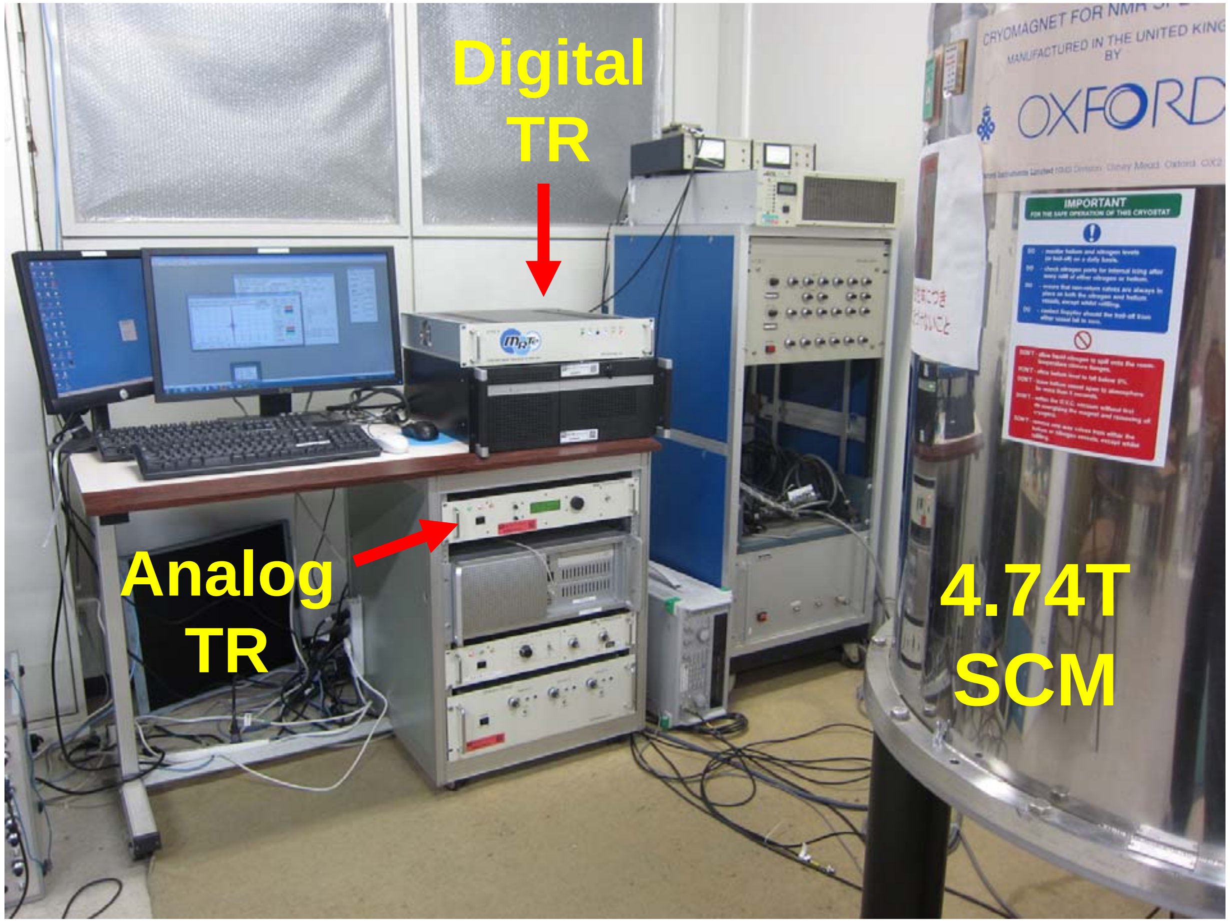
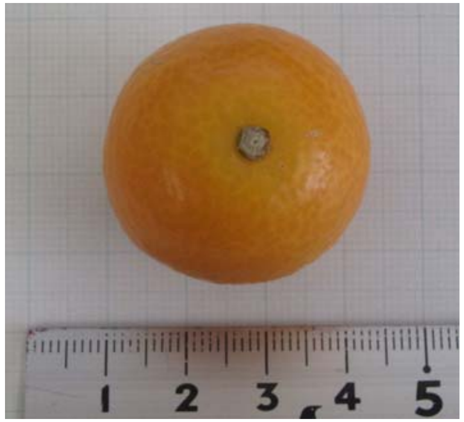
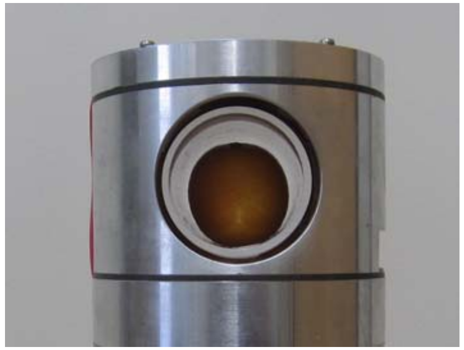
Analog vs Digital :experiments



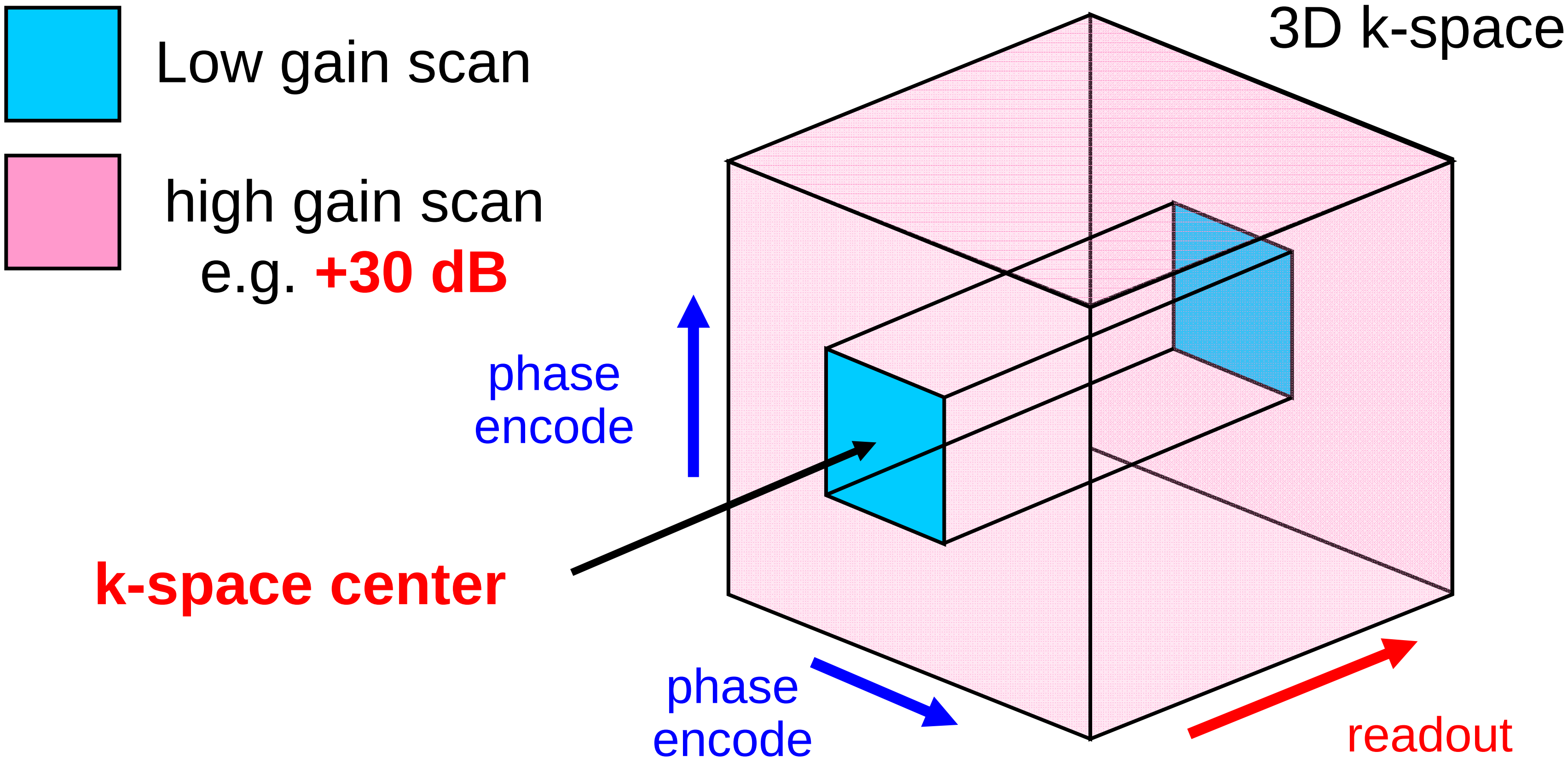




Kumquat in a
solenoid coil probe

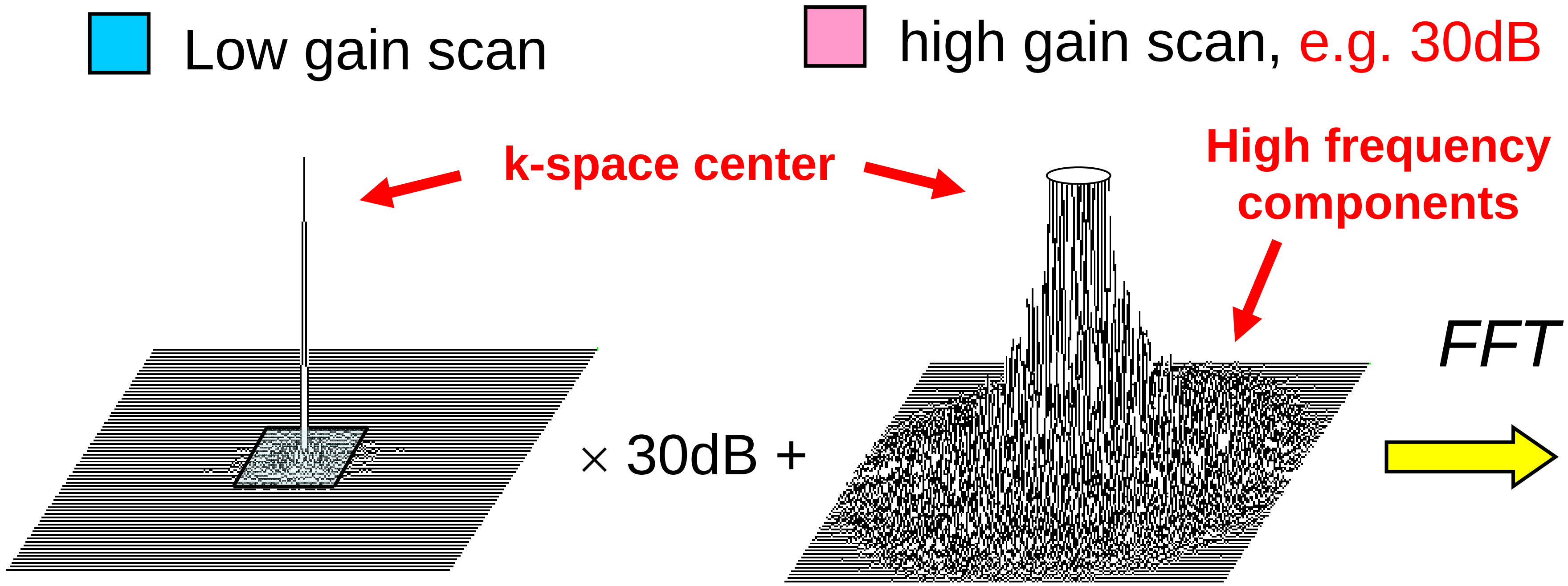
We compared the analog and digital transceivers under the **identical experimental setting**. A fruit sample in a 4.74 T superconducting magnet was used for the test sample (**wide dynamic range MR signal**)

3D data acquisition with gain steeping scan



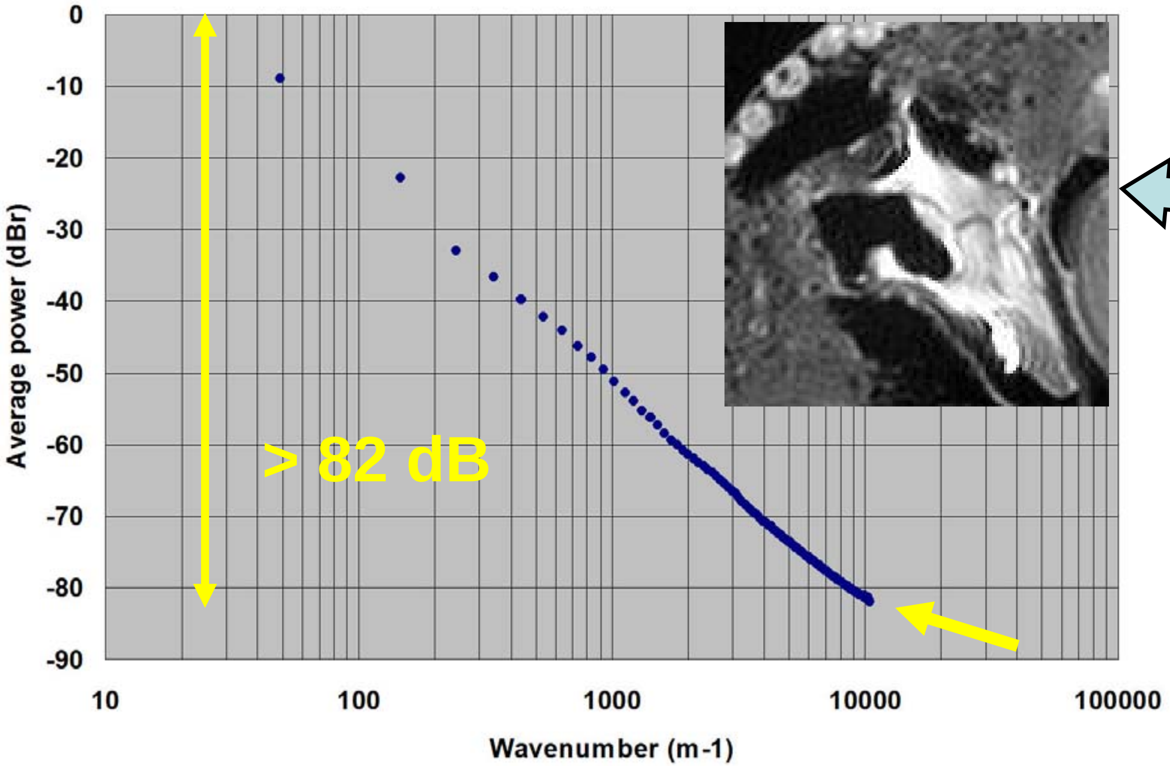
To **extend** the **dynamic range of the MRI receiver**, we used the gain stepping scan for both analog and digital receivers. This is a useful technique to achieve a wide dynamic range for the MRI receiver. Behin R., Bishop J., Henkelman R. M., **Dynamic Range Requirements for MRI**. Concepts in Mag Reson **26B**, 28-35, 2005.

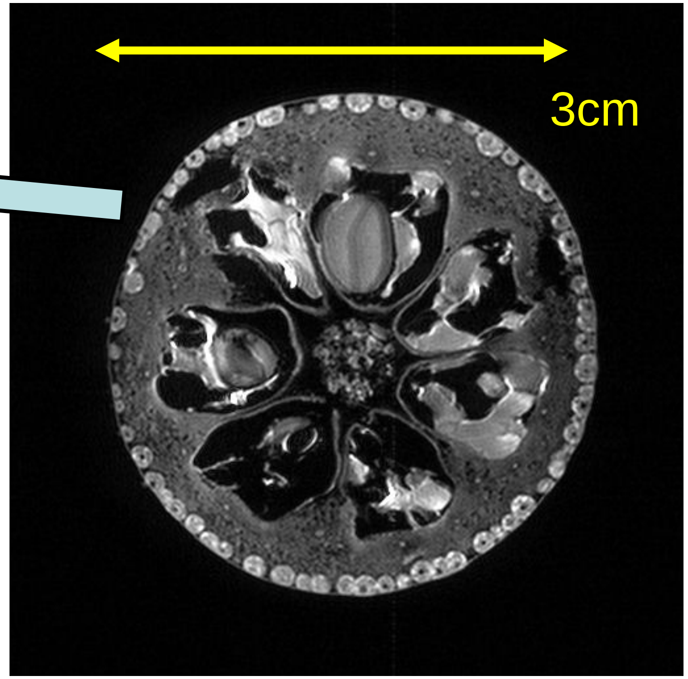
3D data acquisition with gain steeping scan



MR image data are **synthesized using two different scan signal** for image reconstruction. Behin R., Bishop J., Henkelman R. M., **Dynamic Range Requirements for MRI**. CMR **26B**, 28-35, (2005). **A solution to the dynamic range problem in MRI using a parallel image acquisition**. Y. Otake, K. Kose, T. Haishi, CMR **29B**, 161-167(2006).

Dynamic range: with gain stepping scan

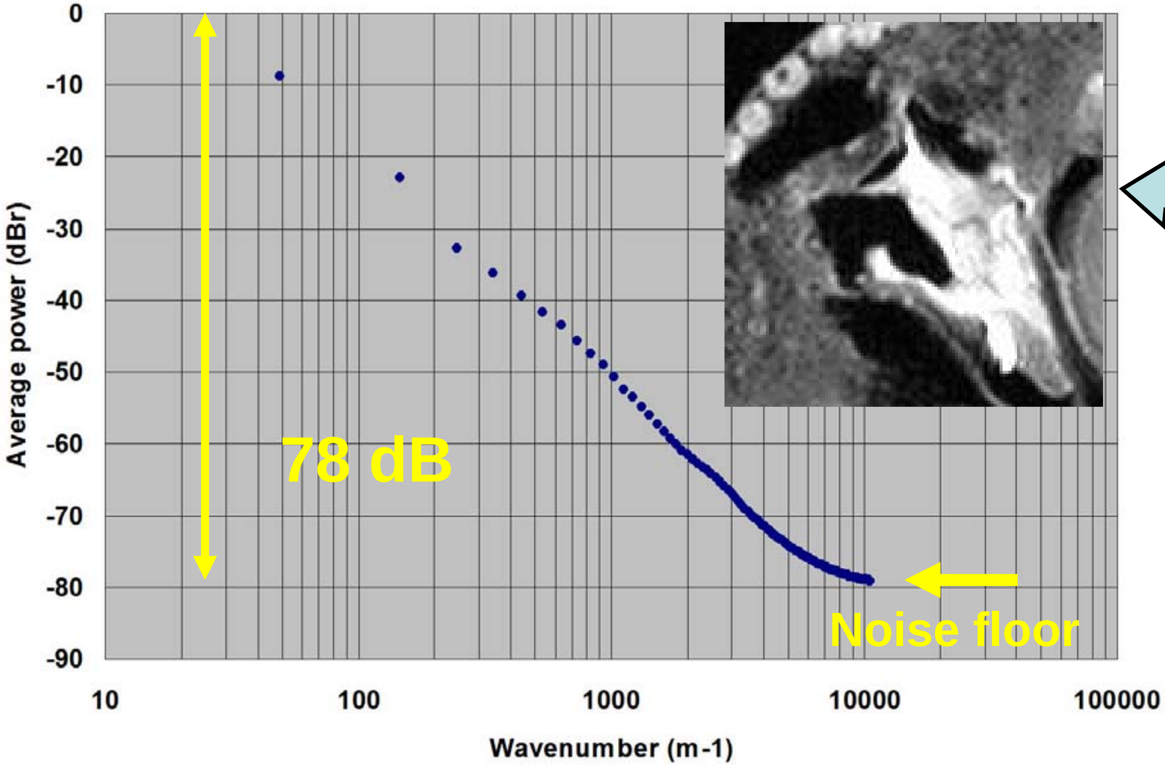


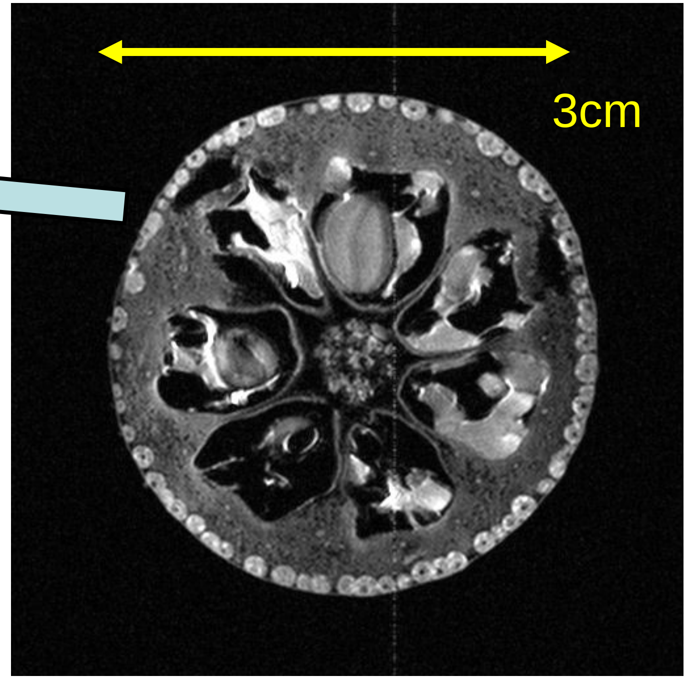


Dual scan (256^3)

The graph shows **relative average signal power** in k-space plotted against the **wavenumber** of the MR signal, obtained with the **gain stepping scan** for 256^3 matrix image. The observed dynamic range is **more than 82 dB and seems to approach 90 dB**. High spatial frequency components are properly sampled and the spatial resolution is fine.

Dynamic range: no gain stepping scan

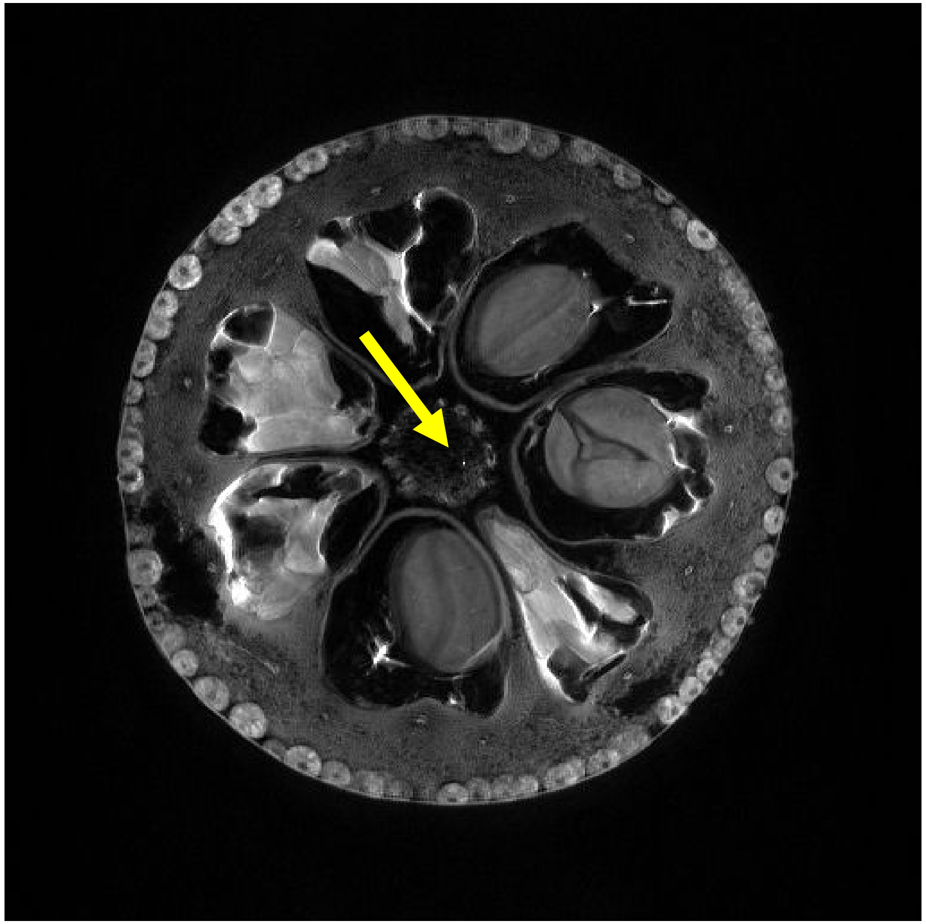




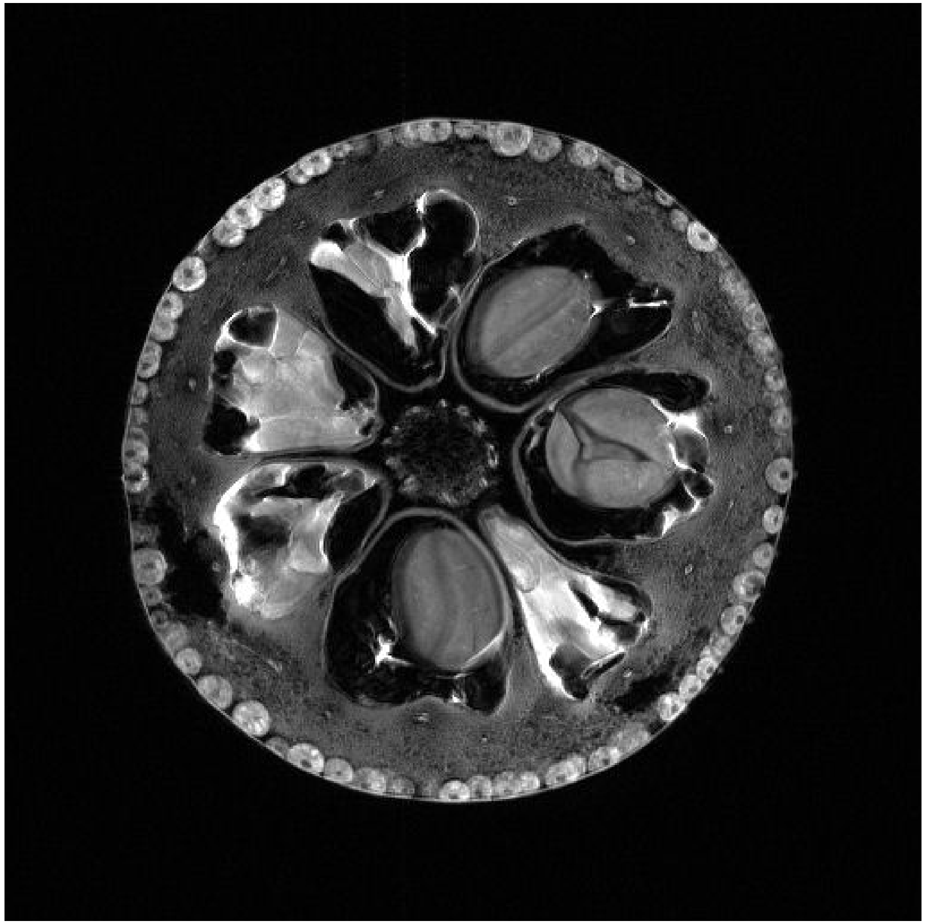
Single scan (256^3)

The graph shows **relative average signal power** in k-space plotted against the **wavenumber** of the MR signal, obtained with **no gain stepping scan** for 256^3 image matrix. A noise floor is observed at **-78 dB**. High spatial frequency components are masked by the **noise floor** and the spatial resolution is degraded.

Analog vs Digital : DC noise?



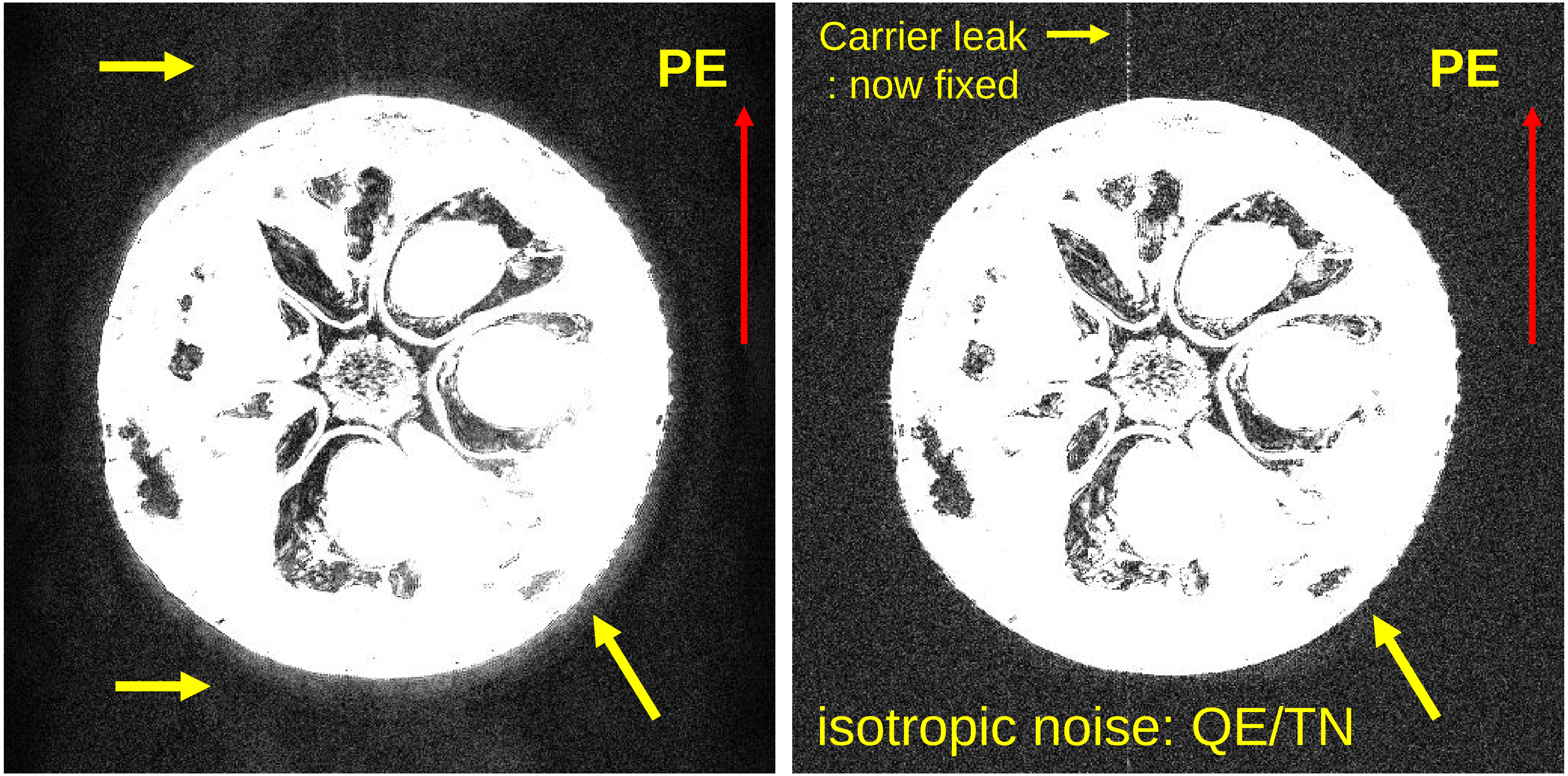
analog (dual)



digital (dual)

Cross sectional images acquired with the analog and the digital transceivers using a 3DSE sequence with TR/TE = 800ms/20ms, FOV = $(40.96\ mm)^3$, image matrix: 512^2 x 64, NEX = 1

Analog vs Digital : Phase stability?



analog (dual) digital (dual)

Isotropic background noise was observed for the digital transceiver. **Ghosting artifact** probably due to reference phase noise is observed for the analog transceiver. Artifacts due to analog circuit nonlinearity or gain mismatch are also seen.

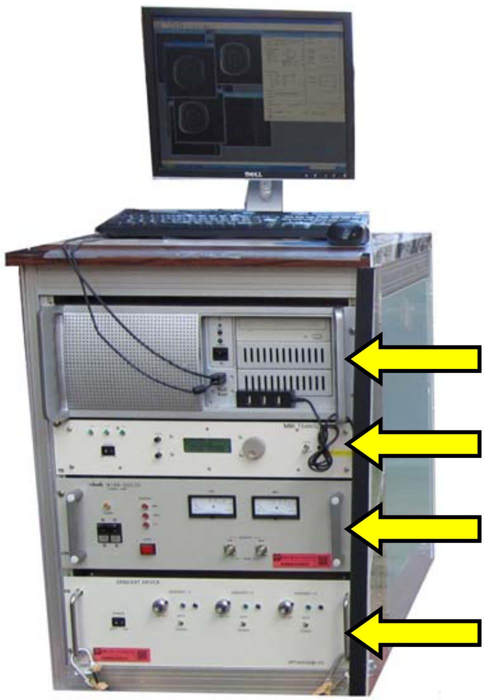
Analog vs Digital : summary

We confirmed the advantage of the digital receiver using the experiment under the identical experimental setting:
No DC artifacts, less artifacts caused by nonlinearity of the analog circuit, no artifacts caused by instability of the reference signal. But the analog receiver can give similar image quality, if the dynamic range problem is properly managed.

Analog

Digital

Portable MRI console?



Host PC, built in PPG, ADC, and DDS

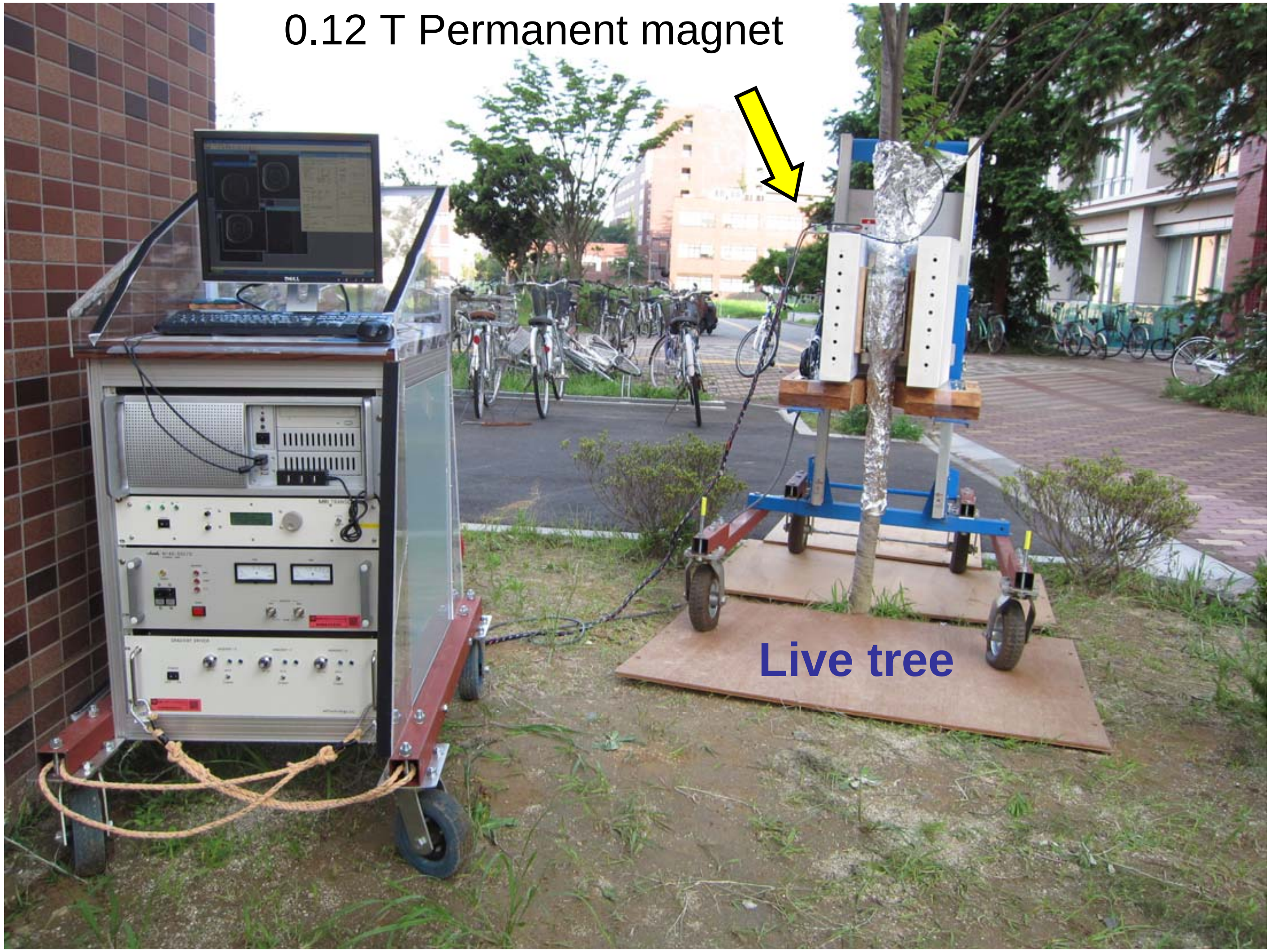
Analog transceiver

RF transmitter

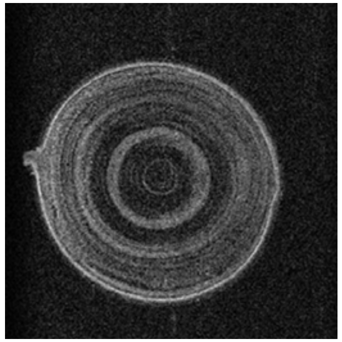
3CH gradient driver

If we assemble an RF transmitter and a 3CH gradient driver in a portable 19-inch rack, we can construct a portable MRI console. K. Kose, T. Haishi, N. Adachi, T. Uematsu, H. Yoshioka, I. Anno. Development of an MR Microscope using a Portable MRI Unit and a Clinical Whole Body Magnet, May, 1999, 7th ISMRM, Philadelphia.

Portable MRI console



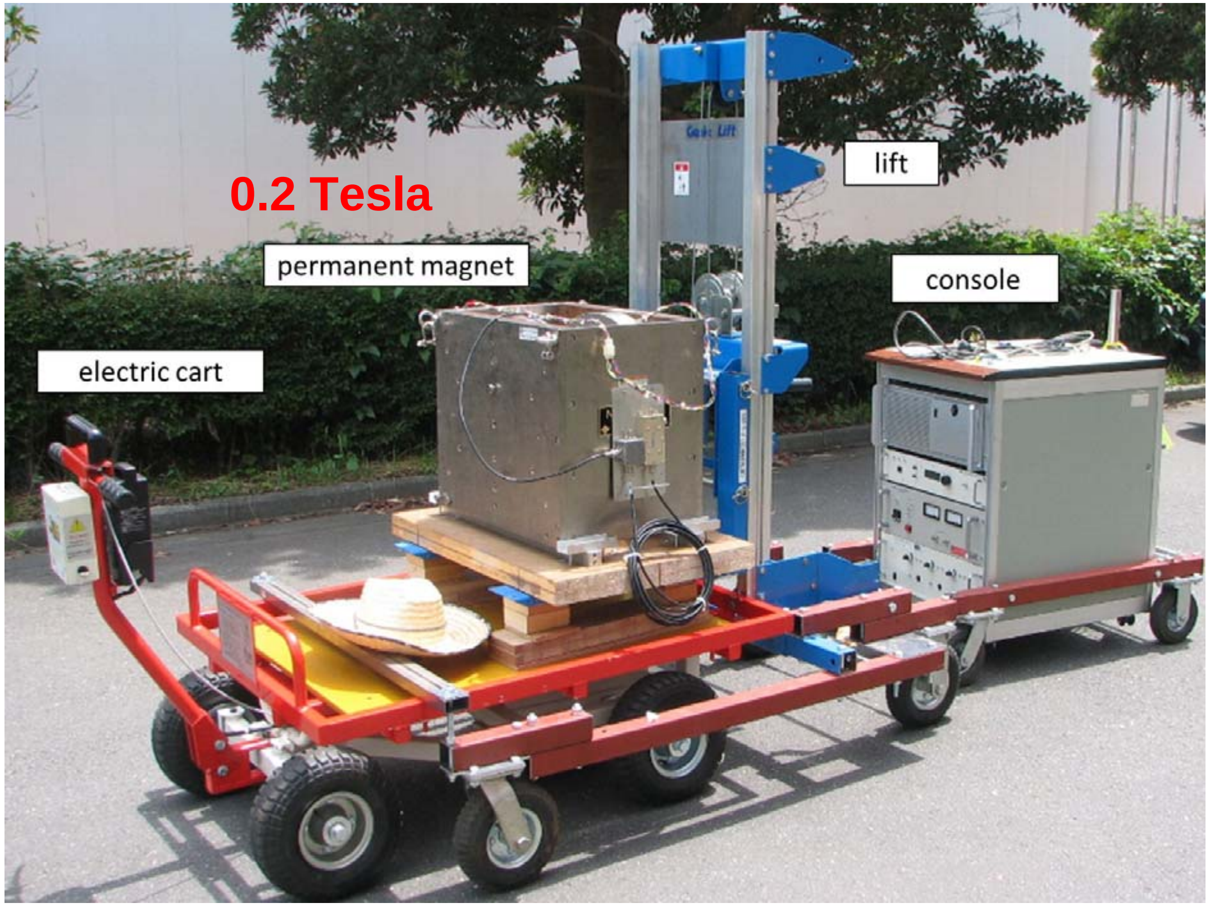
6 cm

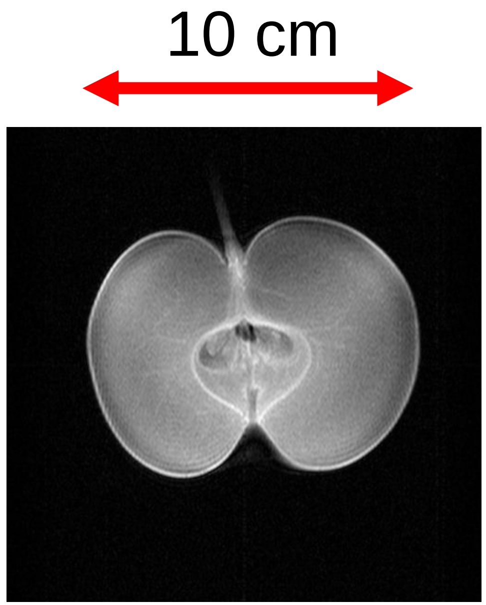


Cross section of a live tree

The portable MRI console can be used even for outdoor experiments.

Electrically mobile MRI





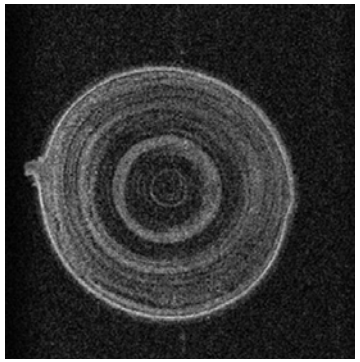
Pear fruit

If the portable MRI console is combined with a permanent magnet and electric cart, an **electrically mobile MRI** can be constructed. Y. Geya et al. Longitudinal NMR parameter measurements of Japanese pear fruit during the growing process using a mobile magnetic resonance imaging system. J. Magn. Reson. **226** (2013) 45-51.

Conclusion

- Various approaches to the MRI console have been reviewed.
- The advantages of the digital transceiver over the analog transceiver have been experimentally demonstrated.
- The compact MRI console will extend possibility of MRI applications.

4.74 T



0.12 T Live