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DDS-based multiple frequencies generator for the RF systems at INFN-LNS

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Abstract We are going to change the present radio-frequency sources with a new one, based on the Direct Digital Synthesis (from now on referred to as DDS) technique [6]. A first prototype with three different sinusoidal signal sources has been tested and the preliminary results give us some confidence for future applications. In brief, we would like to obtain a multiple frequencies system where the present stability between our RF systems is still ensured, together with a more flexible and easier way to synthesise the sinusoidal signals.

Key words Direct Digital Synthesis (DDS) • radio-frequency (RF) • superconducting cyclotron • Italy

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Introduction

On the latest accelerated beams, all the RF systems, the axial buncher [2], the three RF cavities of the superconducting cyclotron [7] and the high energy chopper [2], have been driven from the DDS generator. The phase stability, between these components of the RF System [3], is stable in order to ensure the stability on the extracted and choppered beam. With this new generator based on the Direct Digital Synthesis, we would like to achieve the same stability on the final beam of the old RF source generator system. The main reason for following this new technique in the synthesis of the RF sinusoidal signals is given by the future introduction along the extraction beam line of the Chopper 500 [2]. This new beam chopping system will replace the present High Energy Chopper. The goals of the new chopper system are: the separation time between the accelerated beam bunches of 100÷200 ns and to reduce to 0.5 ns the length of the single bunch. At the moment we have this separation up to 200 ns, with the length of the bunch no less than 1 ns. In order to reduce this bunch length and maintain the same separation time, we ought to drive the new chopping system, the Chopper 500, choosing a non integer multiple harmonic of the fundamental RF cyclotron. The old RF source generator develops integer multiple frequencies, starting with the lowest RF, which generally belongs to the High Energy Chopper. The DDS frequencies generator allows the generation of sinusoidal output signals, highly stable in frequency, phase and amplitude respectively, without any problem between integer or non integer harmonic. To choose the output frequencies you simply address a "new tuning word" by a personal computer via a parallel port to the core of the system. This is a commercial electronic component: the AD9852 on its own evaluation board [4]. We have three boards capable of synthesising three different frequencies and one software program that addresses the boards to generate the different sinusoidal signals. The circuit architecture of the AD9852 allows the generation of a sine output at frequencies up to 120 MHz, which can be digitally tuned at a rate of up to 100 million new frequencies per second. The operative results, the conceptual design, the prototype and the latest status report of the new chopper 500 are presented along with this report.

Conceptual design

We have already seen how the core of the system is based on the Direct Digital Synthesis. We can find the roots of the DDS system in the most general environment of the Digital Signal Processing (DSP) [5]. DSP is one of the greatest technological innovations of recent time. The basic concept consists in a waveform that can be turned into sequences of numbers and then, once processed, back into a waveform. The resulting waveform can be easily tuned in frequency, modulated in phase, amplitude and shape. Starting from a reference clock generator we can obtain, after digital manipulation, a perfect sine wave. If we add a very high stability in amplitude and phase to this sinusoidal signal, the result is an agile and versatile frequency synthesizer. This digital controlled method of generating generic waveforms from a reference source is called DDS. In our case the generic waves are sinusoids. A simplified block diagram shows in Fig. 1 the architecture of a DDS. In this simple model a stable clock generator drives a pro-grammable-read-only memory (PROM) containing the pattern in digital form of a sine wave. As the address counter steps through each memory location, the corresponding digital amplitude of the signal at each location drives a digital-to-analog-converter (DAC) which in turn generates the analog output signal. The inconvenience of the simplified system is that the final output frequency can be changed by reprogramming the PROM or by using a different reference clock. To bypass this problem, a practical DDS implements its architecture using a numerically controlled oscillator (NCO) so that the choice of the output frequencies is obtained simply by addressing a digital word through a parallel port, whilst the clock reference is constant and the PROM is the same. Our system is based on a commercial microchip, the AD9852 providing 48 bits frequency resolution together with a reference clock of 300 MHz gives a resolution of 1 µHz with a maximum frequency output up to 120 MHz.

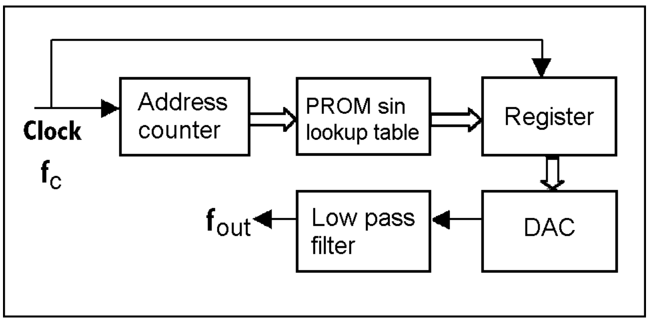

Fig. 1. The architecture of the basic DDS.

The multifrequency sources prototype

There are several ways to synthesise more than one radio-frequency signal in a constant relation of amplitude and phase. In each system the starting point is the same high stable reference clock and from here it develops all the different waveforms for the related devices. Our radio-frequency system consists of three RF cavities of the superconducting cyclotron, an axial buncher placed in the injection beam line and a high energy chopper along the extraction beam line. For each device then, the cavities, buncher and chopper, a different RF signal must be fed. The old RF source generator develops integer multiple frequencies. Starting from the lowest frequency with multiplication by 2, 3, 4 or 5 we can feed all the radio-frequency devices to cover all the related accelerated beams. This system is based on a high stable synthesizer, a couple of RF doublers, a limiting amplifier and variable band pass filters to avoid high order harmonics. Since we have been using integer multiple frequencies, this system has been used for years and the phase stability between the different RF devices has been stable and constant, because the source was an RF synthesiser for the whole system. The future introduction, along the extraction beam line of the cyclotron, of a new beam chopping system called Chopper 500, has changed the relation between the RF signals. In order to obtain a separation time from 100 to 200 ns between the accelerated bunches from the cyclotron, with the length of a single bunch less than 1 ns, the relation between the cyclotron RF and the chopper can become a non-integer number. At this point the solution can be found in a PLL (phase-locked-loop) [1] or DDS system. Both systems are able to generate integer and non-integer frequencies in a constant relation of phase. Local Oscillators or agile frequency synthesizers in the past were the exclusive domain of the PLL-based analog synthesizer but with the new generation of high speed DAC and NCO, up to 48 bits of resolution, there are several reasons why the DDS-based one represents the most simple and versatile solution. For example, if we consider our AD9852 DDS, it has:

- generation of a sine wave output at frequencies up to 120 MHz,
- digitally tuned sine wave at a rate up to 100 million new frequencies per second,
- changing output frequencies without phase discontinuity,
- output frequency resolution, up to 48 bit,
- output frequency switching time, around 40 ns,
- phase noise, related to the clock generator spectral purity,
- 14 bits of digitally controlled phase modulation,
- 12-bit digital multiplier permits programmable amplitude modulation,
- implementation complexity, no longer elements of proper RF design expertise required to implement a DDS solution,
- low cost.

For all the above reasons, a few months ago we assembled our first multiple frequency prototype able to drive three different devices of the radio-frequencies system based on the DDS technique. The preliminary results were very good and since May 2002 we have been driving the RF system with the DDS-based unit. Figure 2 shows the internal view of the prototype cabinet in which the three DDS-boards are placed. Each one carries the core of the

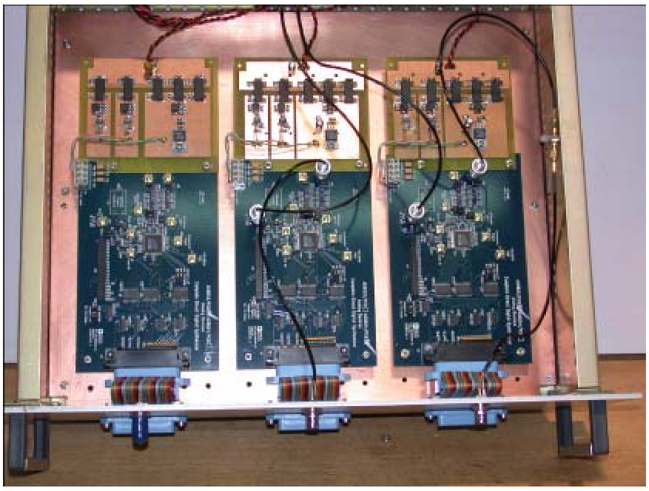

Fig. 2. The internal view of the prototype DDS cabinet.

system, the AD9852, on board. Special attention was taken in the shielding, grounding and decoupling from low to high frequency in order to improve the performances of the entire system. The block diagram of the DDS-prototype is shown in Fig. 3. The 300 MHz reference clock is generated from a precision high stable synthesizer and through a distribution network it reaches each board so allowing perfect synchronization. The power supply for each board has been designed to minimize the mutual induced electrical influence. The three evaluation boards have been mounted on a ground plane to improve the cabinet shielding. Separate digital and analog ground are connected only in one point. A special software in a Windows environment allows us to address the single board by a parallel port through the printer cable. The procedure to synthesise the three frequencies is very easy. You connect the printer cable to the selected board, write the tuning word, including frequency, amplitude and initial phase delay, then send the message to the board. After that, you connect the printer cable from the first board to the other boards and repeat the procedure. The frequency spectrum in Fig. 4 shows an example of the quality of the output signal. We have a relation of about 60 dB between the carrier frequency of 39 MHz and the second harmonic. Usually the second harmonic in a commercial synthesizer can reach 50 dB under the carrier. So, from this point of view this DDS system can be a valid alternative if the bandwidth is under 120 MHz. In our case, this bandwidth is large enough: the bandwidth of the new chopper 500 is 65÷110 MHz, the resonance frequency of the RF cyclotron runs from 15 to 50 MHz, the present high energy chopper can be tuned between 4 and 8.5 MHz and the axial buncher covers a range between 12.5 to 55 MHz. All these kinds of devices have their own frequency tuning with or without integer correlation, but they must be in a precise and constant relation of phase altogether. With the DDS multifrequency source we have successfully tested this stability directly on the accelerated, bunchered and choppered beams in the last three months of cyclotron operation.

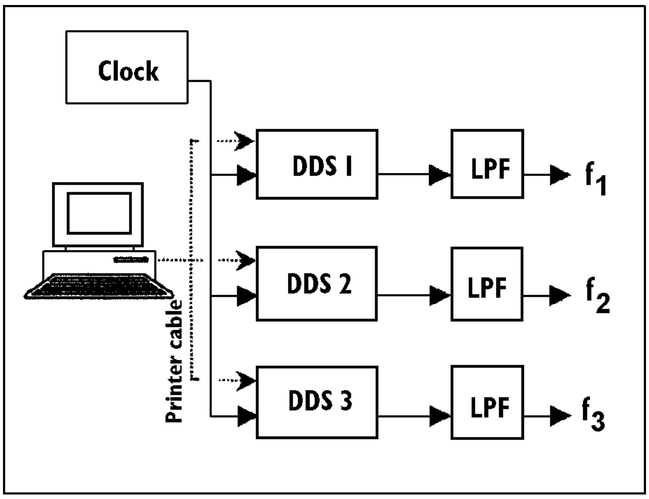

Fig. 3. Block diagram of the DDS-prototype.

Chopper 500 status report

The goal of the Chopper 500 is to ensure a separation time of up to 200 ns between two consecutive accelerated bunches and a width of 500 ps FWHM in a single bunch. This could be achieved if we drive the chopping system with a non-integer harmonic of the RF cyclotron. So the main reason to develop the described DDS-based multifrequency source is to give perfect synchronization between the chopper and cyclotron. The two sine waves in Fig. 5, are the products of two of the three DDS-boards. The upper sinusoidal signal is the RF of the cyclotron, the lower sinusoid is the Chopper 500 harmonic. This harmonic is 3.125 times higher than the upper sine wave, the cyclotron one. This means that in every eight periods of RF cyclotron there will be one point when the two waves meets at 0°. In the other seven cases the sinusoids will be in a phase relation capable of suppressing the remaining bunches. In order to obtain the right separation time, we can decide this multiplication factor in the operative bandwidth of the chopper. Once the single bunch is selected at 0°, to obtain a width of 0.5 ns FWHM, a high voltage is applied to induce a fast variation of the electrical field at a time interval of ±0.25 ns during the passage of the particles. In Fig. 5 the waveforms on the oscilloscope display an RF cyclotron sine wave of 20 MHz and the chopper signal of 62.5 MHz: the relation is 3.125. If we superimpose the two waves, as is

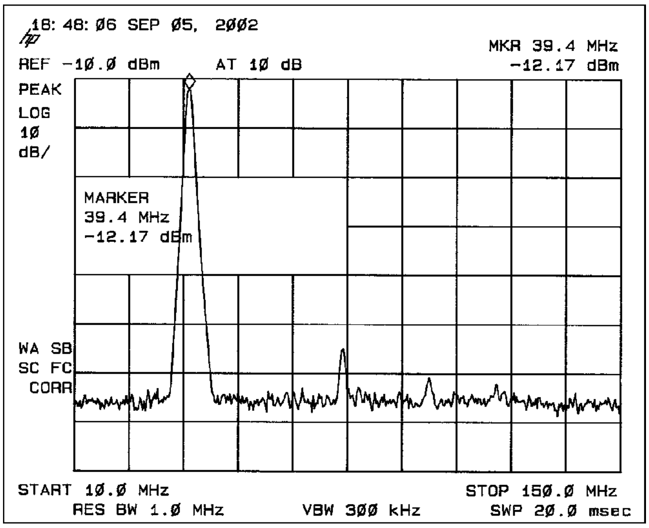

Fig. 4. Frequency spectrum of the output DDS signal.

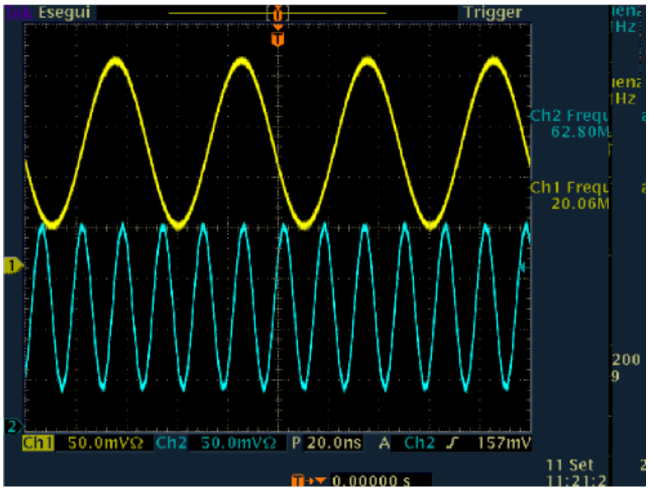

Fig. 5. Cyclotron and Chopper sinusoids from the DDS.

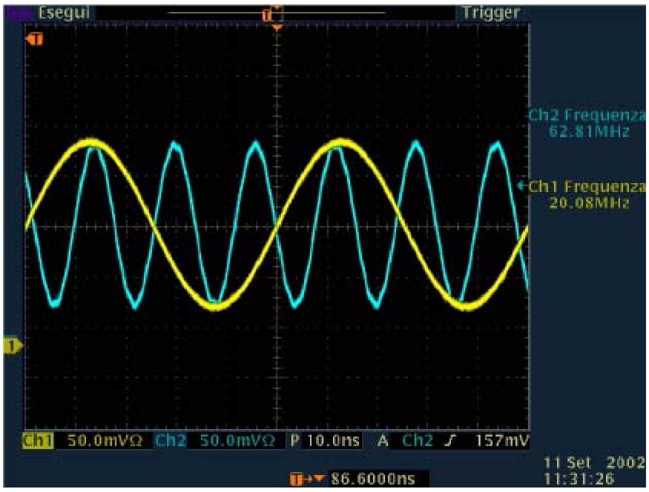

Fig. 6. The two waves superimposed.

shown in Fig. 6, the overlapping at 0° is clearly visible. All the main components of the Chopper 500 are on site, but only the 50 kW power amplifier, the driver and its control system have been installed and tested successfully on the dummy load. The other components, RF cavity, coupling system, 3”1/8 rigid line, reflectometer and power RF switch are ready to be installed.

Conclusion

The DDS-based multiple frequencies system is a valid solution every time the generation of several signals is requested in a constant relation of phase. The system is extremely simple to install and to use. You need a personal computer, a printer cable, a parallel port and an electronic board in which the selected DDS microchip is placed. The same system is very versatile for many other applications linked to some parts of a control RF system. For example, the extremely low switching time together with the possibility of modulating the output sine wave in amplitude can be used as a turn on/off system for the RF cavities. In addition, the possibility to shift the phase of the waveform allows the DDS to become a delay line of the output RF signals before the latter are applied to the devices. There is also the possibility to change the frequency tuning word without any interruption in the continuity of the waveform. The possibility to modulate the signal generated can be used for the amplitude and phase stabilization loops. The low cost at the end is another important reason why we should convince ourselves of the application of this system for our purposes. But the main reason for us to choose the DDS is the introduction of the Chopper 500 driven by its non-integer harmonic sine wave compared to the RF cyclotron sinusoid. All the apparatus and devices of the entire RF system are currently fed by the DDS-based synthesis. We have achieved a high phase stability for the whole system and for all the related accelerated bunchered and choppered beams. The timing of the beams has been maintained constant and locked throughout the different experiments. We are confident that the future introduction in the extraction beam line of the new Chopper 500 will maintain the same stability on the accelerated beam.

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