Stimulation Tutorial

1. Basic concepts and terms

1.1. Stimulation Signal Form

There are two types of electrical stimulation: voltage stimulation where the voltage is kept at constant amplitude during stimulation and current stimulation where the current is kept at constant amplitude during stimulation. The BIC3232 implant does bi-phasic, charge balanced current stimulation.

The stimulation functions have the following form:

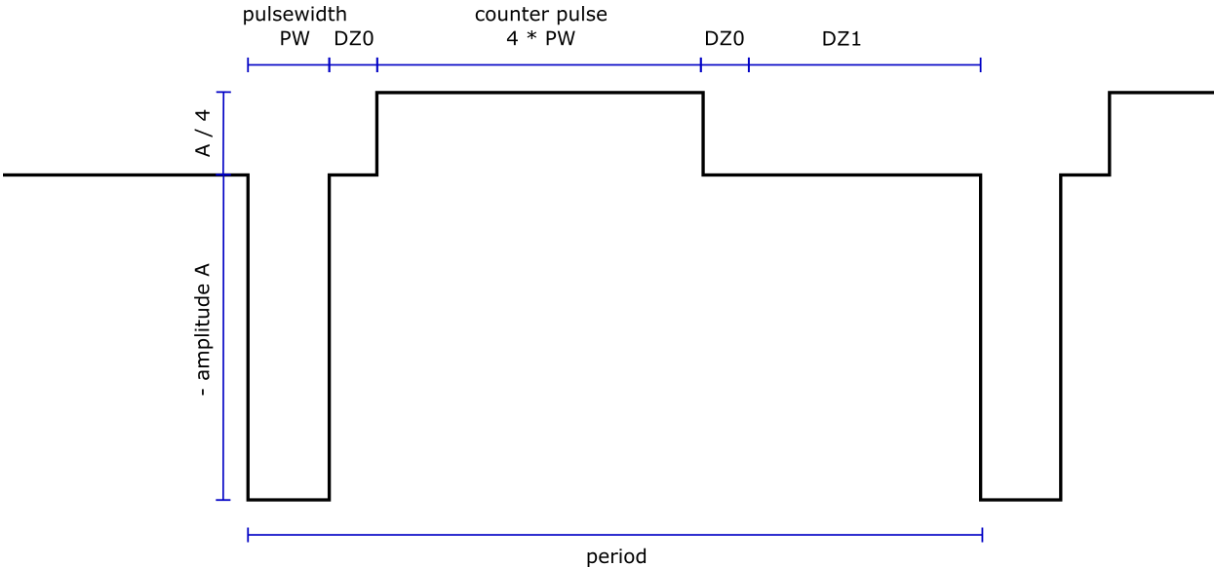

Figure 1: BIC3232 stimulation form and parameters

With the following adjustable parameters:

- **A:** The amplitude of the stimulation pulse. Is specified in milliampere.
- **PW (Pulse width):** The time duration where A milliampere is stimulated by the implant.
- **DZ0 (Dead zone 0):** Between the stimulation pulse and the counter pulse, and after the counter pulse, there is a dead zone where no stimulation is performed by the implant.
- **DZ1 (Dead zone 1):** After the second dead zone 0, there is a pause called dead zone 1 until the next bi-phasic pulse starts.
- **Repetition:** The repetition parameter defines how often a bi-phasic impulse (the whole function displayed above) is consecutively applied.

And the following parameters which arise from the upper parameters:

- **Period:** The time between the start times of two bi-phasic pulses is the period of the stimulation (i.e., period = PW + DZ0 + 4·PW + DZ0 + DZ1).
- **Counter pulse:** The counter pulse follows the first DZ0 and serves for charge balancing. In order to achieve charge balancing, the area of the counter pulse always has opposite polarity than the first pulse and the same area ((4 · PW) · (A / 4)) as the first pulse.

These parameters define a signal form consisting of five rectangular parts: first pulse, DZ0, counter pulse, DZ0 and DZ1. Some parameter combinations are not allowed (e.g., due to hardware limitations or safety considerations) and are therefore considered invalid. For more details on this, see section 1.2.

1.2. Constraints on the stimulation signal form

The following constraints on the signal form must be adhered to. Otherwise, the BIC C++ API will throw an exception.

1.2.1. Hardware constraints

Table 1: Hardware Constraints on the signal form

Parameter	Allowed values
Amplitude of first pulse (A)	[0mA, 6.120mA] in steps of 12µA
Pulse width of first pulse (PW)	[0µs, 2550µs] in steps of 10µs*
Amplitude of dead zone 0 (DZ0)	0mA
Duration of dead zone0 (DZ0)	[10µs, 2550µs] in steps of 10µs*
Amplitude of counter pulse	A/4
Pulse width of counter pulse	4·PW
Amplitude of dead zone 1 (DZ1)	0mA
Duration of dead zone (DZ1)	[10µs, 20400µs] in steps of 80µs*
Repetitions	[1, 255]

*The BIC C++ API can process values within these intervals that are between these steps (i.e., the API will not throw an exception). However, the values are rounded down to the next allowed value before the implant starts to stimulate (e.g., when sending down parameter A=19µA will be rounded down to 12µA and thus a stimulation with 12µA will be executed).

1.2.2. Safety Constraints

- The stimulation charge (A · PW) must not exceed 5µC. This value depends on the electrode's material and diameter and is specific for our electrodes.
- The stimulation function duty cycle ($\frac{T}{5 \cdot PW}$) must not exceed XXX.

1.3. Stimulation Function composition

A stimulation function consists of 4 signals with different amplitudes (A0 – A3) and equal pulse and pause durations.

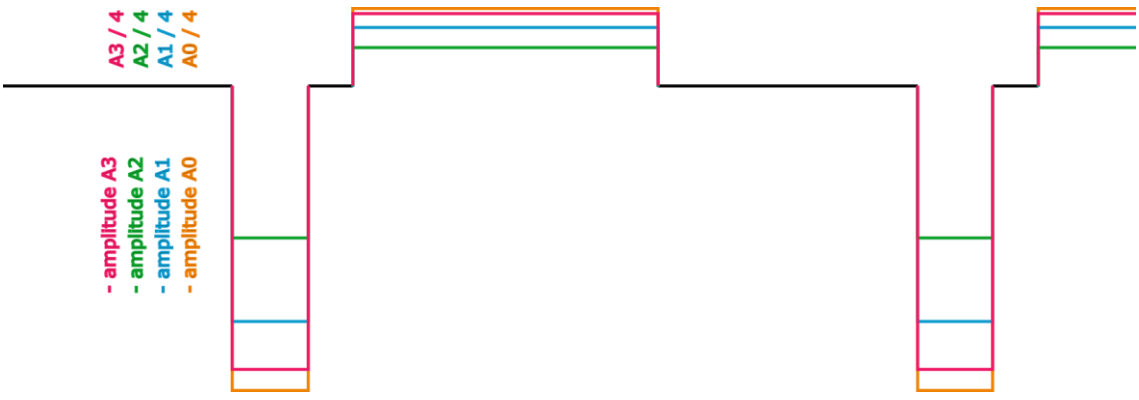

Figure 2: Stimulation function containing four amplitudes

Amplitude 0 will be applied on one or more selectable source electrodes (see virtual source electrodes in Section 1.4.).
Amplitudes 1, 2 and 3 are applied on the hard-wired source electrode channels 1, 2 and 3, respectively. This setting is shown in Figure 3.

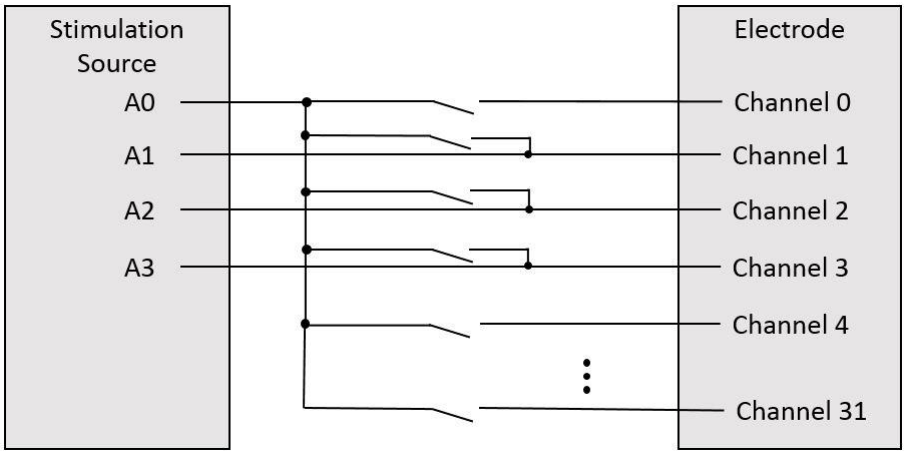

Figure 3: Stimulation source and corresponding electrode channels

For more details on the configuration of the electrodes for Amplitude 0, see Section 1.4 and 1.5.

1.4. Electrodes

In addition to the signal form, the electrode channels to which the stimulation should be applied must be defined.

Stimulation is usually applied between two points: one source electrode and one destination electrode (e.g., a ground electrode and another stimulation channel). The BIC3232 implant allows to combine several electrodes into one composite electrode termed 'virtual electrodes'. Consider the following example: stimulation channels 1, 2 and 3 are combined to a virtual source electrode, and channels 7, 8 and 9 are combined into a virtual destination electrode. A stimulation applied to these virtual electrodes would mean that the implant-internal pulse generator's source contact is electrically connected to channels 1, 2 and 3 and the generator's destination contact is connected to channels 7, 8 and 9. This allows more degrees of freedom to shape the electric field of stimulation.

The BIC3232 supports up to 32 channels for measurement and stimulation. However, depending on the attached electrodes, the actual number of usable channels may be less (e.g., if a custom electrode has 27 channels). In addition to these 32 channels, the ground electrode (GND) can be used a destination electrode.

The BIC3232 allows up to 4 different stimulation amplitudes to be applied simultaneously (duration must be equal), see Section 1.3.
Three electrodes are hard-wired as sources for amplitude 2, 3 and 4. The virtual source electrode for amplitude 1 can be configured for every stimulation function.

Note that not all channel configurations and combinations are allowed (e.g., due to hardware limitations or safety constraints) and are therefore considered invalid. For more details on this, see section 1.5.

1.5. Constraints on the channels

Electrode channels are addressed using indices (i.e., natural positive numbers). The channel indices for BIC3232 implants are 0, 1, …, 31. The ground electrode (GND) has a special index 'c_gnd', see section 2.1 for details.

Virtual source and destination electrodes may not include the hard-wired electrode channels (channel 1, 2 and 3 for Amplitude 1, 2 and 3, respectively), if the corresponding amplitude (Amplitude 1, 2, 3) is not 0mA.

Virtual source and destination electrodes may not include electrodes that are used as measurement reference at the same time.

Table 2: Constraints on virtual electrodes

Parameter	Constraints / allowed values
General constraints	• Virtual source electrode and virtual destination electrode must be disjunct. • Virtual source electrode and virtual destination electrode may not include channels that are used as reference channels for measurement at the same time
virtual destination electrode	• Valid channels: 0 - 31 or c_gnd • At least one channel must be selected as destination • At most 32 channels may be selected as destination • Selected channels may not include the hard-wired source channels if the applied amplitude at the hard-wired source channel is > 0mA
virtual source electrode	• Valid channels: 0 - 31 • At least one channel must be selected as source for Amplitude 0, if Amplitude 1, 2 and 3 = 0mA. • At most 32 channels may be selected as source. • Selected channels may not include the hard-wired source channels if the applied amplitude at the hard-wired source channel is > 0mA

2. BIC C++ API Stimulation explained

The BIC C++ API provides the means to programmatically control the stimulation with a BIC3232 implant. In the following text, the typical steps for starting and stopping stimulation are described.

2.1. How to stimulate

1. **Create an IStimulationCommand instance.**

First, a pointer to an IStimulationCommandFactory instance is obtained (Figure 4, line 1). This factory must be used to create all stimulation-related parameter objects. In line two, the factory's createStimulationCommand() method is called to obtain an empty stimulation command.

2. **Create an IStimulationFunction instance.**

First, the factory's createStimulationFunction() method is called in order to create an empty stimulation function (Figure 4, line 3). Subsequently the signal form is defined by repeatedly calling createRect4AmplitudeStimulationAtom() (Figure 4, line 4 – 8). Please note that the amplitudes and durations of the atoms must comply with the constraints defined in Section 1.2.
For BIC3232 implants it is required that there are always 5 atoms that correspond to the five elements of the signal form described in Section 1.1 (first pulse, DZ0, counter pulse, DZ0, DZ1).

Finally, the atoms are appended to the function object (Figure 4, line 9 – 13).

The example stimulation function defines a signal form with a duration of 12620µs (=20µs + 10µs + 80µs + 10µs + 12500µs). By default, functions are applied once (repetitions = 1). By setting the repetitions to 17 (cf. Figure 4, line 14), the stimulation function now has duration of 214540µs and the bi-phasic impulses are now applied with a frequency of 79.239Hz (= 1 / 0.01262s). Pulse width of the first pulse is 20µs. Amplitude 1 is 3 mA, amplitudes 2, 3 and 4 are 1 mA.

In lines 15 to 21 the source and destination electrodes are defined. In this example, the electrode channels with the indices 0 and 9 are defined as source electrodes and the electrode c_gnd (ground electrode) and 6 are defined as destination electrodes. Please note that channel indices for BIC3232 implants start with 0.
Amplitude 1 is applied at these source channels ('virtual source electrode').
Amplitudes 2, 3 and 4 are each applied at the corresponding hard-wired electrode.

3. Append function to command.

The previously defined stimulation function is then appended to the IStimulationCommand (Figure 4, line 22). Repeat steps 2 and 3 until all desired functions are defined. Functions are executed in the order they were appended.

4. Start stimulation

Stimulation is started by calling the startStimulation() function of an IImplant instance (Figure 4, line 23).

5. Stop stimulation

Stimulation stops after a command has been executed. However, stimulation can also be stopped at any time by calling the stopStimulation() method of an IImplant instance.

```
1  IStimulationCommandFactory* factory = createStimulationCommandFactory();
2  IStimulationCommand* cmd = factory->createStimulationCommand();
3  IStimulationFunction* function = factory->createStimulationFunction();
4  IStimulationAtom* atom1 = factory. createRect4AmplitudeStimulationAtom(
       3000.0 /*microA*/, 1000.0 /*microA*/, 1000.0 /*microA*/, 1000.0 /*microA*/,
       20 /*micros*/);
5  IStimulationAtom* atom2 =
       factory. createRect4AmplitudeStimulationAtom (0.0 /*microA*/,
       0.0 /*microA*/, 0.0 /*microA*/, 0.0 /*microA*/, 10 /*micros*/);
6  IStimulationAtom* atom3 = factory. createRect4AmplitudeStimulationAtom(
       -3000.0/4000.0 /*microA*/, -1000.0/4000.0 /*microA*/,
       -1000.0/4000.0 /*microA*/, -1000.0/4000.0 /*microA*/, 4 * 20 /*micros*/);
7  IStimulationAtom* atom4 = factory. createRect4AmplitudeStimulationAtom (
       0.0 /*microA*/, 0.0 /*microA*/, 0.0 /*microA*/, 0.0 /*microA*/, 10 /*micros*/);
8  IStimulationAtom* atom5 = factory. createRect4AmplitudeStimulationAtom (
       0.0 /*microA*/, 0.0 /*microA*/, 0.0 /*microA*/, 0.0 /*microA*/,
       12500 /*micros*/);
9  function->append(atom1);
10 function->append(atom2);
11 function->append(atom3);
12 function->append(atom4);
13 function->append(atom5);
14 function->setRepetitions(17);
15 std::set<::uin16_t> virtSource;
16 virtSource.insert(0);
17 virtSource.insert(9);
18 std::set<::uin16_t> virtDest;
19 virtDest.insert(CBic3232Constants::c_gnd);
20 virtDest.insert(6);
21 function->setVirtualStimulationElectrodes(virtSource, virtDest);
22 cmd->append(function);
23 implant->startStimulation(cmd);
```

Figure 4: Code example

2.2. How to implement low frequency stimulations

The maximum durations for pulse width, DZ0 and DZ1 define a maximum total duration and a minimum frequency for stimulations (cf. Section 1.2).

If the desired stimulation frequency would exceed the maximum number of 20400µs for DZ1 by Nµs, then repeatedly append two functions f1 and f2 where f1 contains parameters for the bi-phasic pulse compliant with the constraints in Table 1 and f2 contains stimulation parameters with amplitude 0mA and total duration of Nµs. Please note that f2 must comply with the stimulation constraints (cf. Section 1.2), which means it must consist of five atoms with valid duration values and amplitudes of 0mA each.