Microwave neural processing and broadcasting with spintronic nano-oscillators

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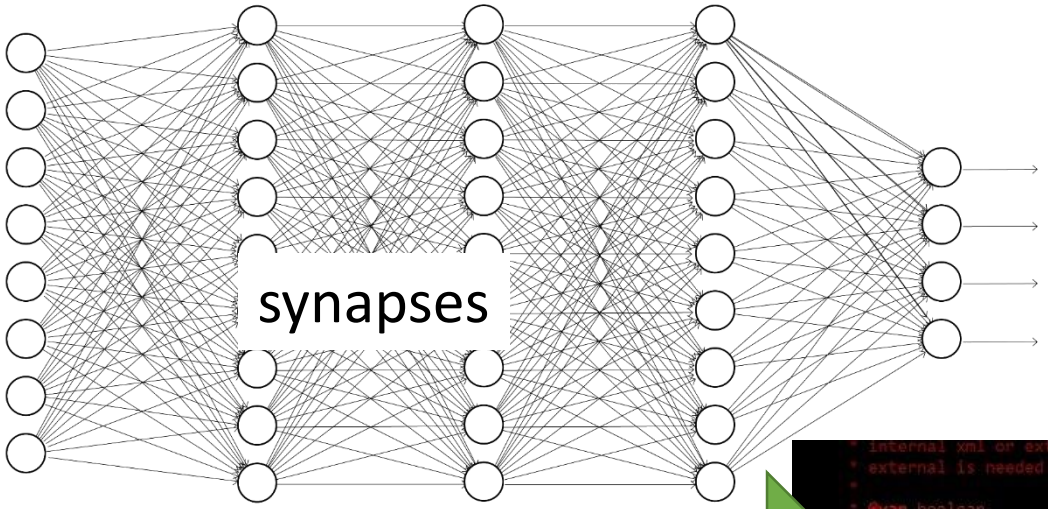
bioSPINspired

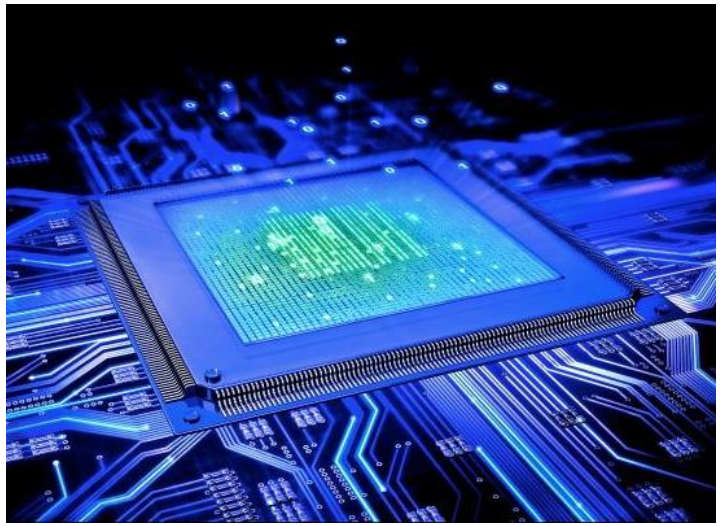
Neural networks run on unoptimized hardware



```
 * internal xml or external
 * external is needed when running in static mode
 *
 * @var boolean
 */
define('PSI_INTERNAL_XML', false);

if (version_compare("5.2", PHP_VERSION, ">")) {
    die("PHP 5.2 or greater is required!!!");
}
if (!extension_loaded("pcre")) {
    die("phpSysInfo requires the pcre extension to php in order to work
        properly.");
}

require_once APP_ROOT.'/includes/autoloader.inc.php';

// Load configuration
require_once APP_ROOT.'/config.php';

if (!defined('PSI_CONFIG_FILE') || !defined('PSI_DEBUG')) {
    $tpl = new Template("/templates/html/error_config.html");
    echo $tpl->fetch();
    die();
```

0011011

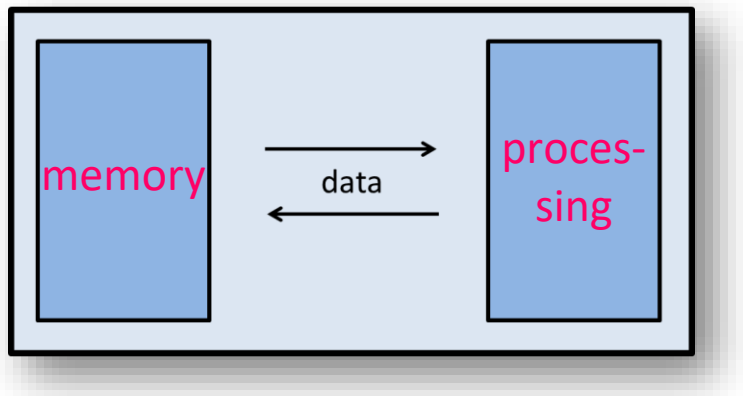
GPUs, TPUs, FPGAs



Entangling memory and processing allows for fast and energy efficient computing

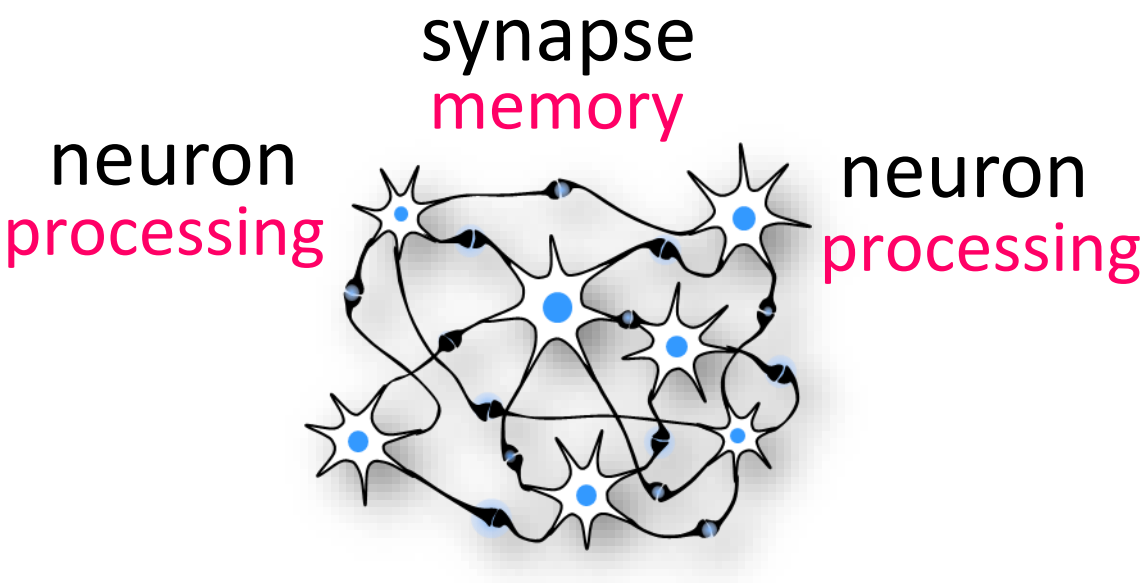
Digital computer

CPUs, GPUs, TPUs, FPGAs



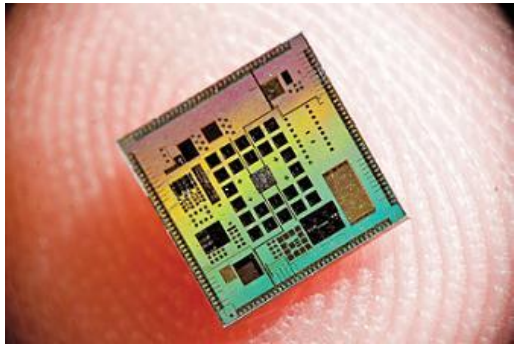
100 W/cm^2

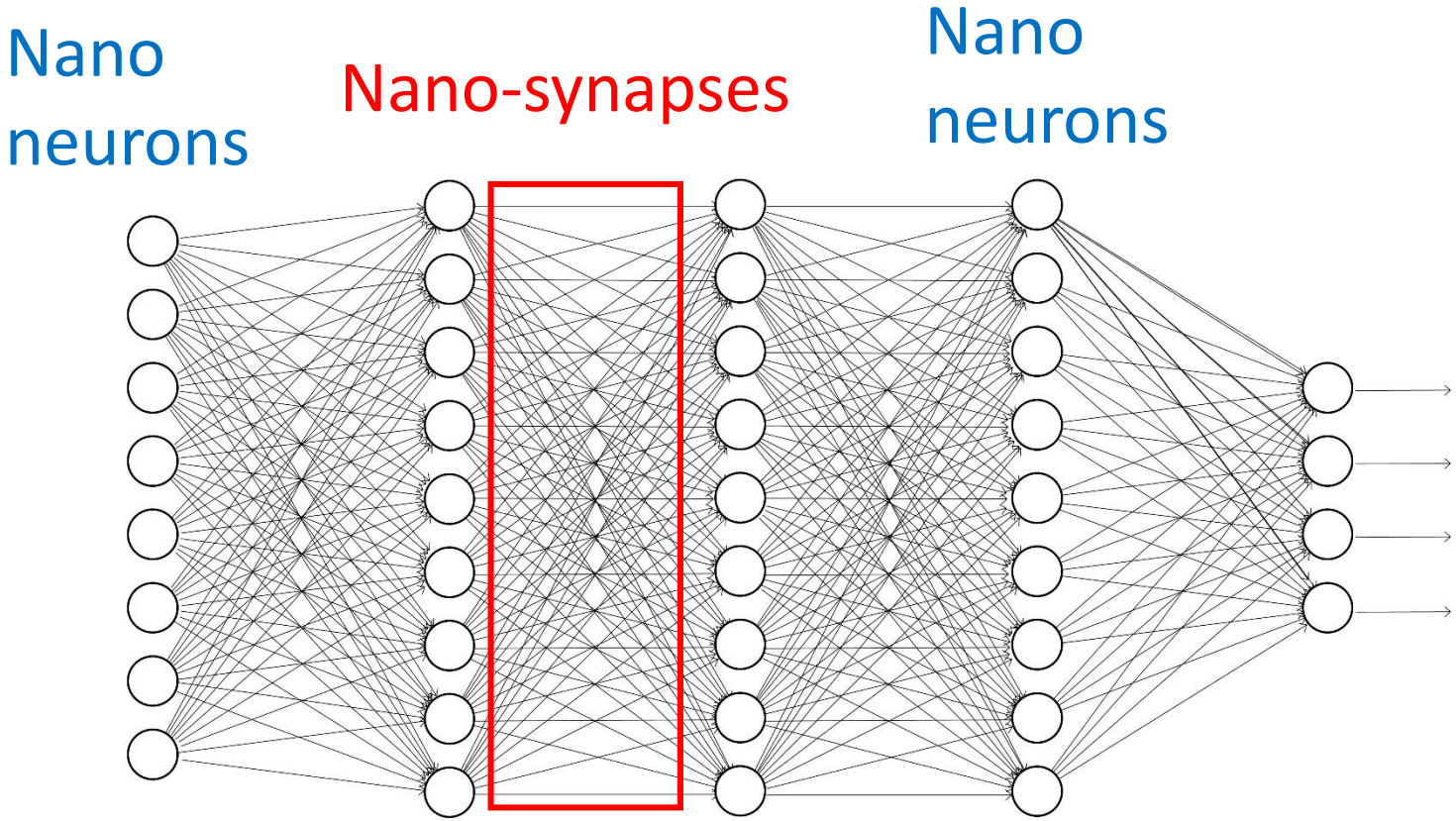
Brain



20 W in total !

Can we build small neuromorphic chips that run deep neural networks ?



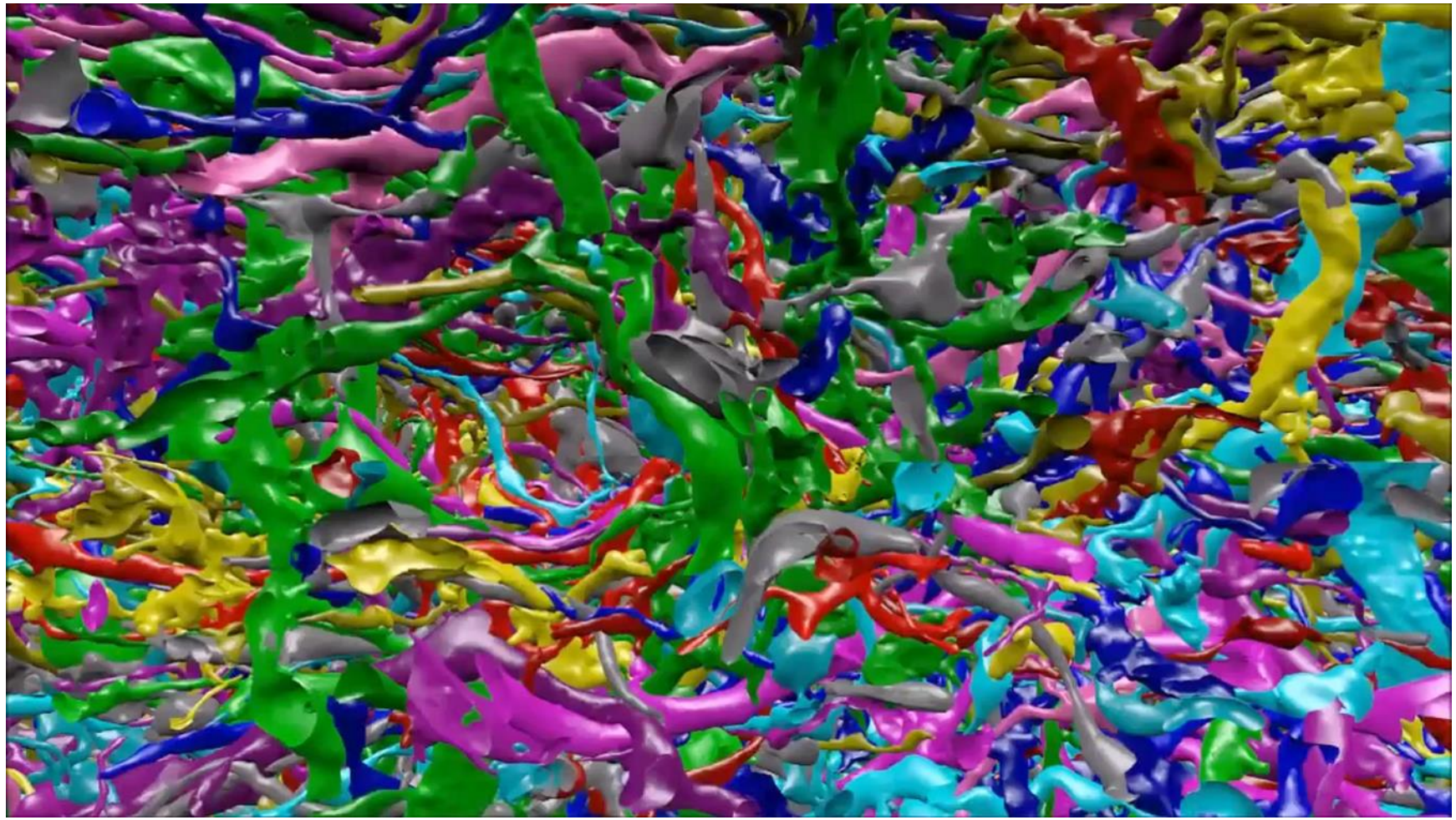


Hundred millions of neurons and synapses in a 1 cm^2 chip

→ Each device smaller than 1 μm^2

Future AI will be massively interconnected

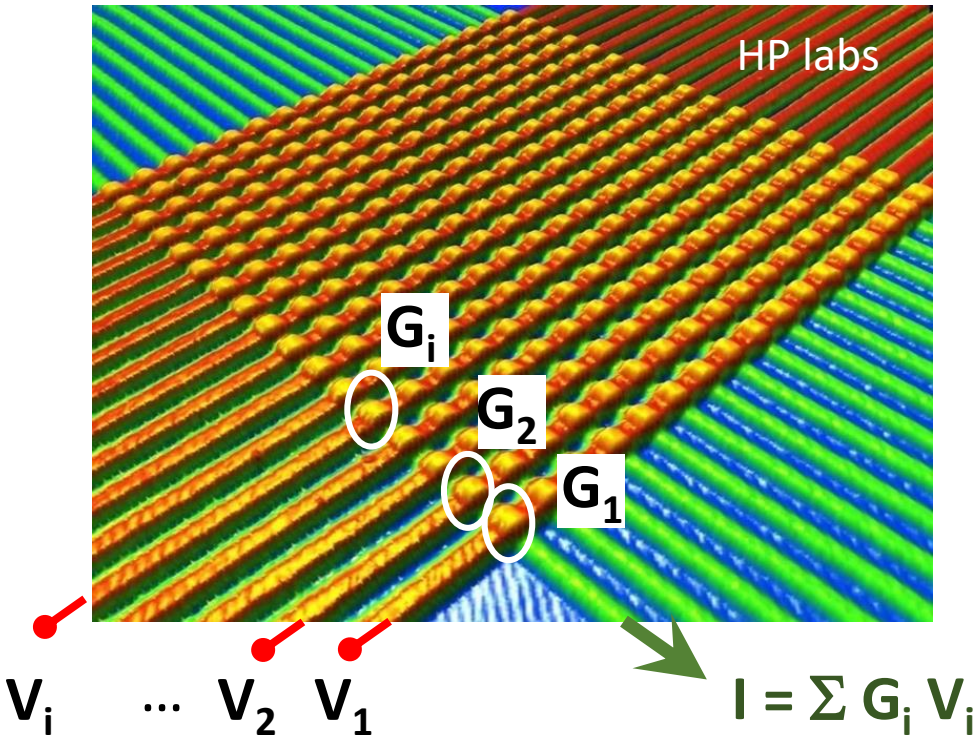
Brain: 10^4 synapses/neurons

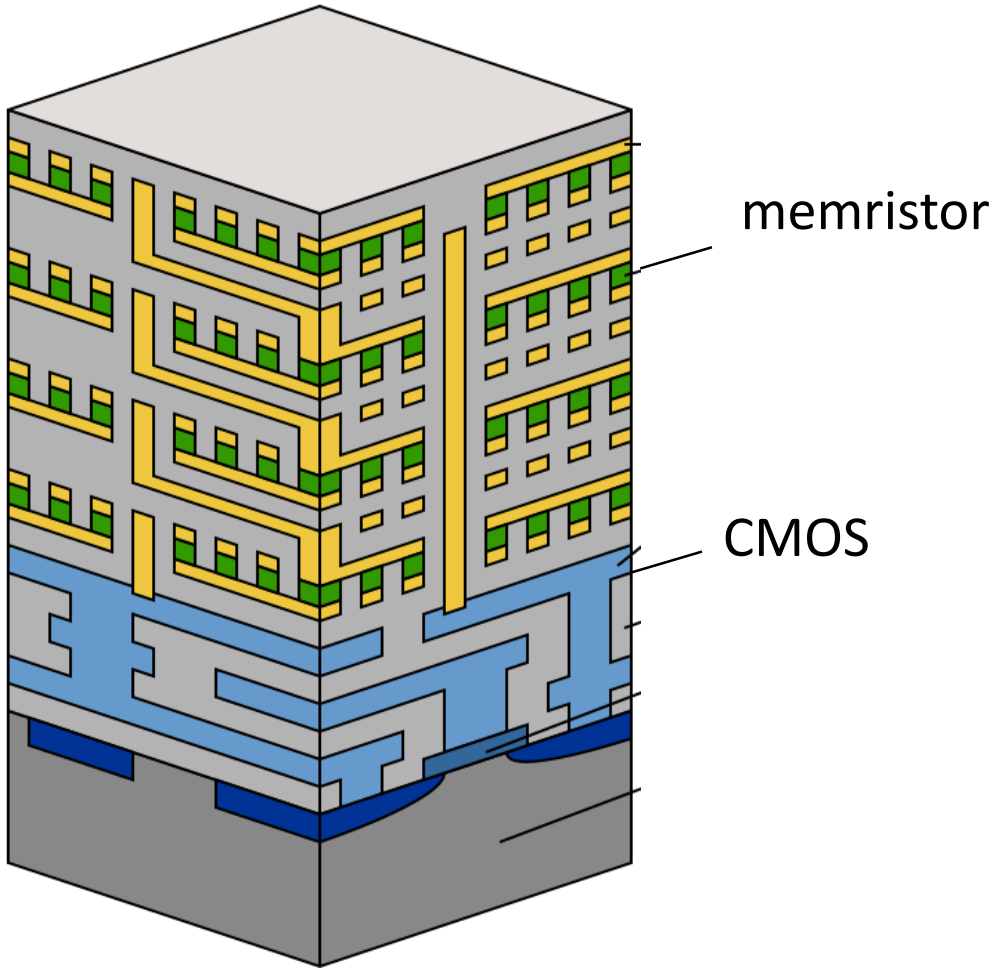


Moritz Helmstaedter lab, retina flight 2013

Main trend : CMOS neurons + Memristive synapses

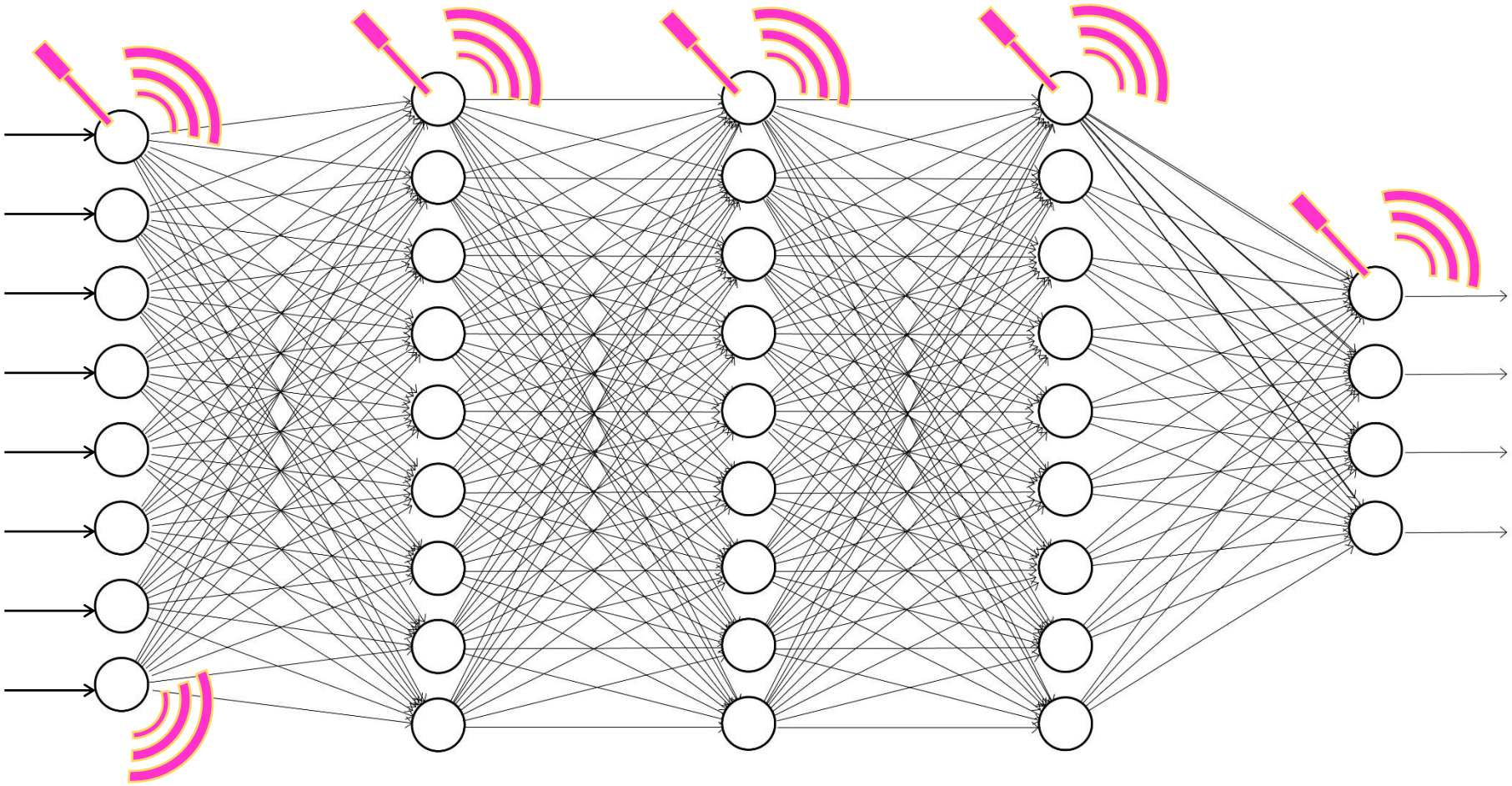
10 000 synapses per neuron ?





Strukov and Williams, PNAS 106, 20155 (2009)

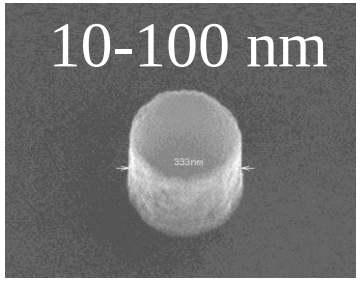
Wireless deep learning through RF communications



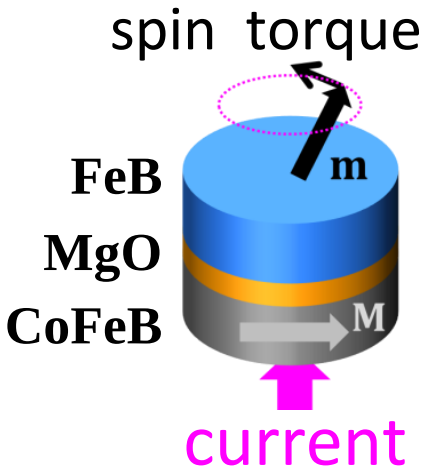
Magnetic nano-oscillators are non-linear nano-radios

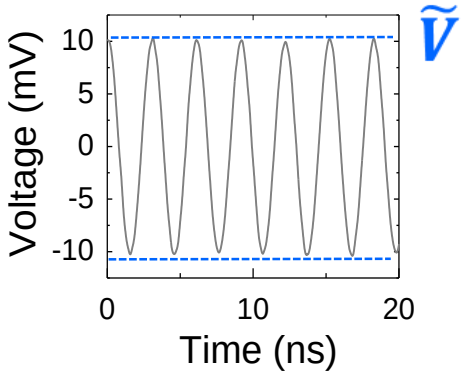
Nanoscale, fast (GHz), non-linear and easily measurable

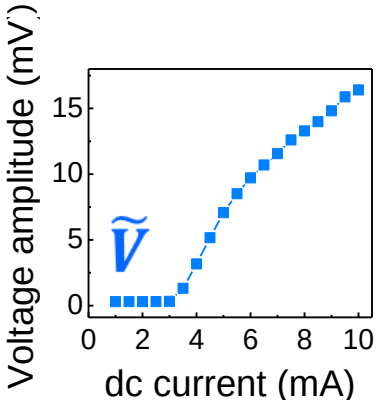
magnetic tunnel junction



compatible with CMOS





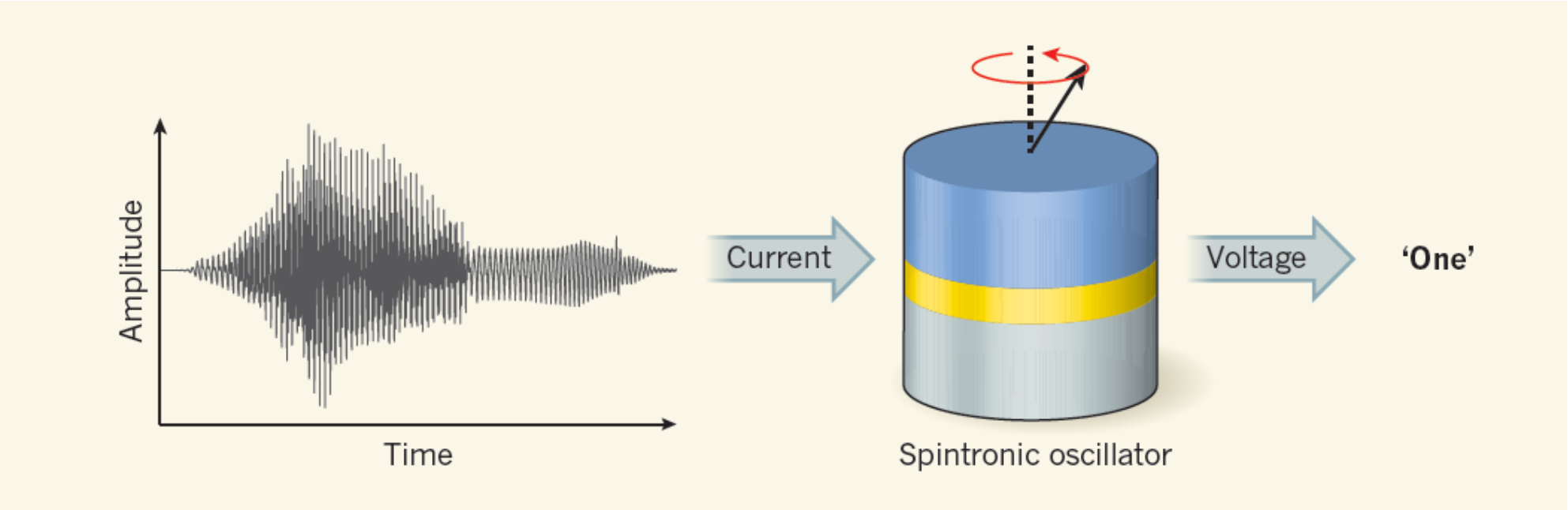


Same structure as magnetic memories

N. Locatelli, V. Cros and J. Grollier, Spin-torque building blocks, Nature Mat. 13, 11 (2014)

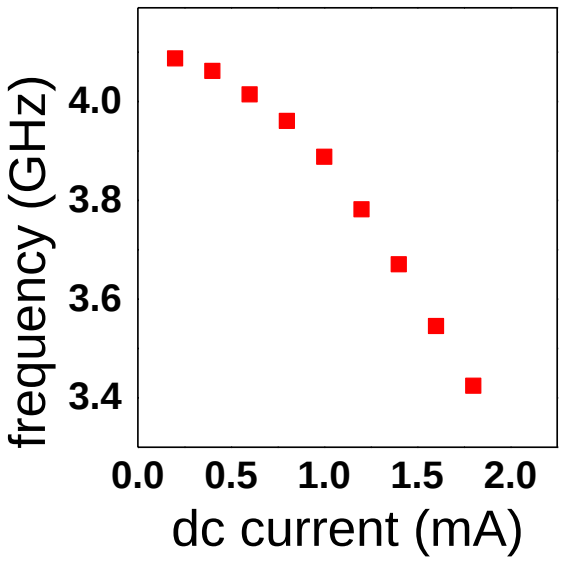
Due to its stability and non-linearity, a single magnetic oscillator can emulate an assembly of neurons and perform neuromorphic computing

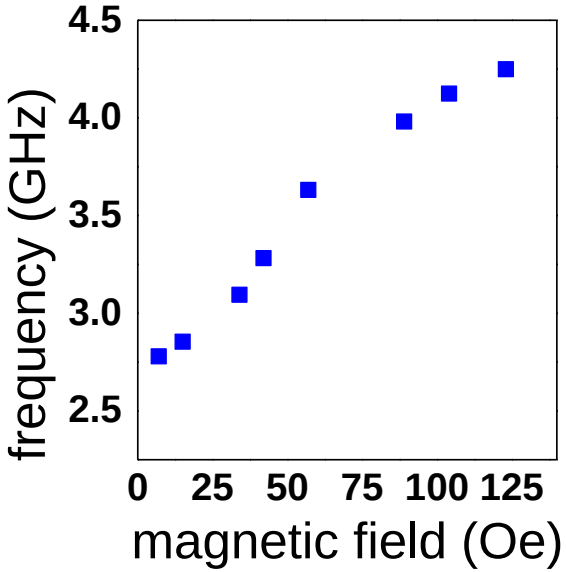
Spoken digit recognition through reservoir computing



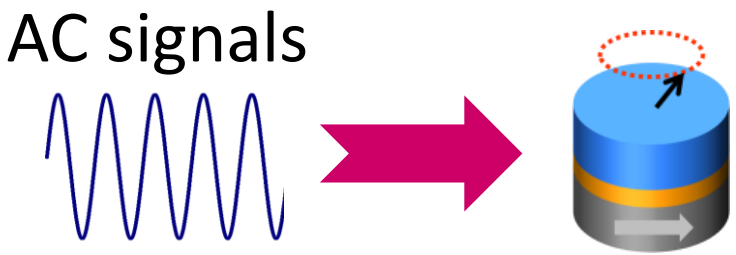
J. Torrejon, M. Riou, F. Abreu Araujo et al, Nature 547, 428 (2017)

Spin-torque nano-oscillators have a high tunability : they are radio-receivers



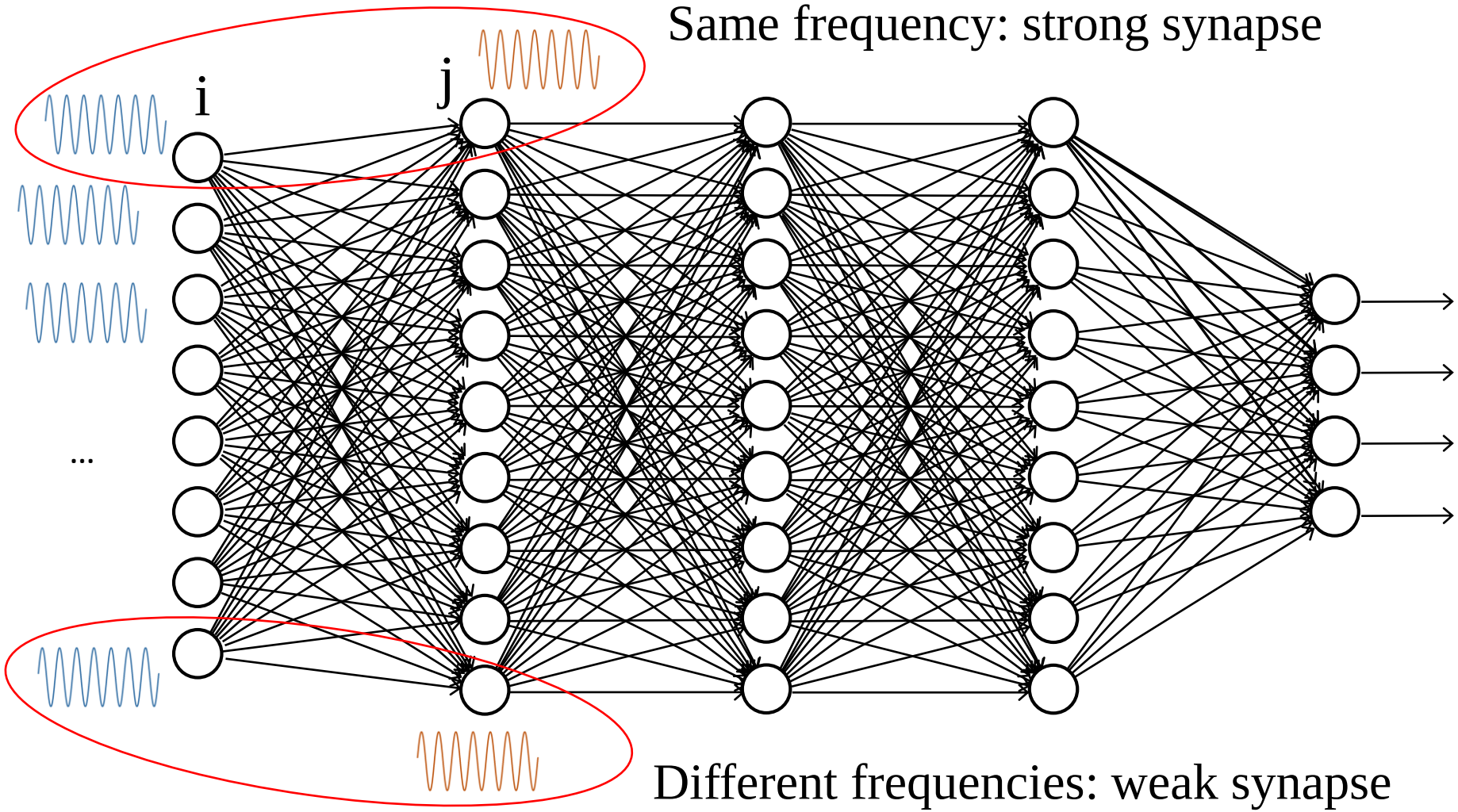


Enhanced sync ranges

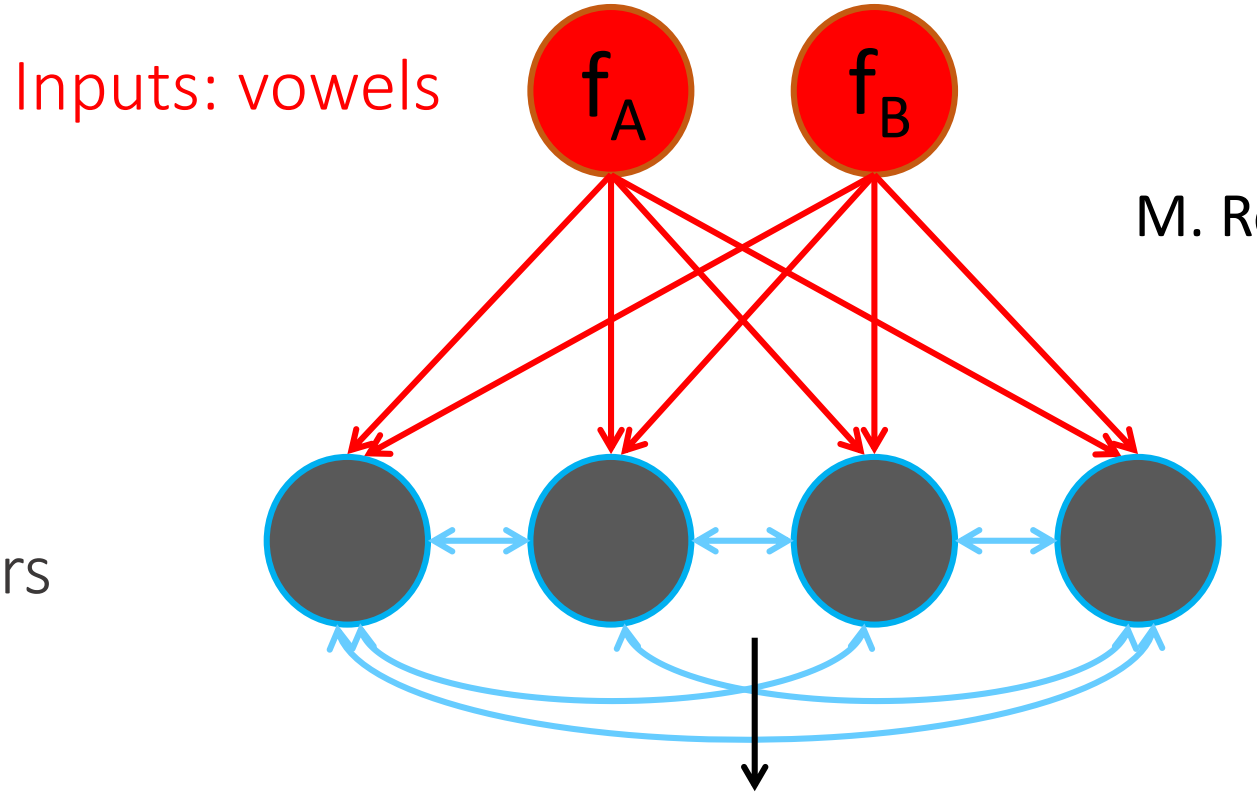


A. Slavin and V. Tiberkevich, IEEE TM 45, 1875 (2009)

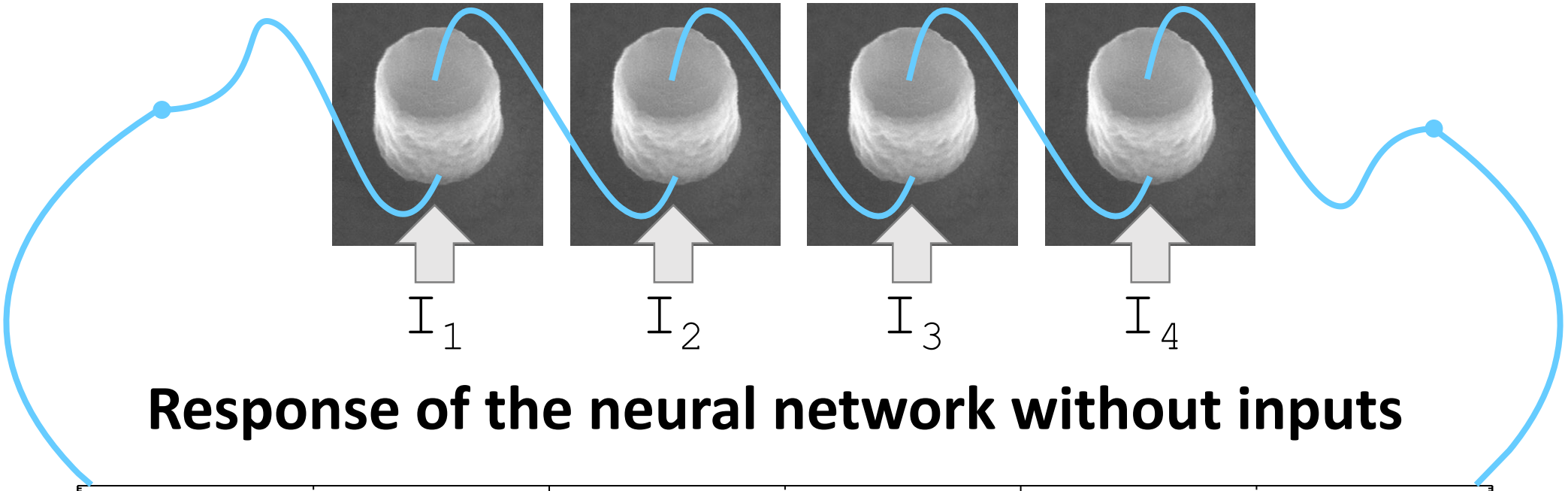
The oscillators ability to mutually interact opens the path to RF on-chip communication between neuron layers



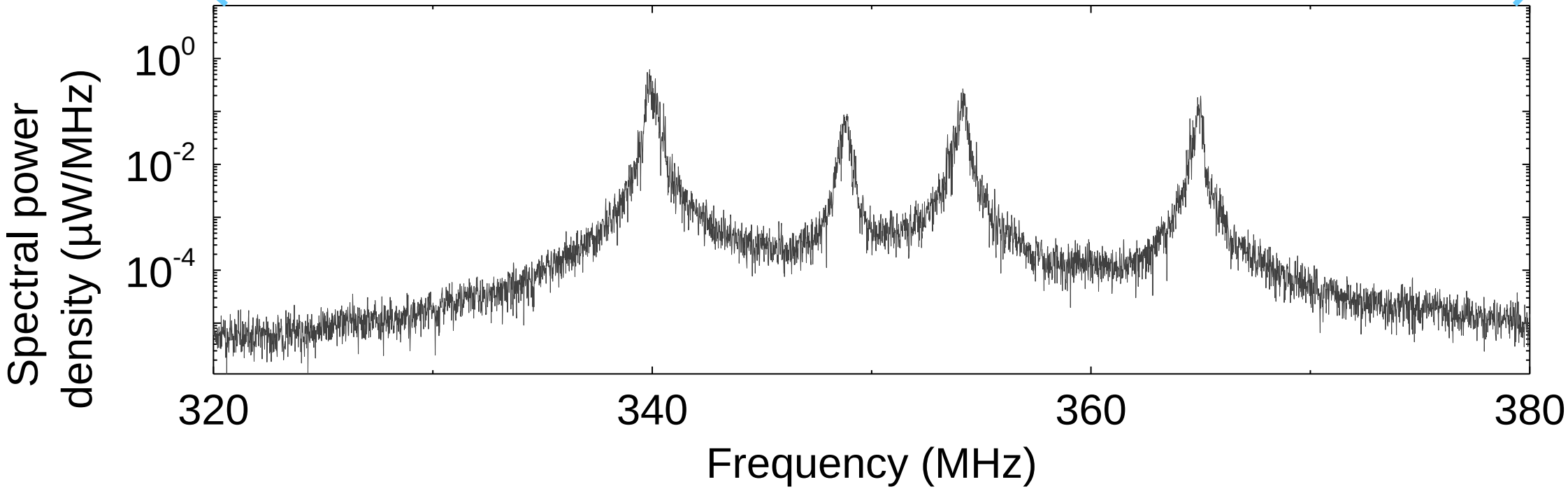
Vowels classification with spin-torque oscillator neural network

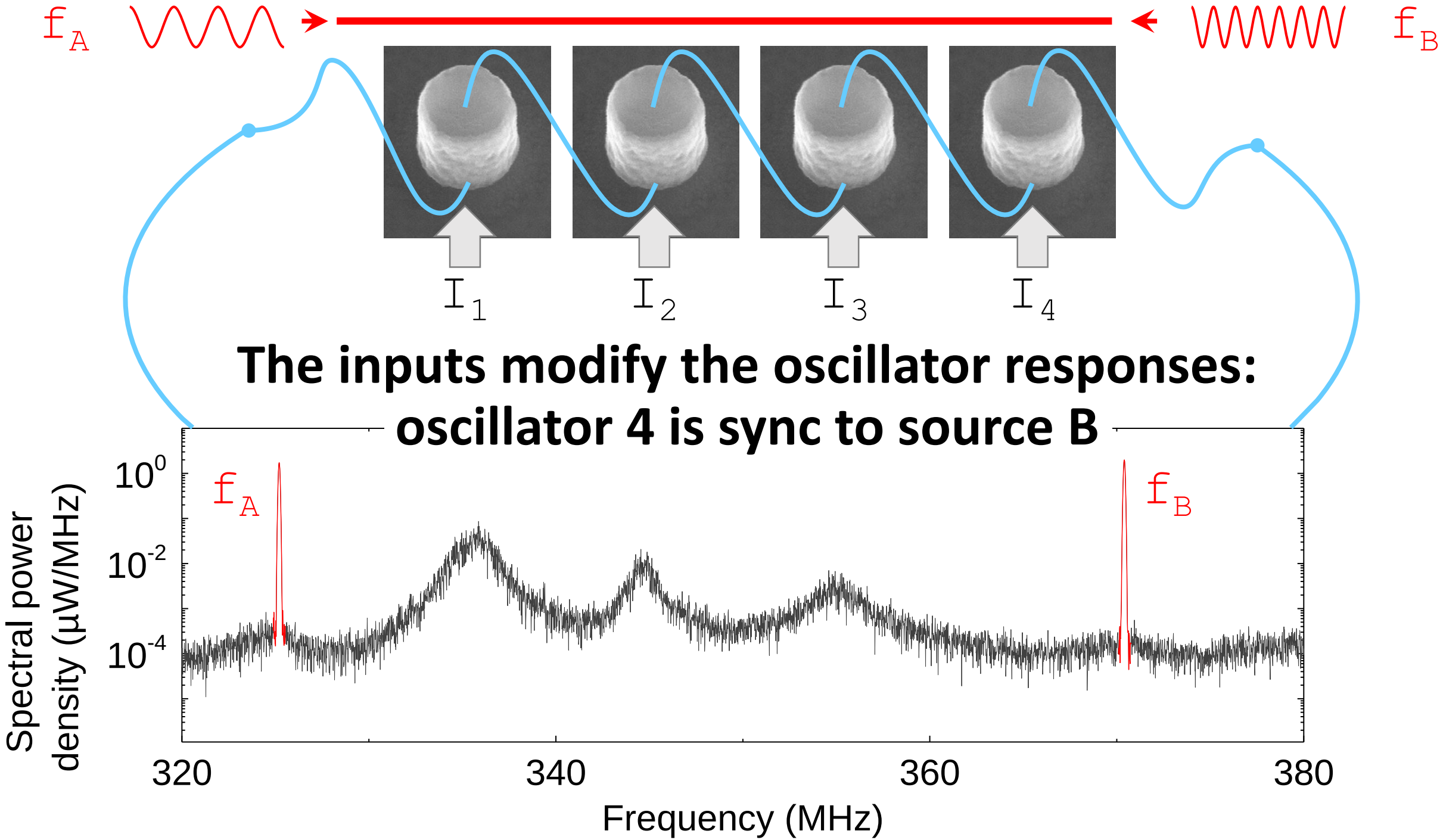


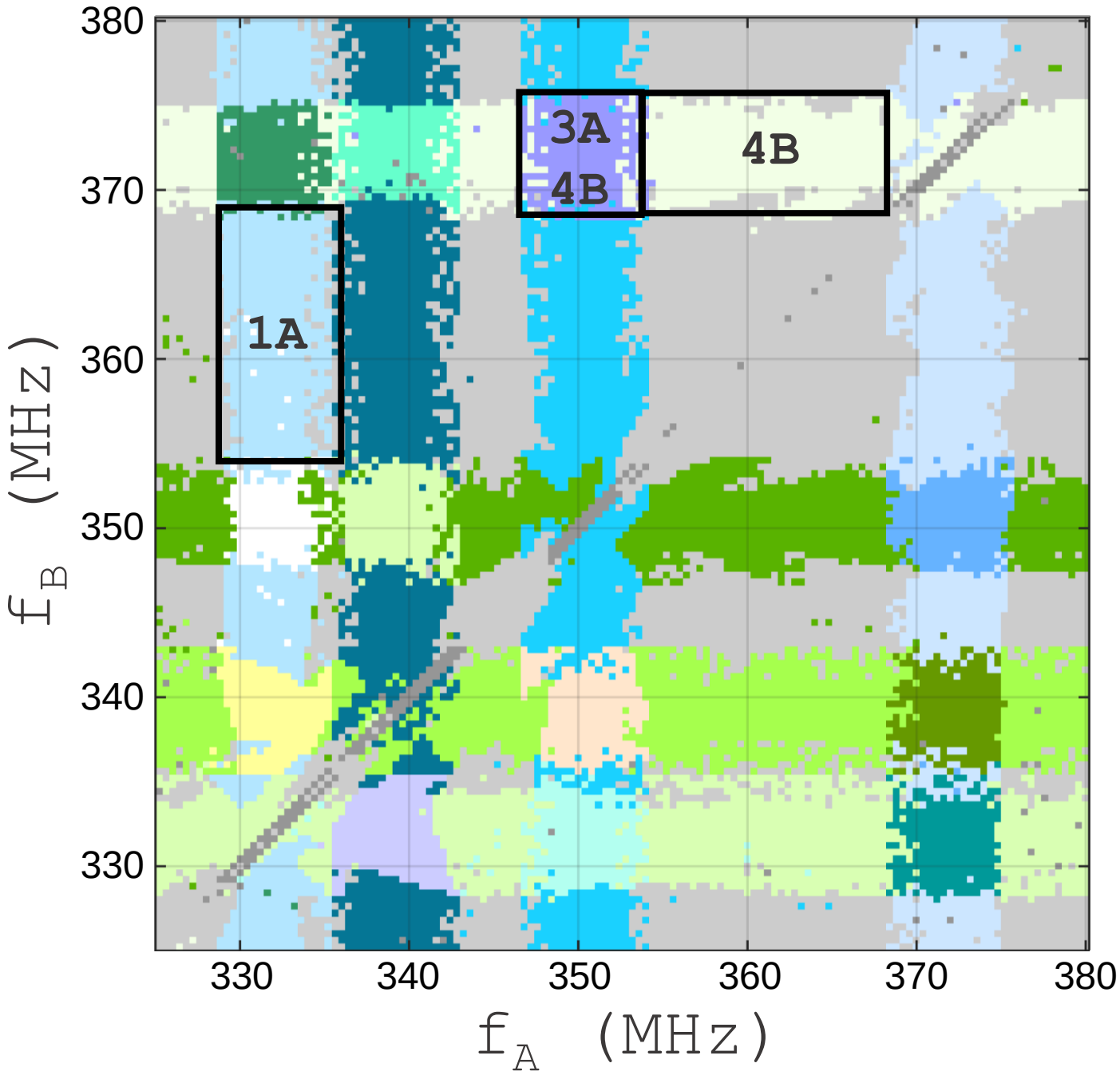
M. Romera, P. Talatchian et al,
Nature 563, 230 (2018)



Response of the neural network without inputs




f_A
f_B
I_1
I_2
I_3
I_4
The inputs modify the oscillator responses:
oscillator 4 is sync to source B
f_A
f_B
Spectral power density (μW/MHz)
10^0
10^{-2}
10^{-4}
320
340
360
380
Frequency (MHz)

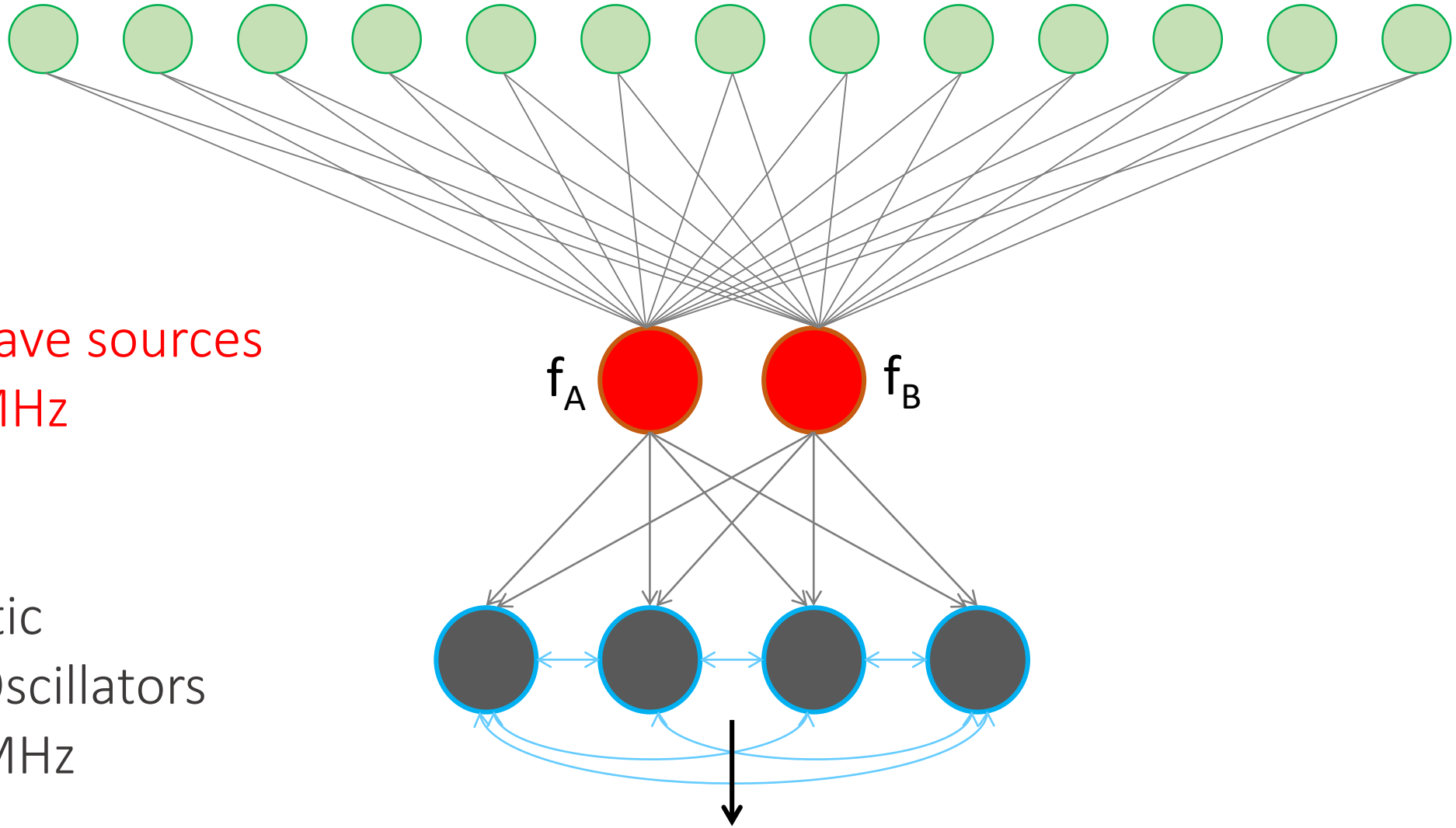


We summarize all these measurements in a map where the different synchronization states have different colors

Input vowels
~ 1 kHz

Hillebrands Michingan database

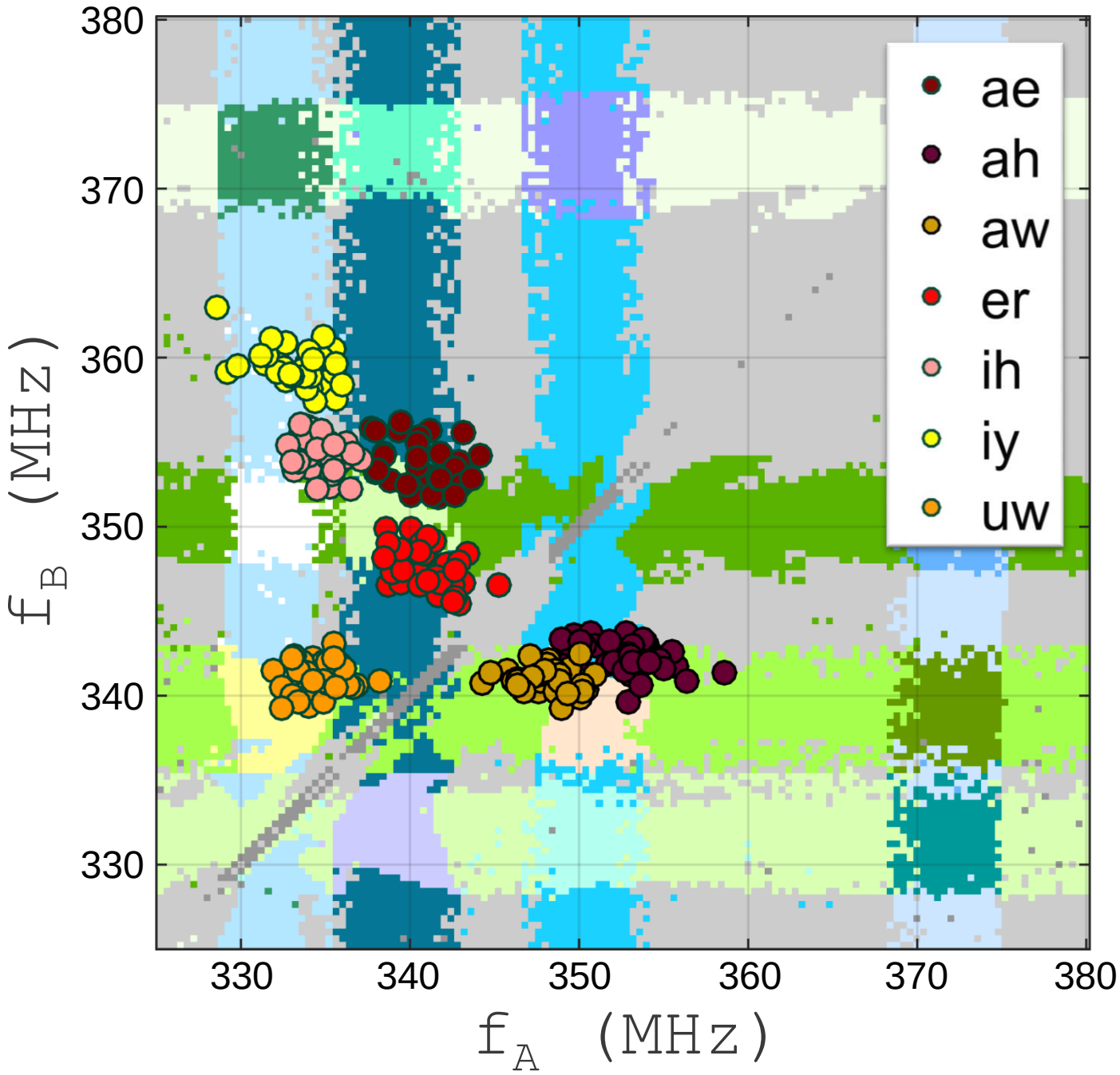
12 formant frequencies + 1 bias



Microwave sources
~ 300 MHz

Magnetic
Nano-Oscillators
~ 300 MHz

Outputs: synchronized states

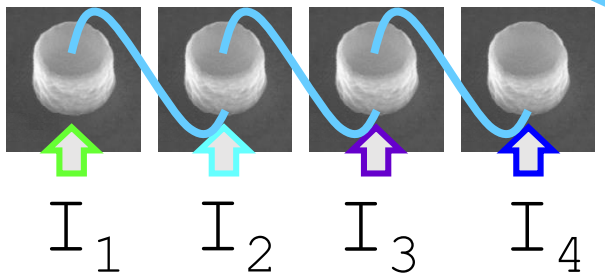


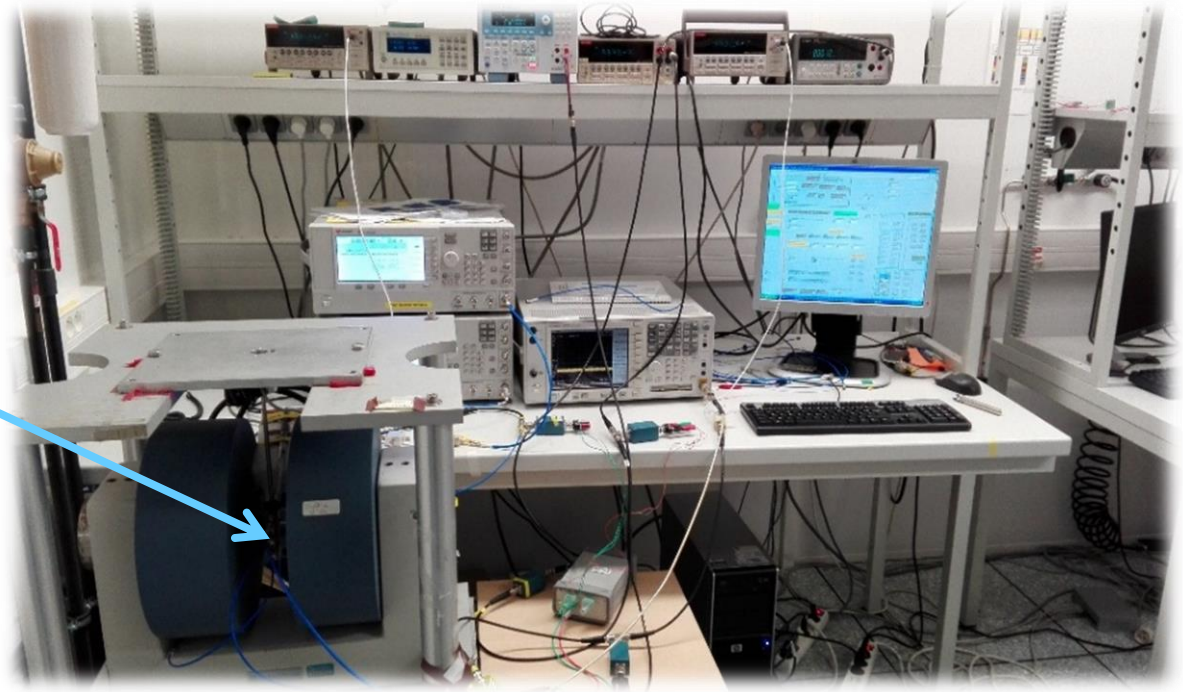
For classification, all the points corresponding to one vowel should fall in a single synchronization region

We train the network by tuning the currents through the oscillators according to an online learning rule

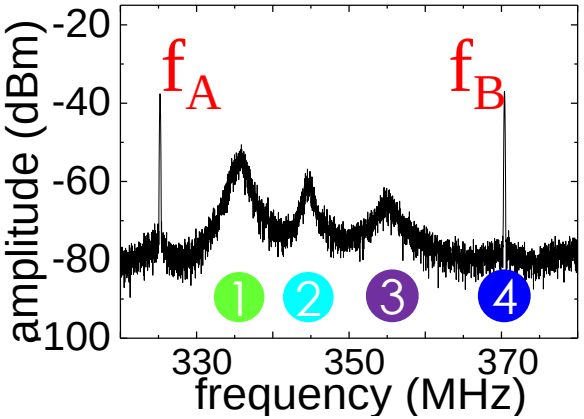
Experimental set-up ⟷ Computer (Learning algorithm)

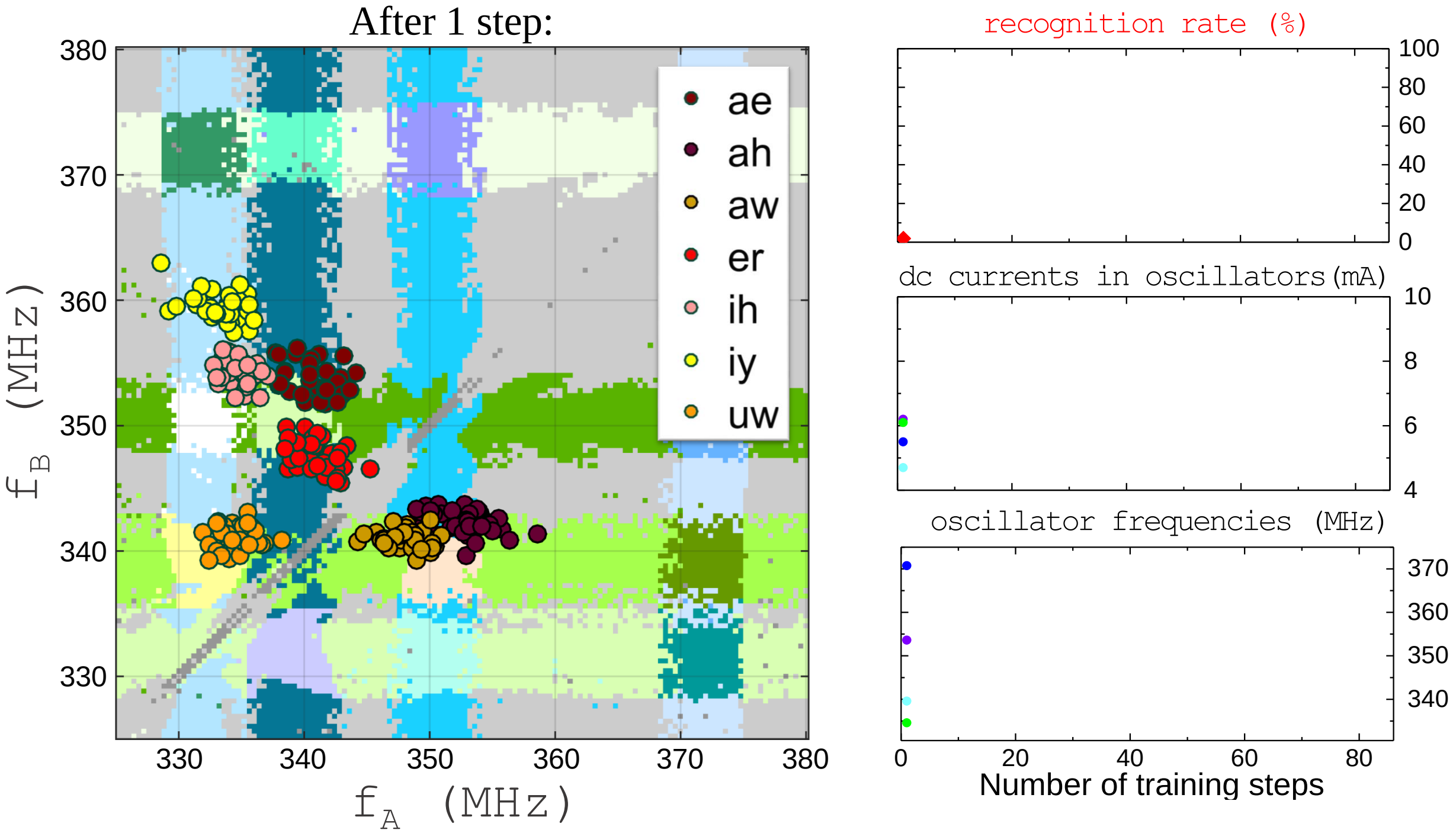
Oscillators

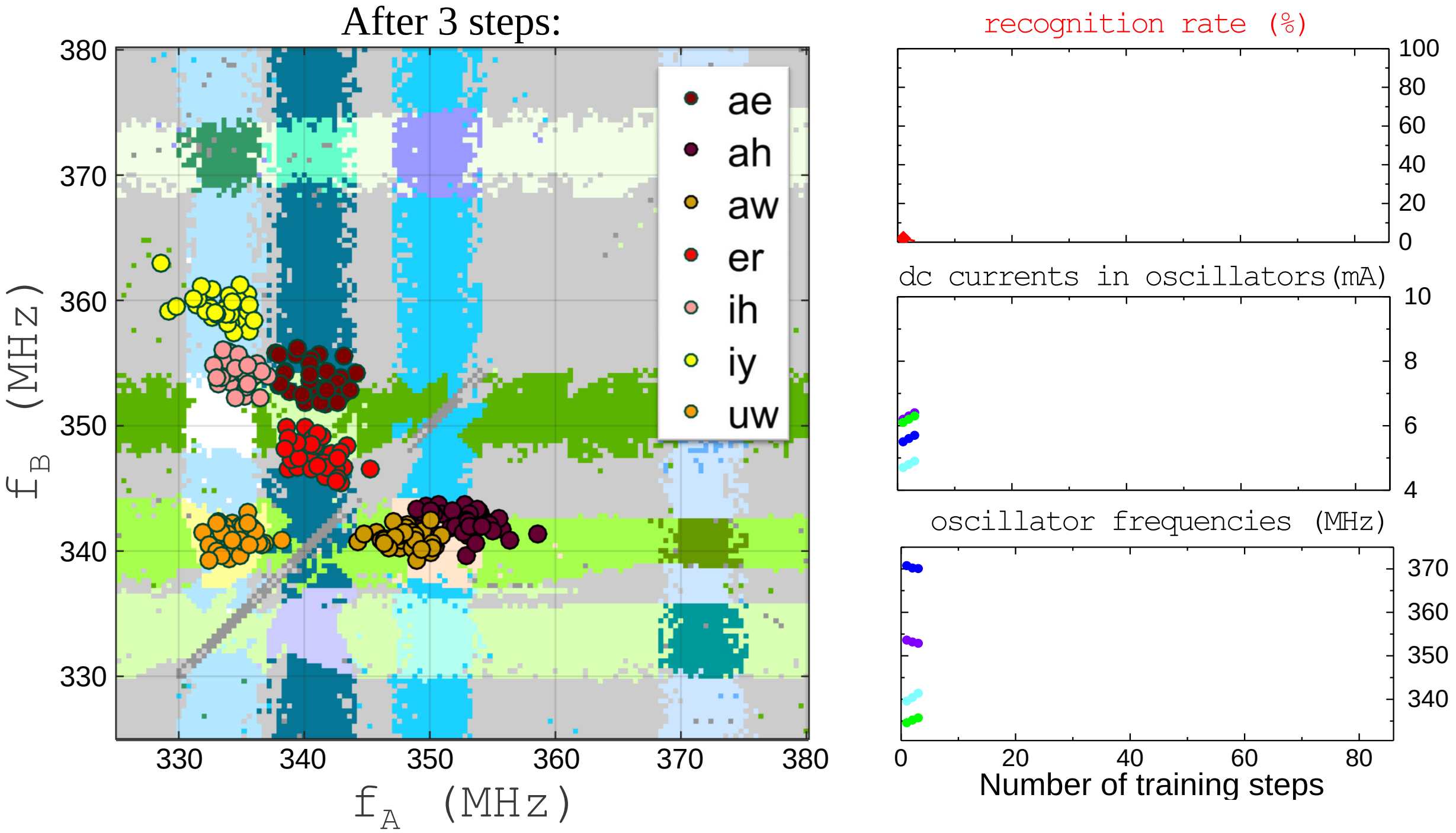


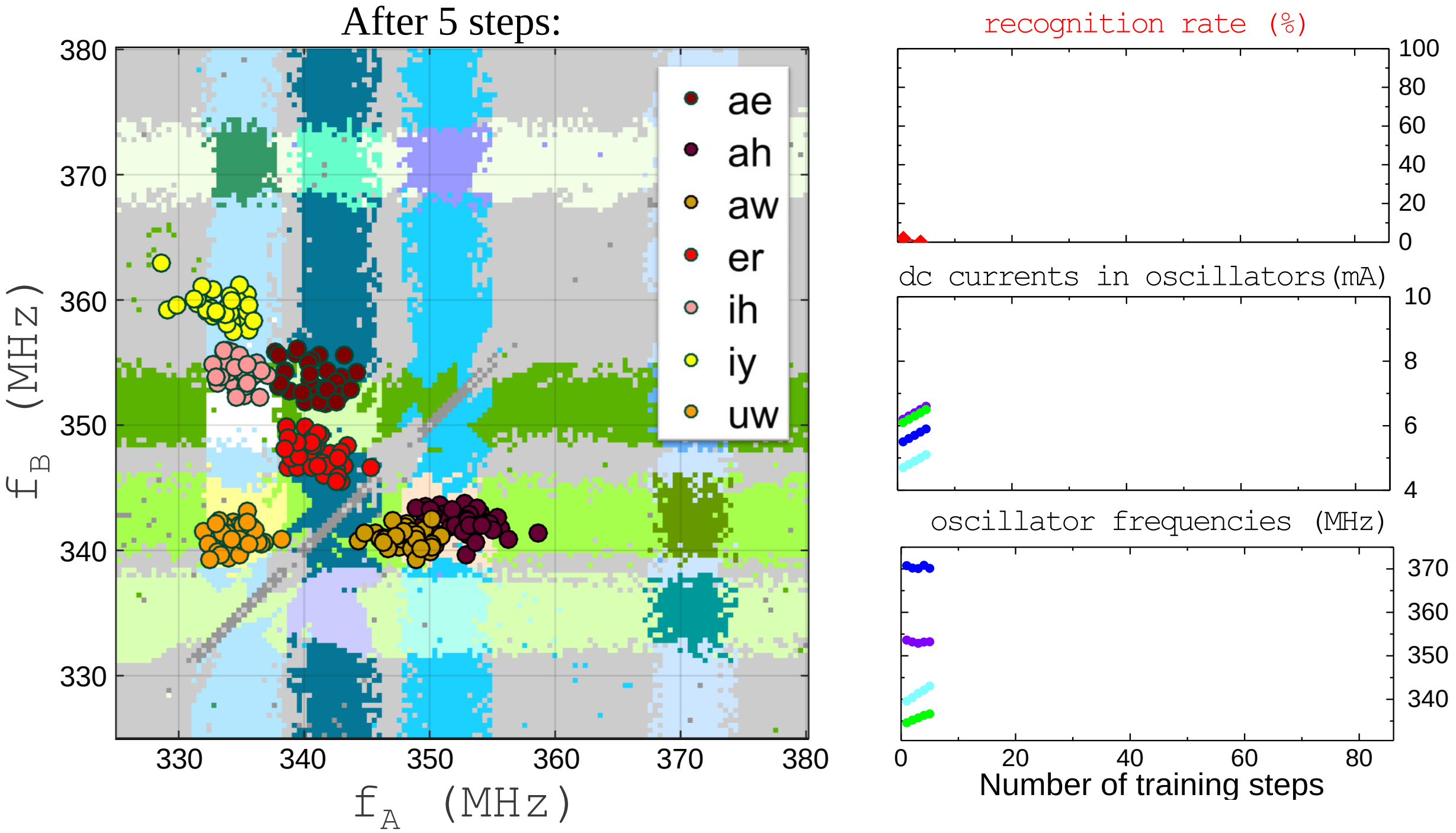


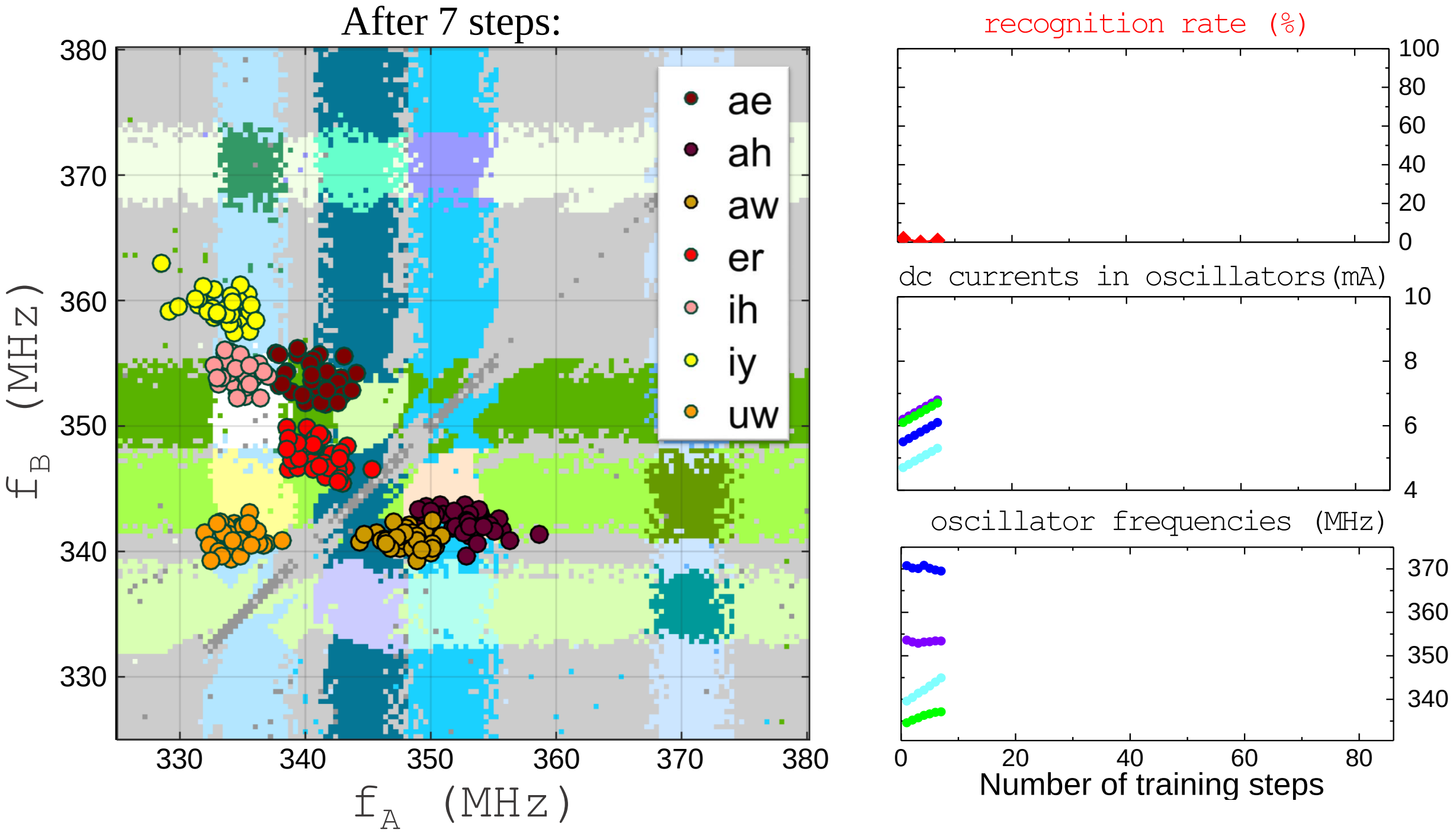
ex: « iy » 4B

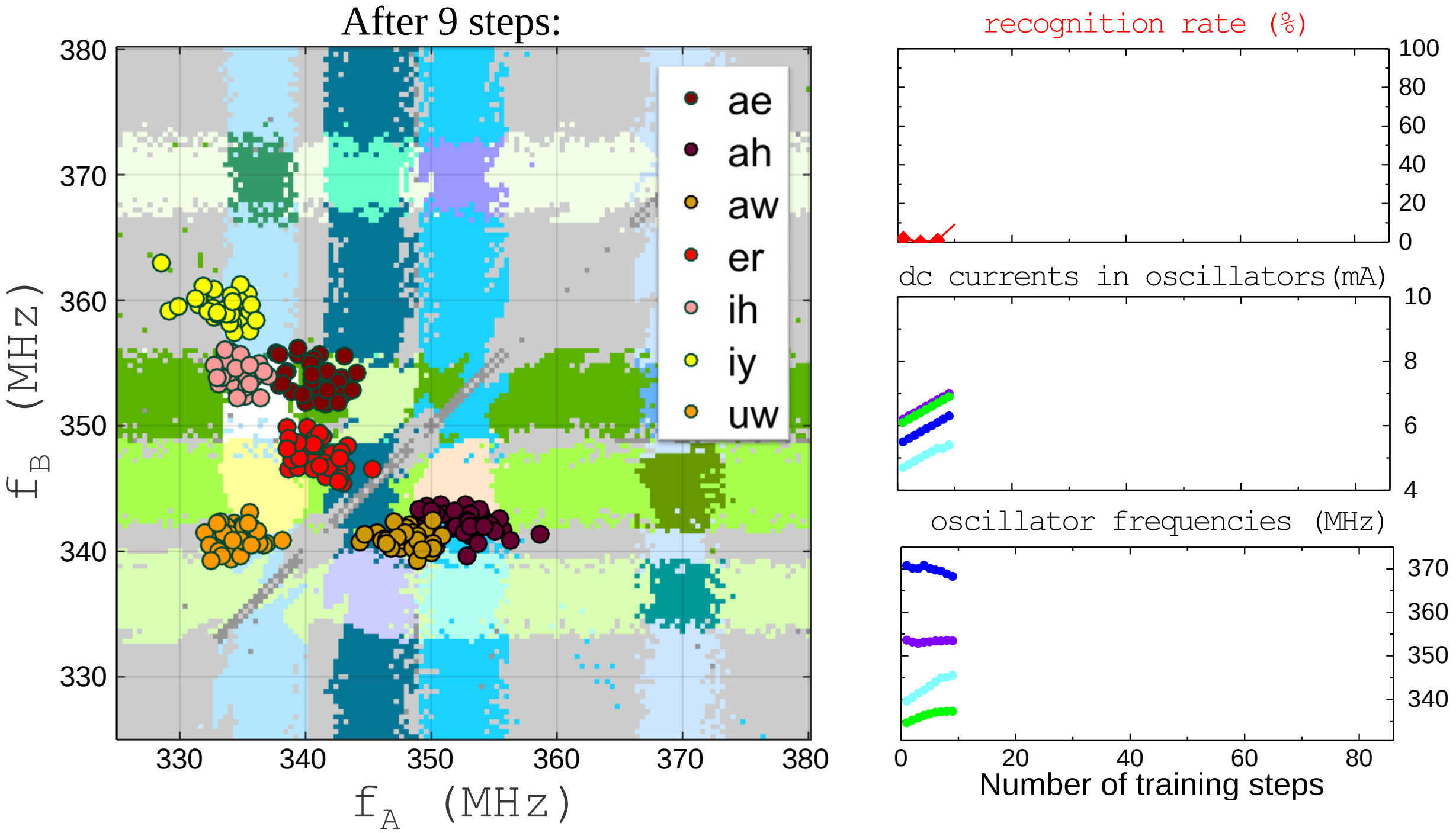


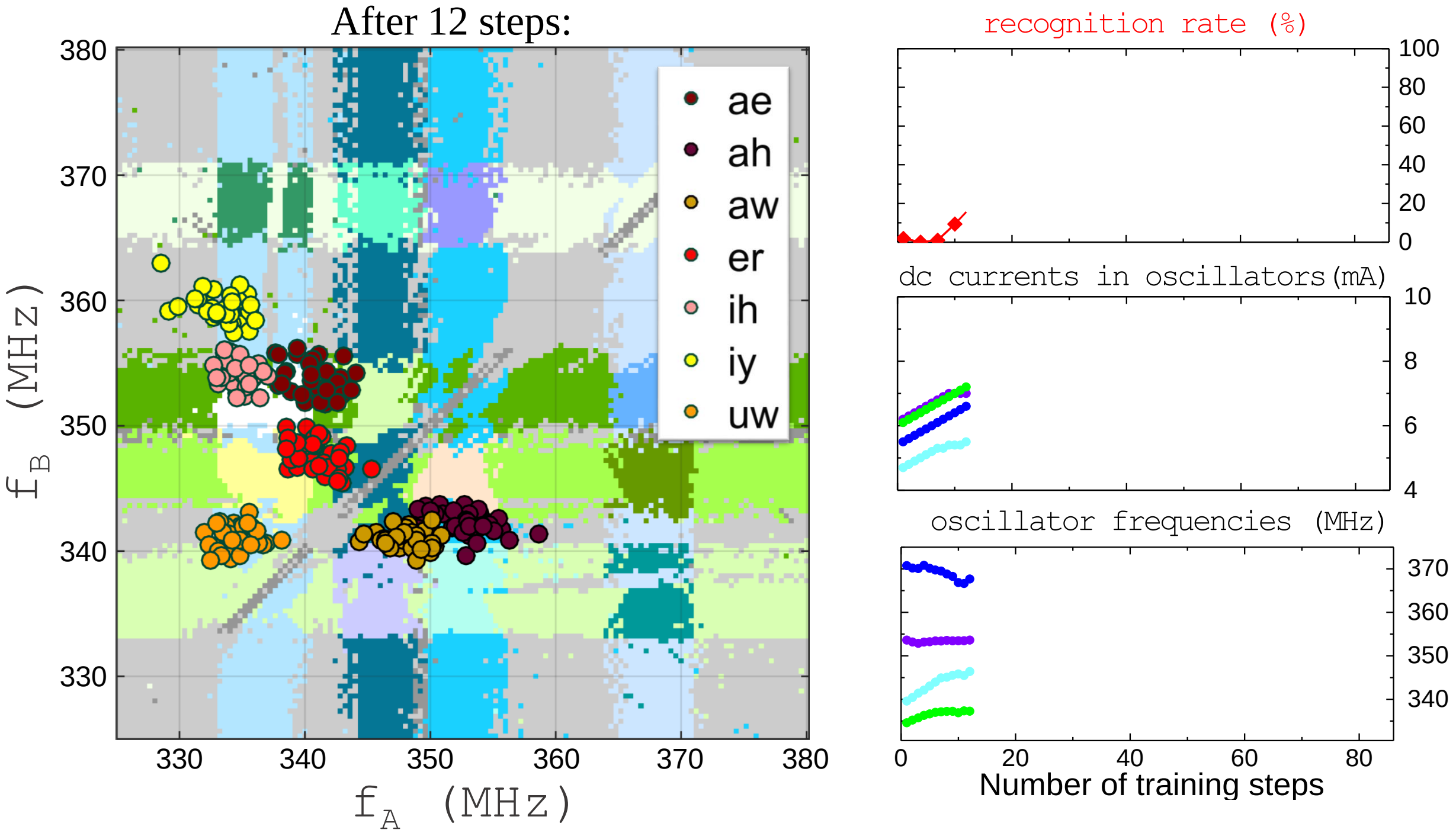

After 1 step:
ae
ah
aw
er
ih
iy
uw
380
370
360
350
340
330
330
340
350
360
370
380
f_B (MHz)
f_A (MHz)
recognition rate (%)
100
80
60
40
20
0
dc currents in oscillators (mA)
10
8
6
4
oscillator frequencies (MHz)
370
360
350
340
0
20
40
60
80
Number of training steps

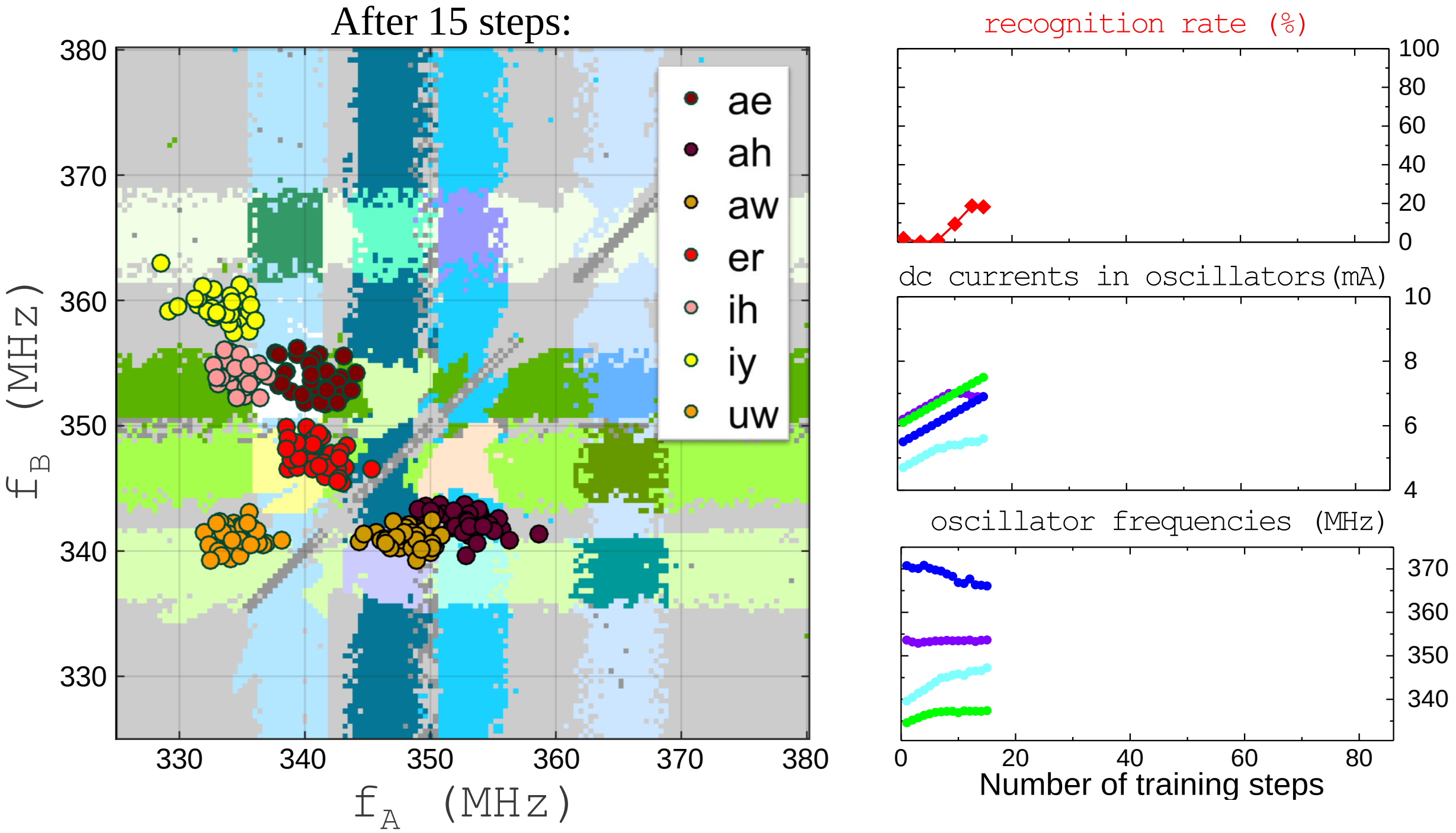

After 3 steps:
ae
ah
aw
er
ih
iy
uw
380
370
360
350
340
330
330
340
350
360
370
380
f_B (MHz)
f_A (MHz)
recognition rate (%)
100
80
60
40
20
0
dc currents in oscillators (mA)
10
8
6
4
oscillator frequencies (MHz)
370
360
350
340
0
20
40
60
80
Number of training steps


After 5 steps:
ae
ah
aw
er
ih
iy
uw
380
370
360
350
340
330
330
340
350
360
370
380
f_B (MHz)
f_A (MHz)
recognition rate (%)
100
80
60
40
20
0
dc currents in oscillators (mA)
10
8
6
4
oscillator frequencies (MHz)
370
360
350
340
0
20
40
60
80
Number of training steps

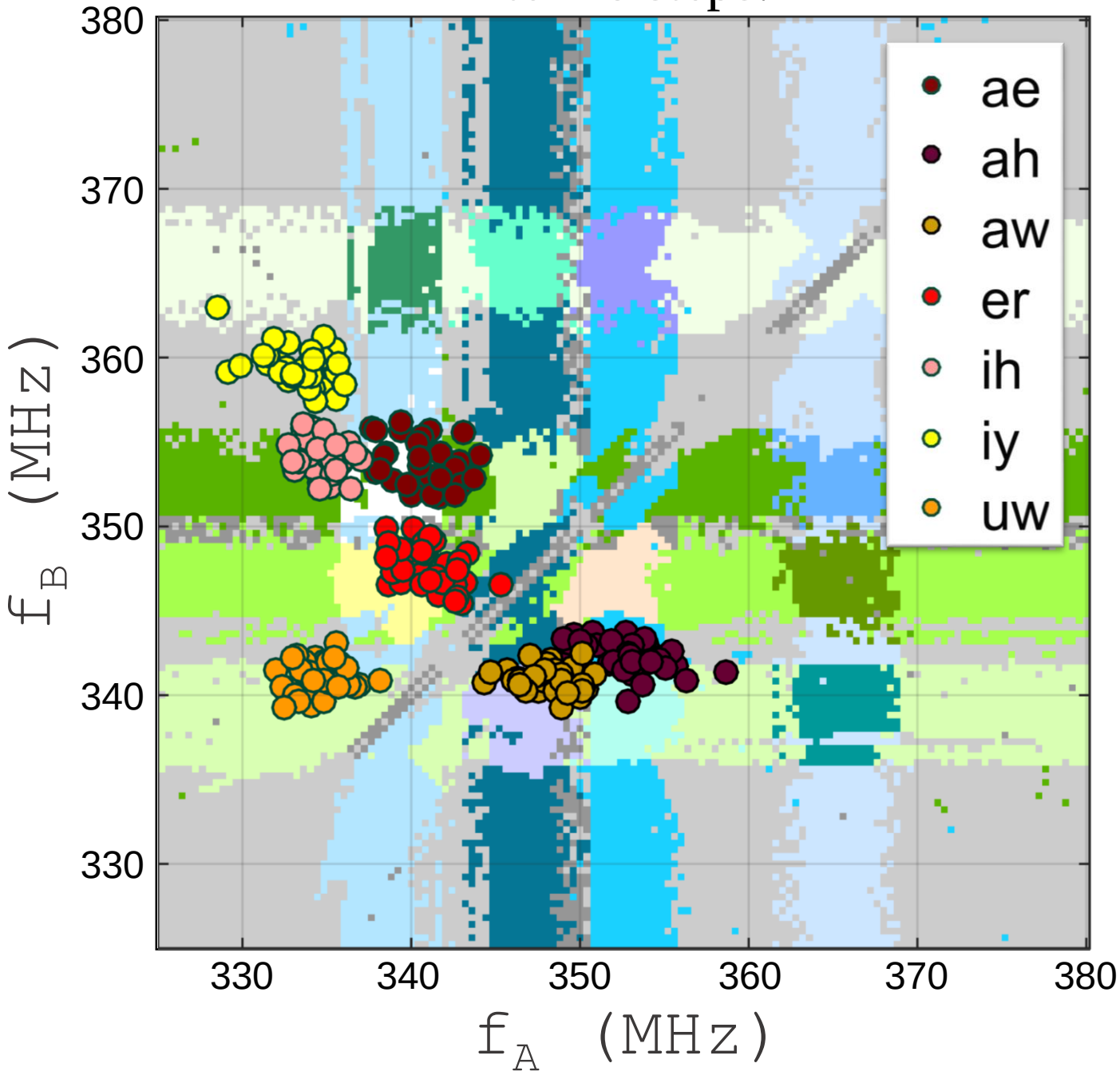

After 7 steps:
ae
ah
aw
er
ih
iy
uw
380
370
360
350
340
330
330
340
350
360
370
380
f_B (MHz)
f_A (MHz)
recognition rate (%)
100
80
60
40
20
0
dc currents in oscillators (mA)
10
8
6
4
oscillator frequencies (MHz)
370
360
350
340
0
20
40
60
80
Number of training steps

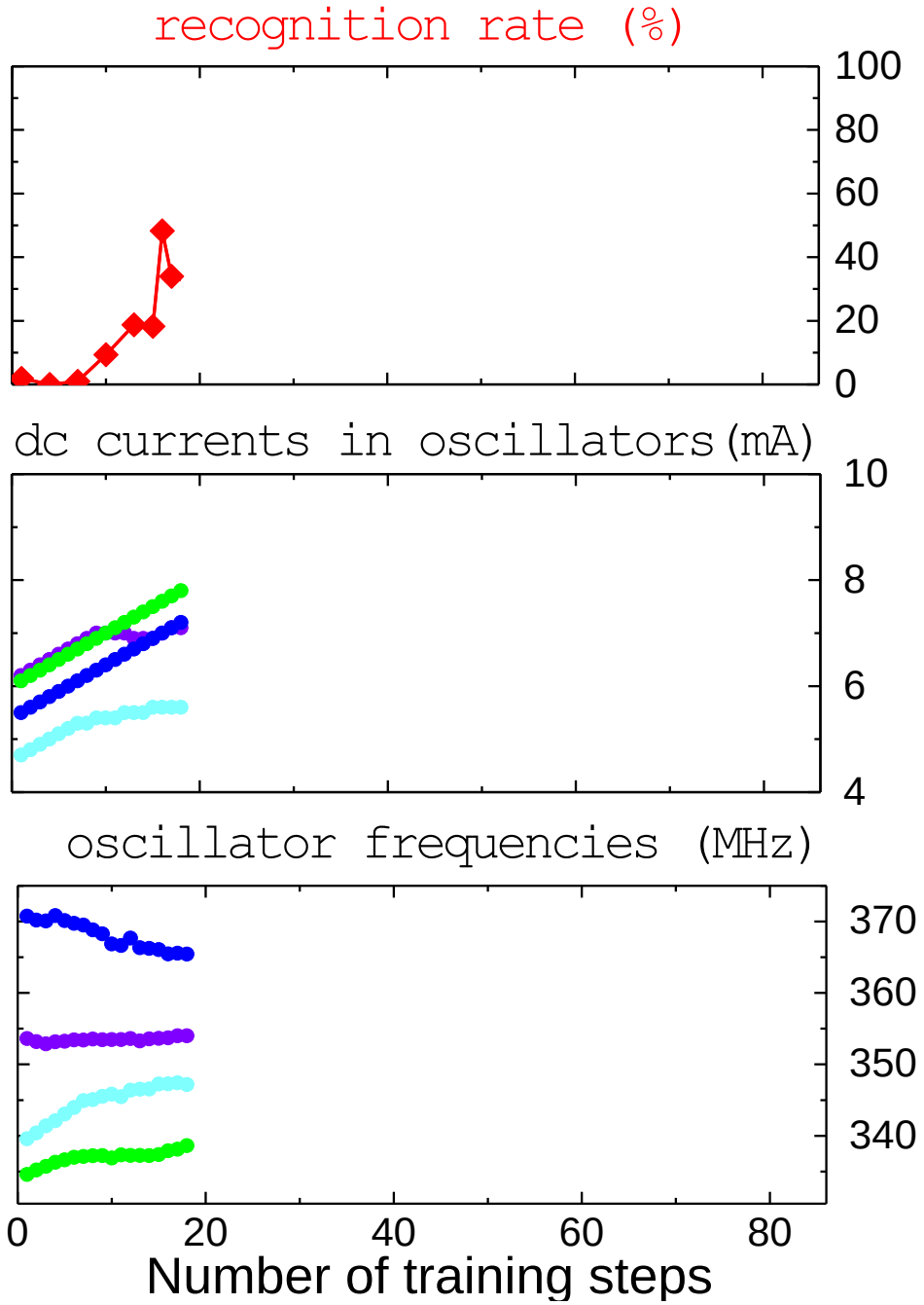

After 9 steps:
ae
ah
aw
er
ih
iy
uw
380
370
360
350
340
330
330
340
350
360
370
380
f_B (MHz)
f_A (MHz)
recognition rate (%)
100
80
60
40
20
0
dc currents in oscillators (mA)
10
8
6
4
oscillator frequencies (MHz)
370
360
350
340
0
20
40
60
80
Number of training steps


After 12 steps:
ae
ah
aw
er
ih
iy
uw
380
370
360
350
340
330
330
340
350
360
370
380
f_B (MHz)
f_A (MHz)
recognition rate (%)
100
80
60
40
20
0
dc currents in oscillators (mA)
10
8
6
4
oscillator frequencies (MHz)
370
360
350
340
0
20
40
60
80
Number of training steps

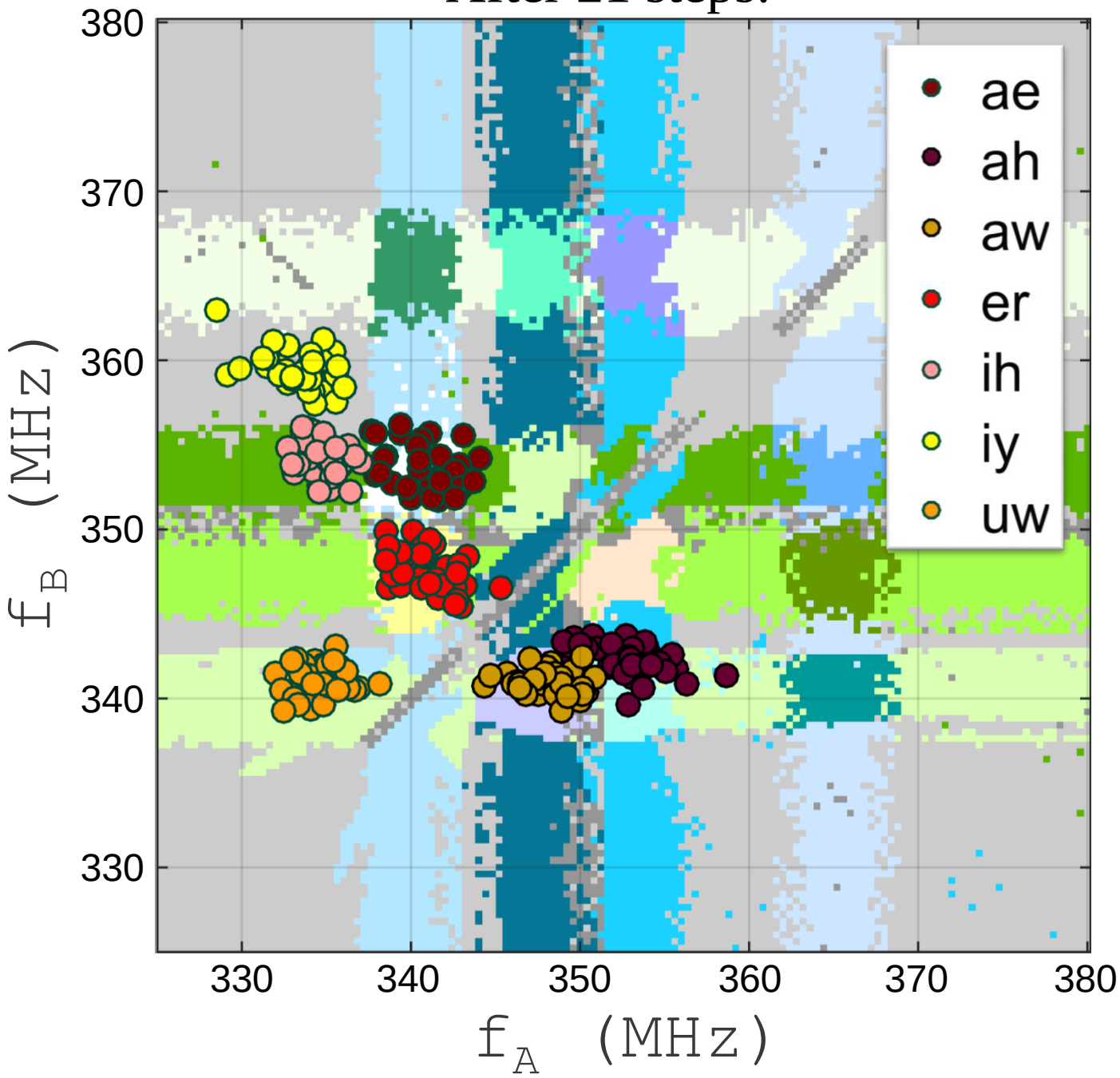

After 15 steps:
ae
ah
aw
er
ih
iy
uw
380
370
360
350
340
330
330
340
350
360
370
380
f_B (MHz)
f_A (MHz)
recognition rate (%)
100
80
60
40
20
0
dc currents in oscillators (mA)
10
8
6
4
oscillator frequencies (MHz)
370
360
350
340
0
20
40
60
80
Number of training steps

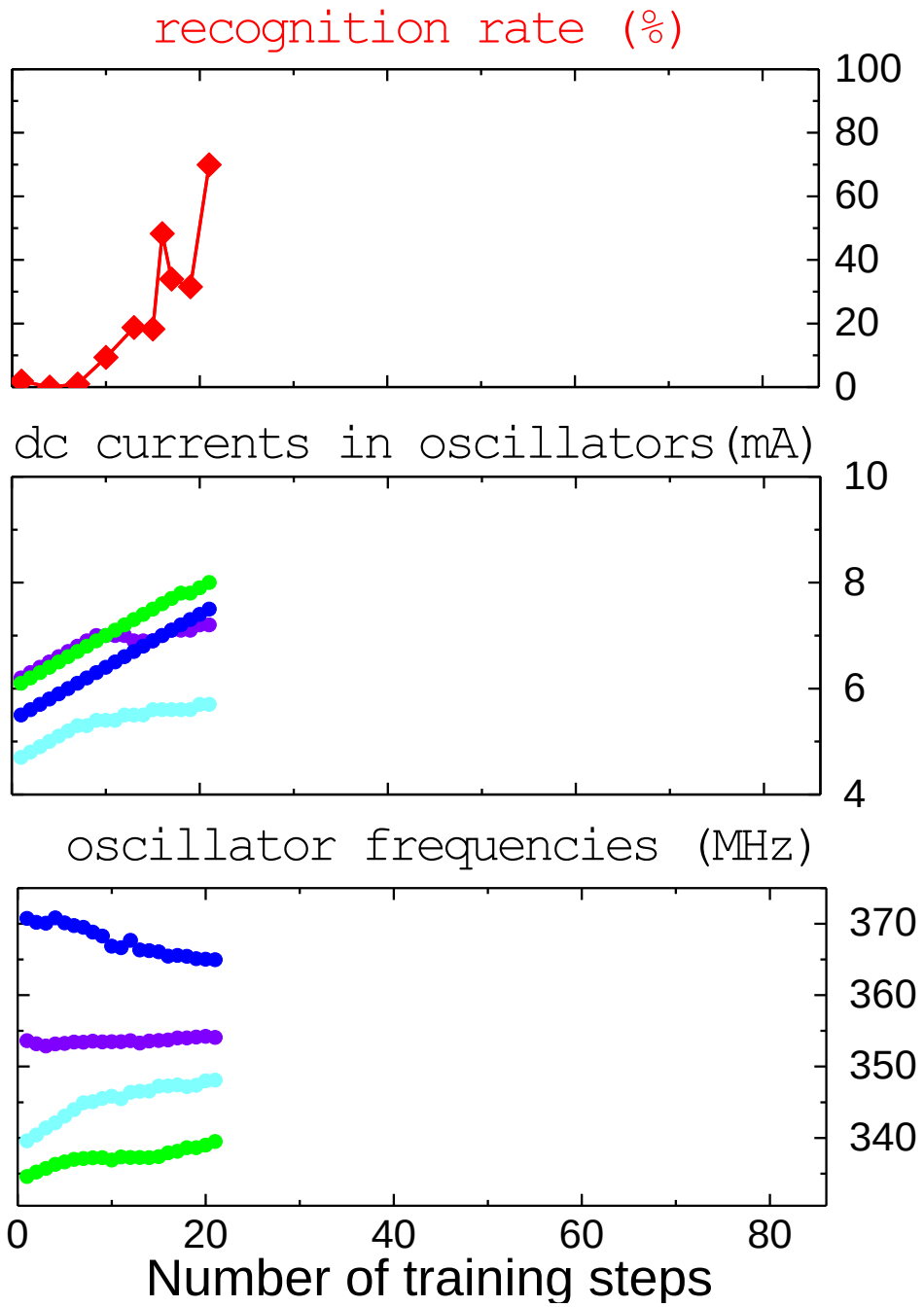
After 18 steps:



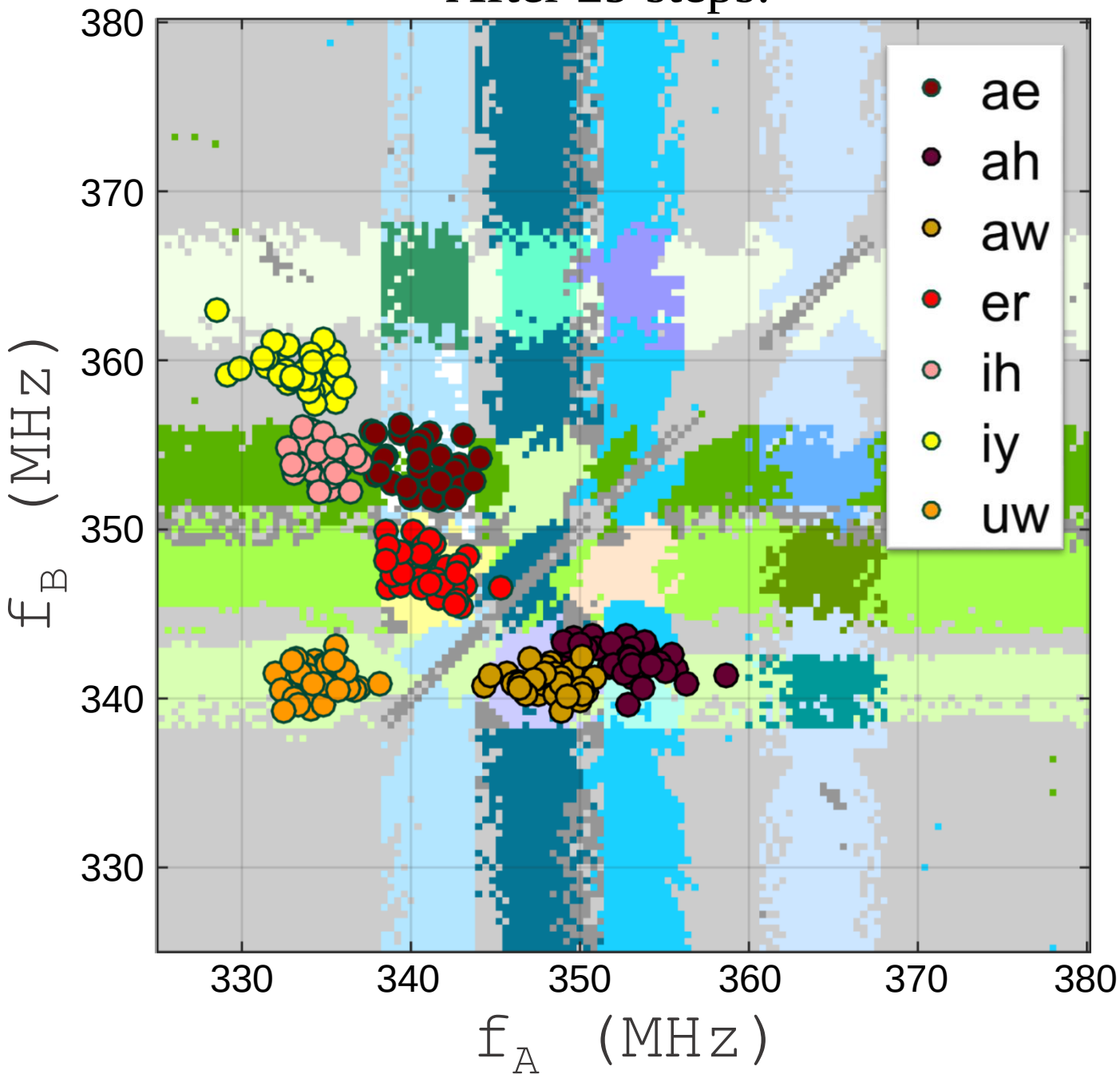


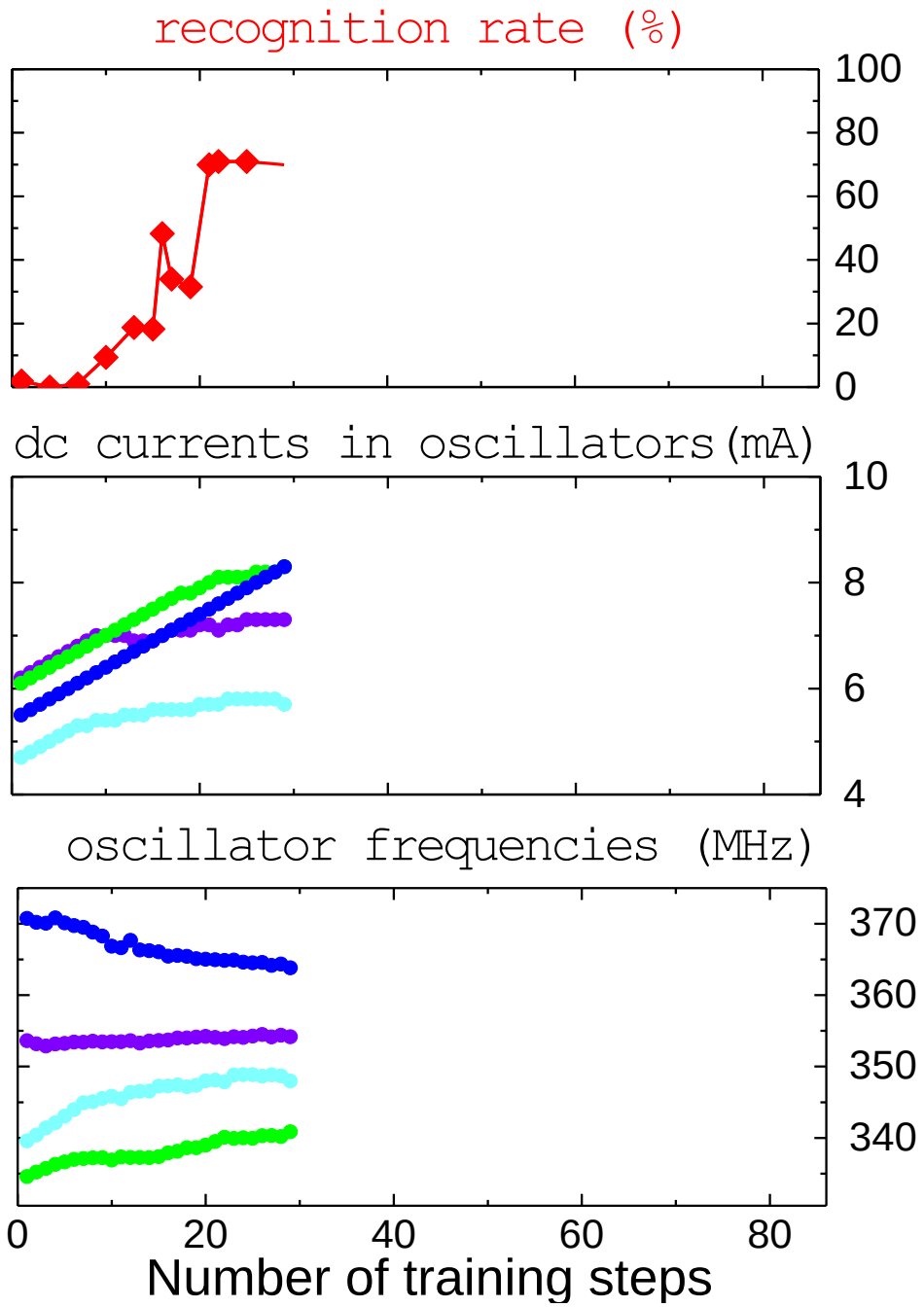
After 21 steps:

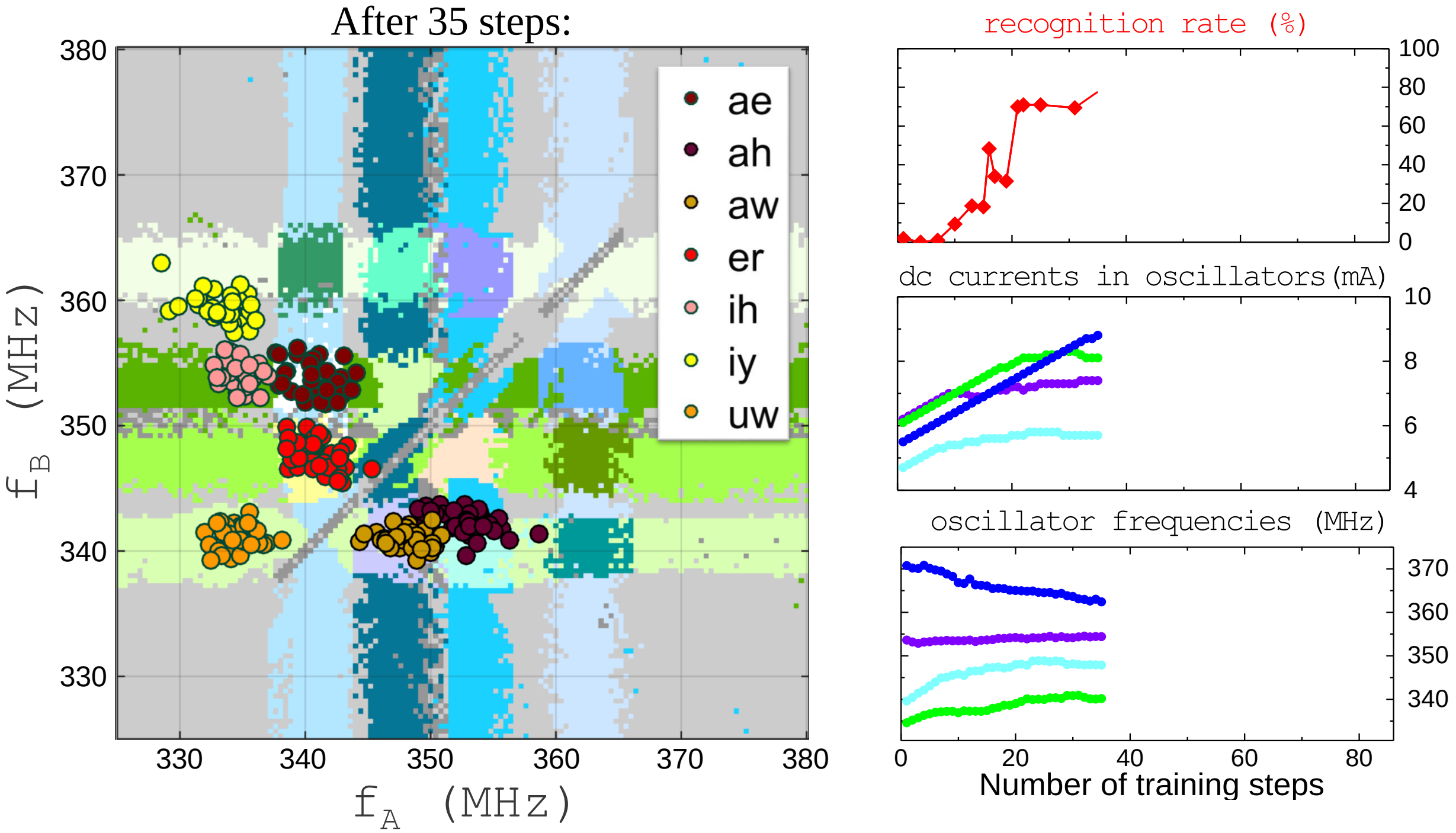


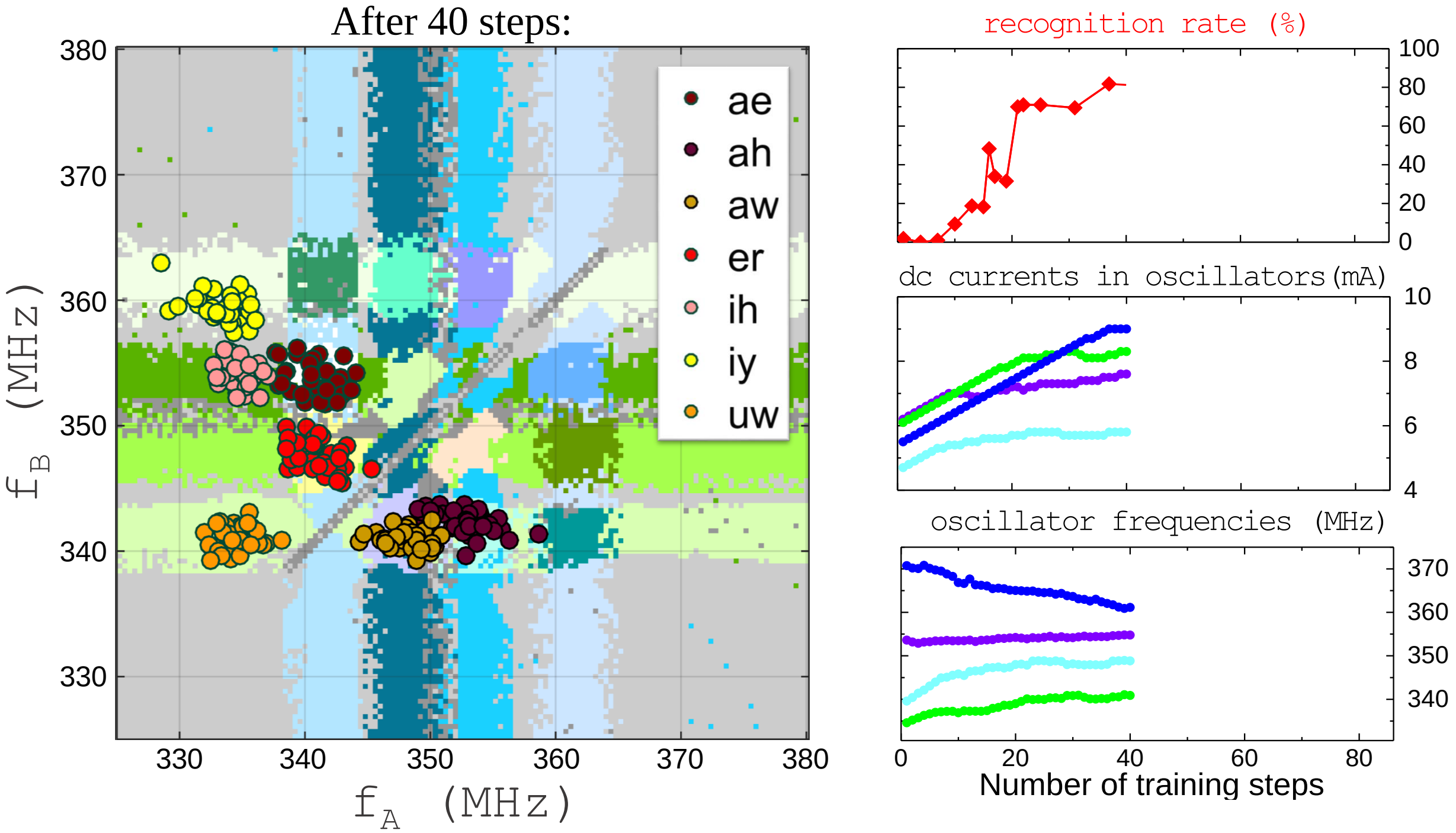


After 29 steps:

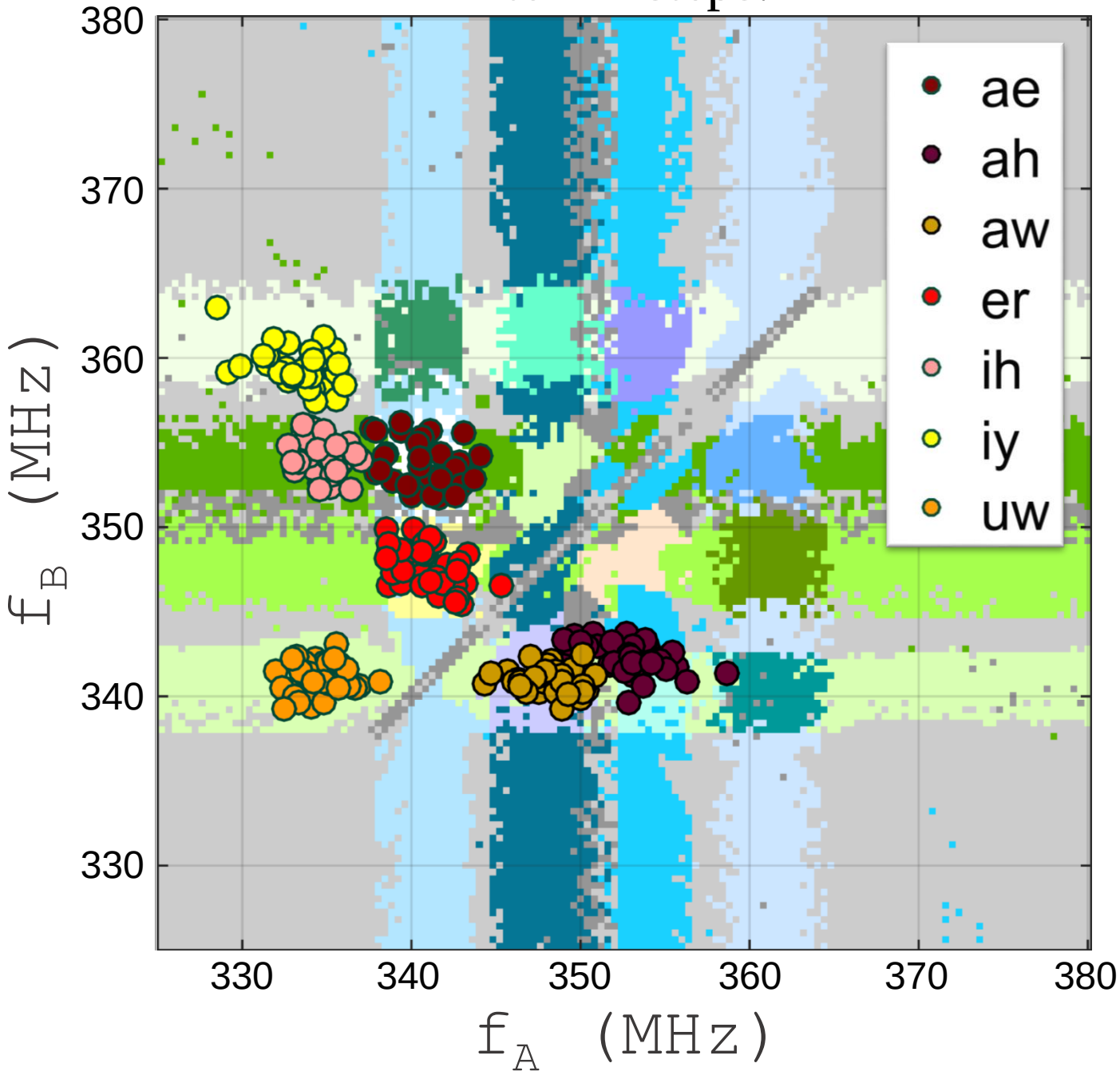


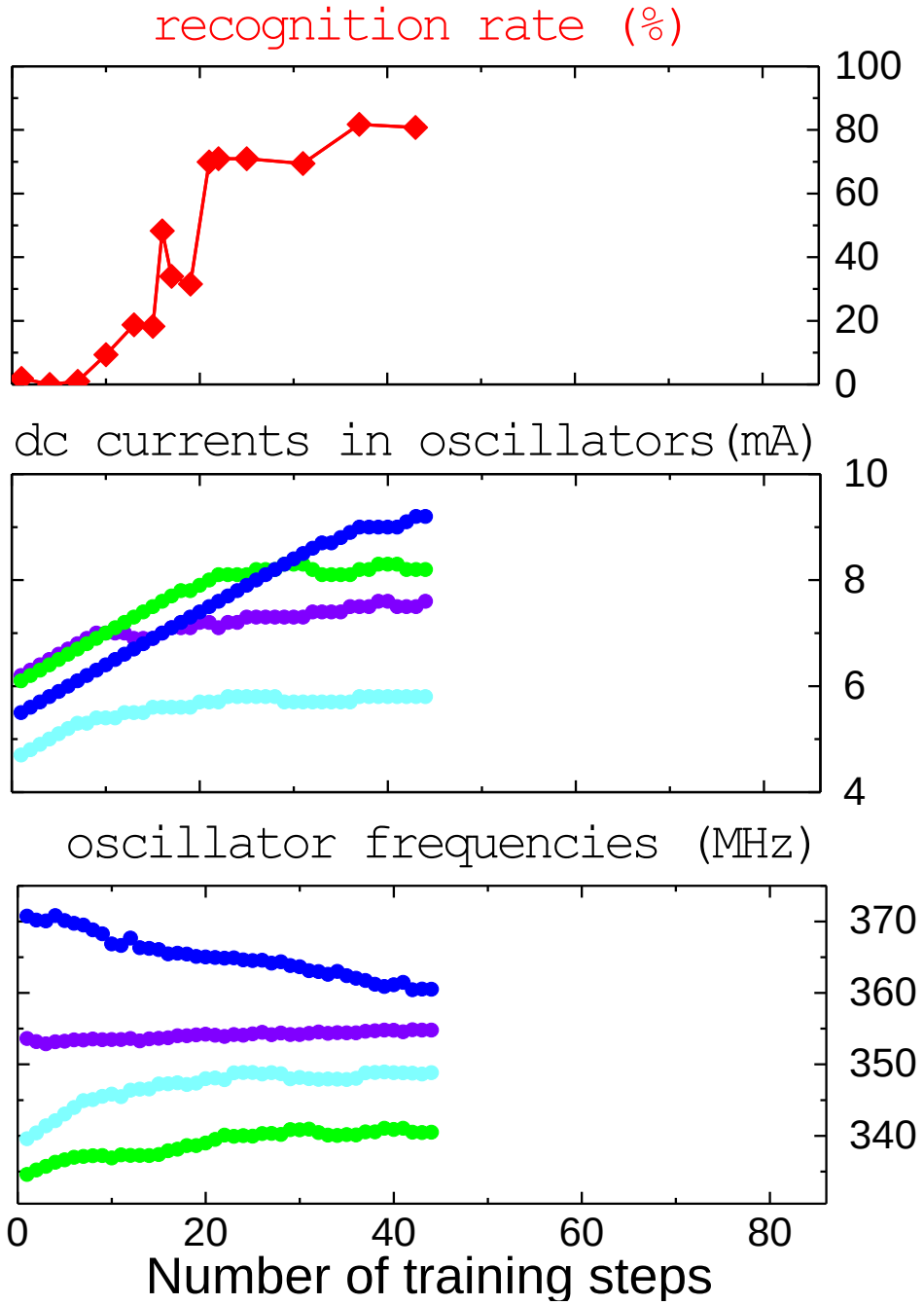


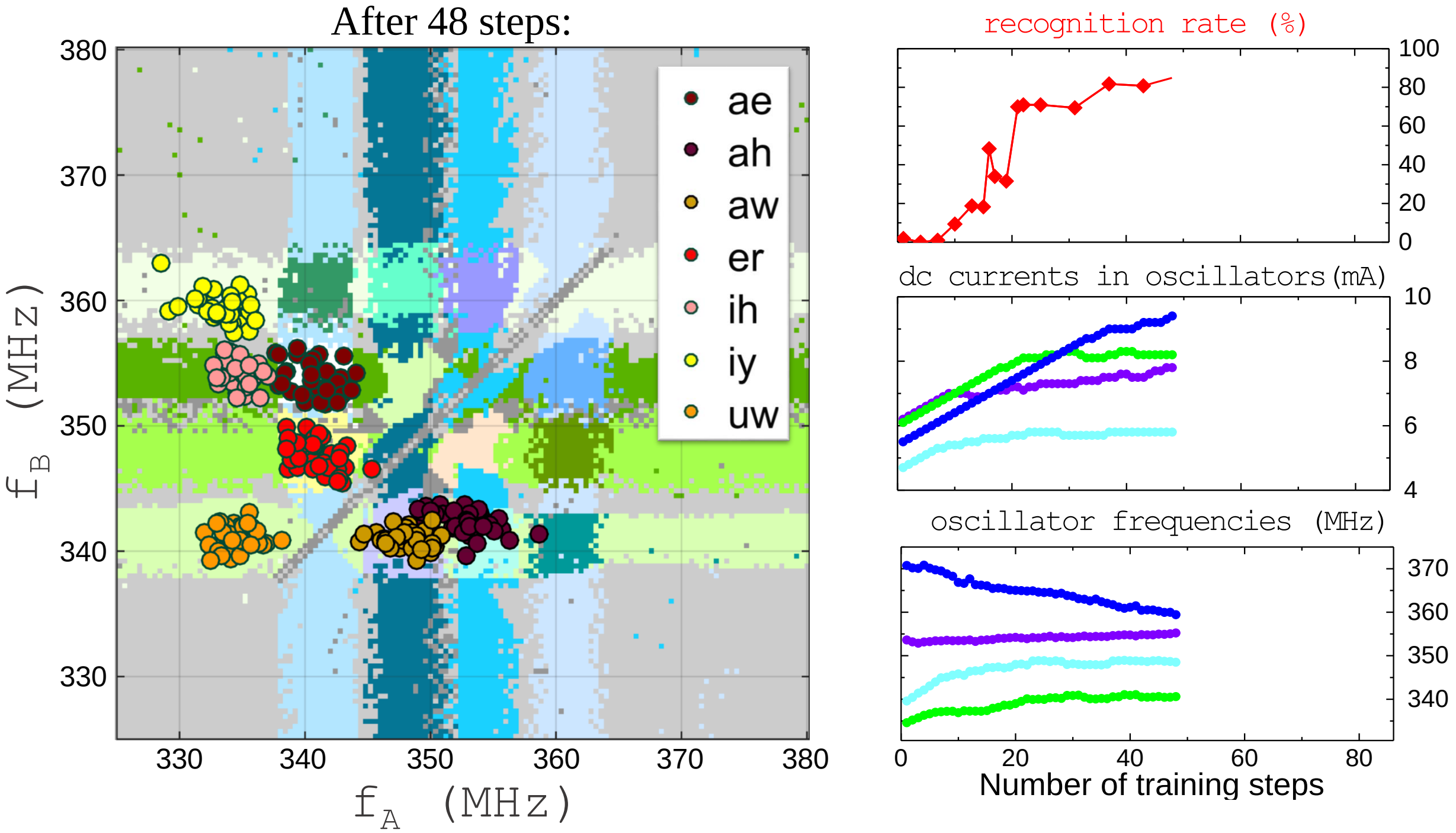

After 35 steps:
ae
ah
aw
er
ih
iy
uw
380
370
360
350
340
330
330
340
350
360
370
380
f_B (MHz)
f_A (MHz)
recognition rate (%)
100
80
60
40
20
0
dc currents in oscillators (mA)
10
8
6
4
oscillator frequencies (MHz)
370
360
350
340
0
20
40
60
80
Number of training steps

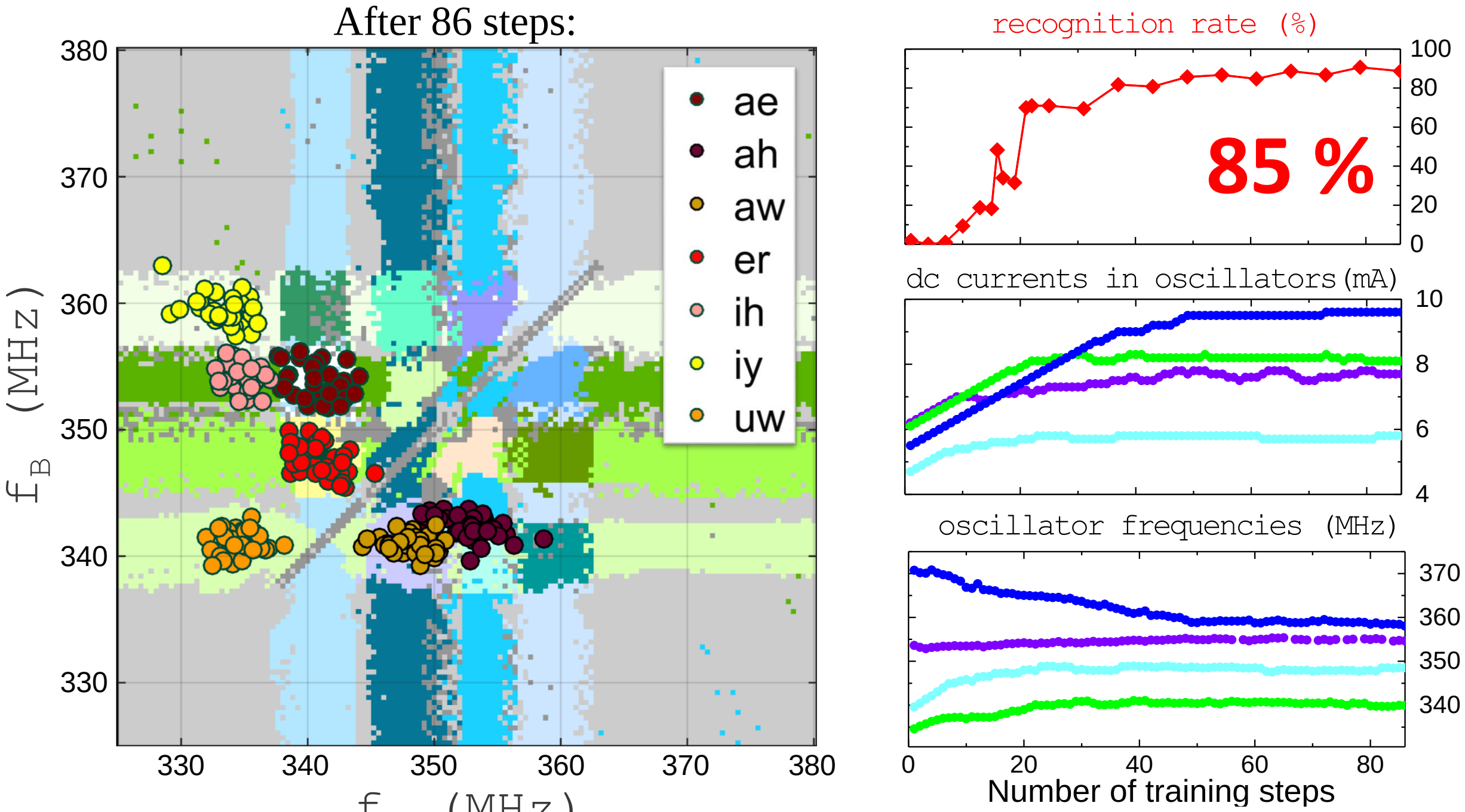

After 40 steps:
ae
ah
aw
er
ih
iy
uw
380
370
360
350
340
330
330
340
350
360
370
380
f_B (MHz)
f_A (MHz)
recognition rate (%)
100
80
60
40
20
0
dc currents in oscillators (mA)
10
8
6
4
oscillator frequencies (MHz)
370
360
350
340
0
20
40
60
80
Number of training steps

After 44 steps:

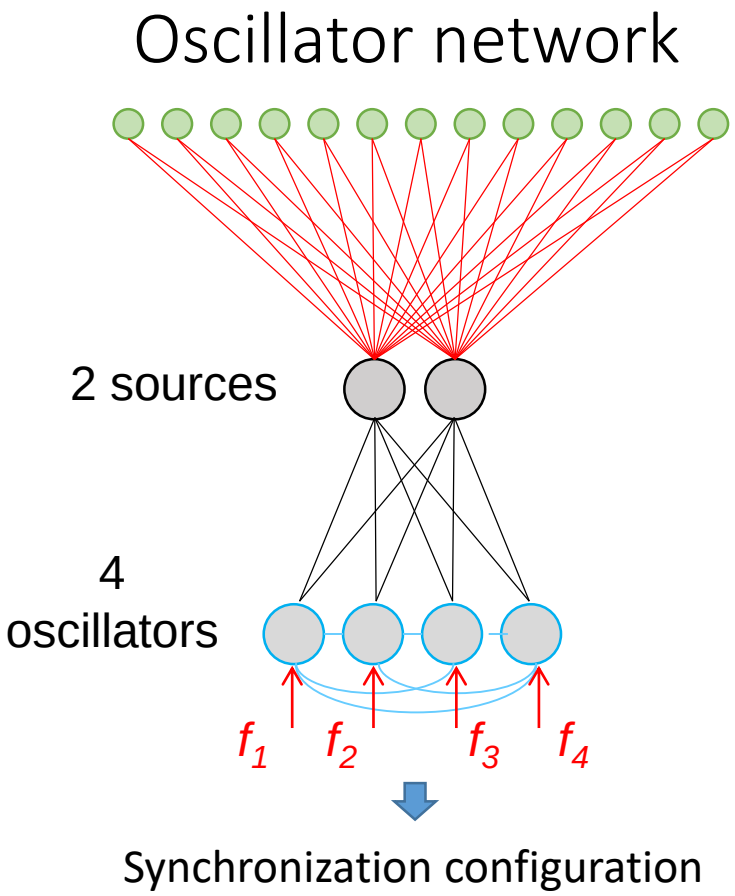


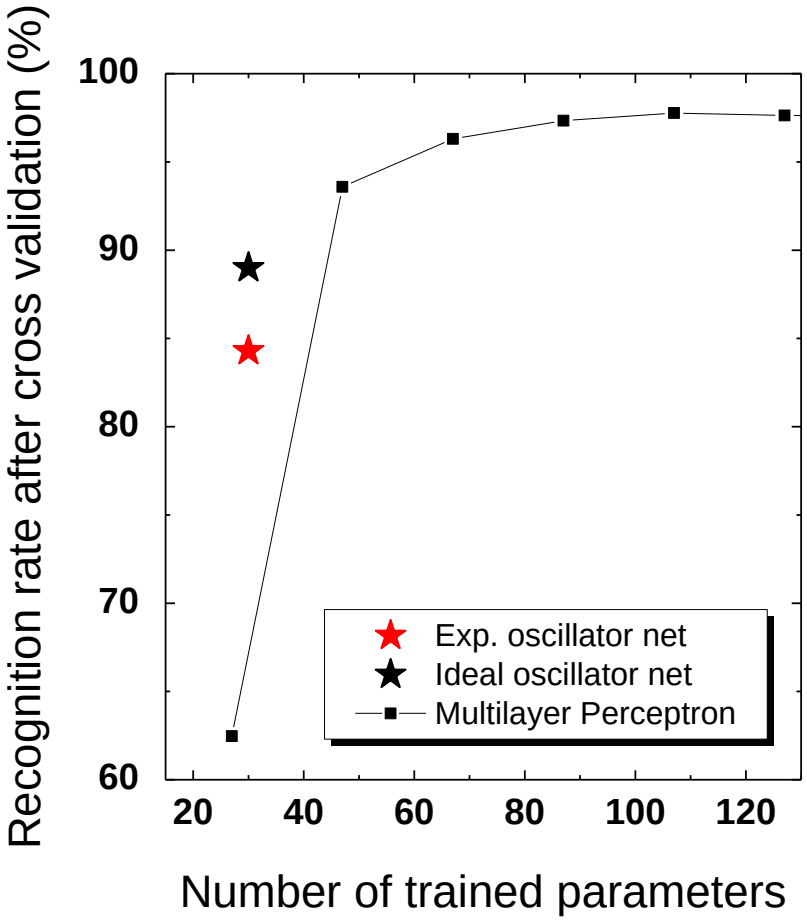


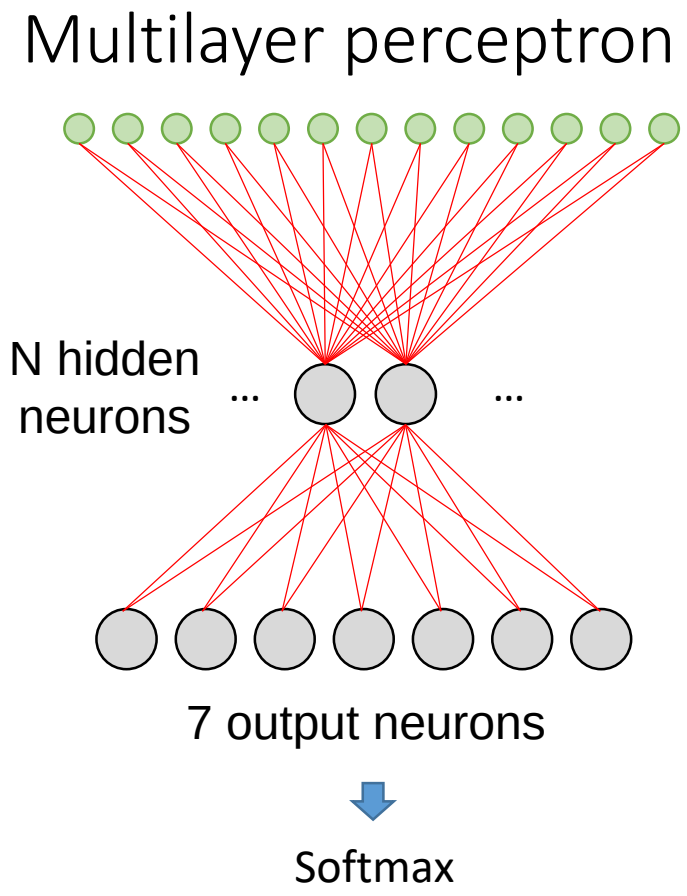

After 48 steps:
ae
ah
aw
er
ih
iy
uw
380
370
360
350
340
330
330
340
350
360
370
380
f_B (MHz)
f_A (MHz)
recognition rate (%)
100
80
60
40
20
0
dc currents in oscillators (mA)
10
8
6
4
oscillator frequencies (MHz)
370
360
350
340
0
20
40
60
80
Number of training steps


After 86 steps:
ae
ah
aw
er
ih
iy
uw
380
370
360
350
340
330
330
340
350
360
370
380
f_B (MHz)
f_A (MHz)
recognition rate (%)
100
80
60
40
20
0
85 %
dc currents in oscillators (mA)
10
8
6
4
oscillator frequencies (MHz)
370
360
350
340
0
20
40
60
80
Number of training steps

The oscillator network has a better recognition rate than a multilayer perceptron with an equivalent number of trained parameters

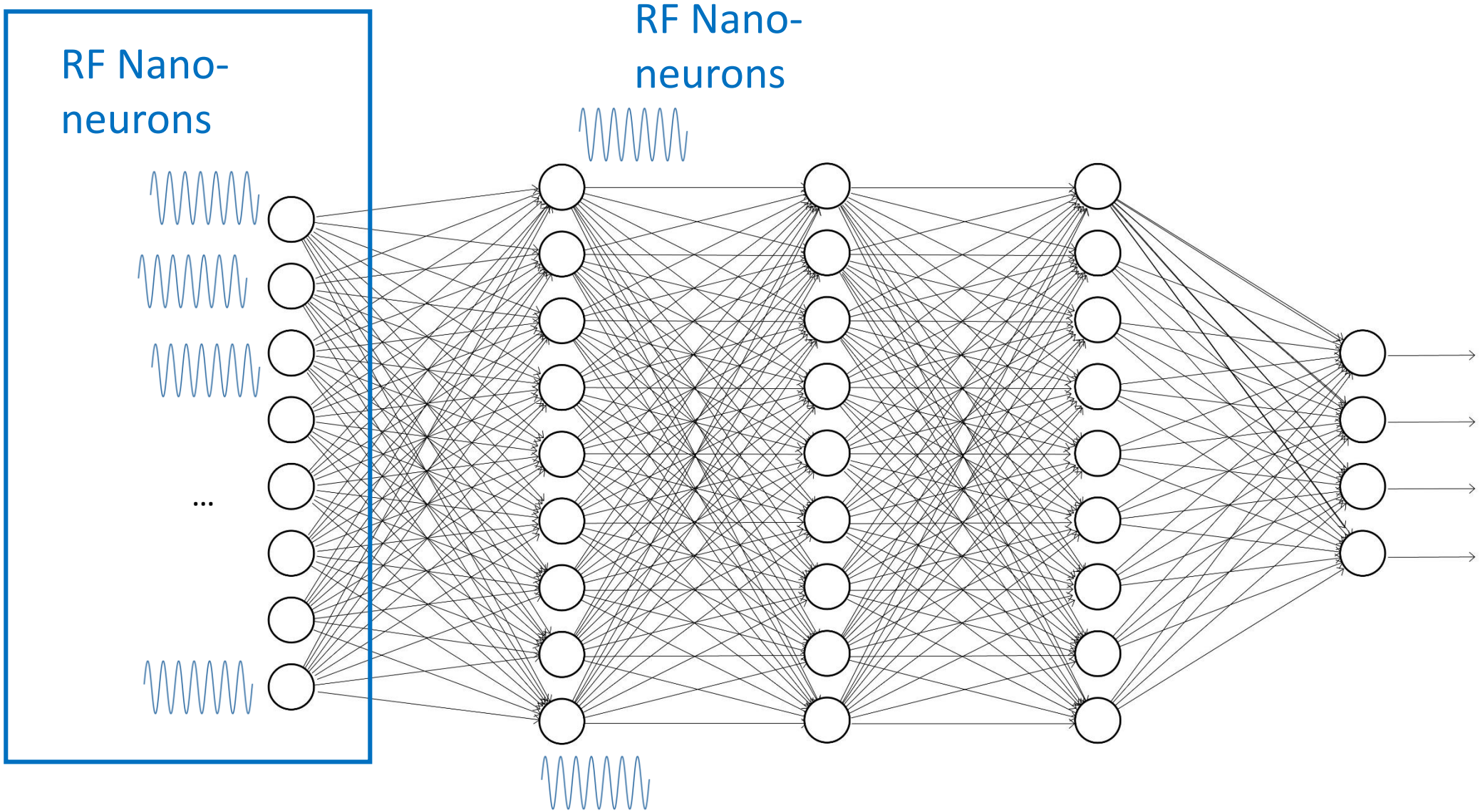






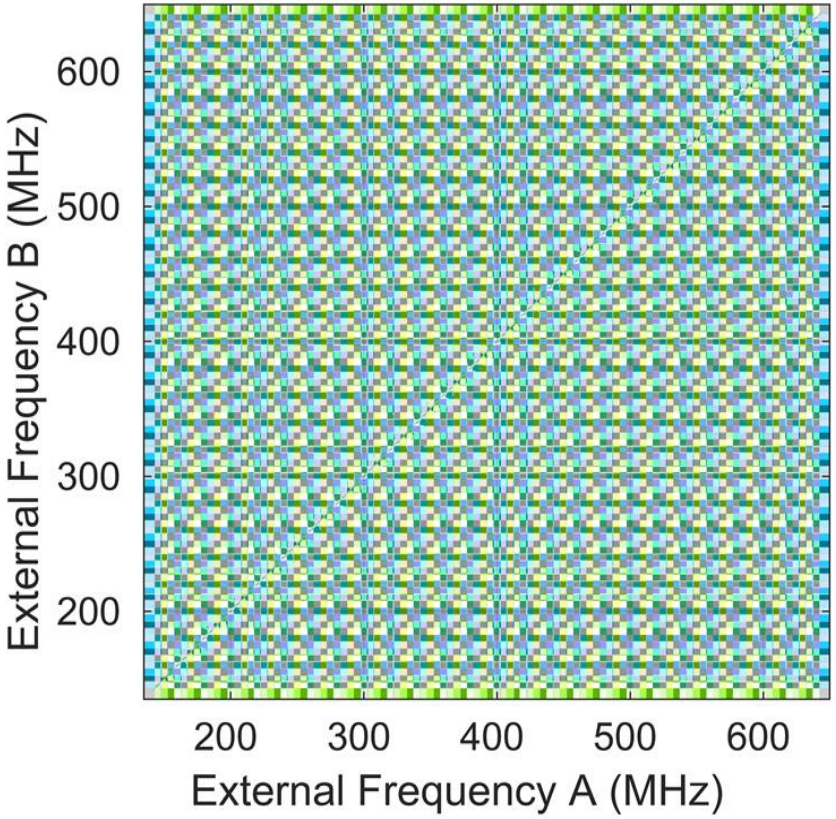
What’s next ?

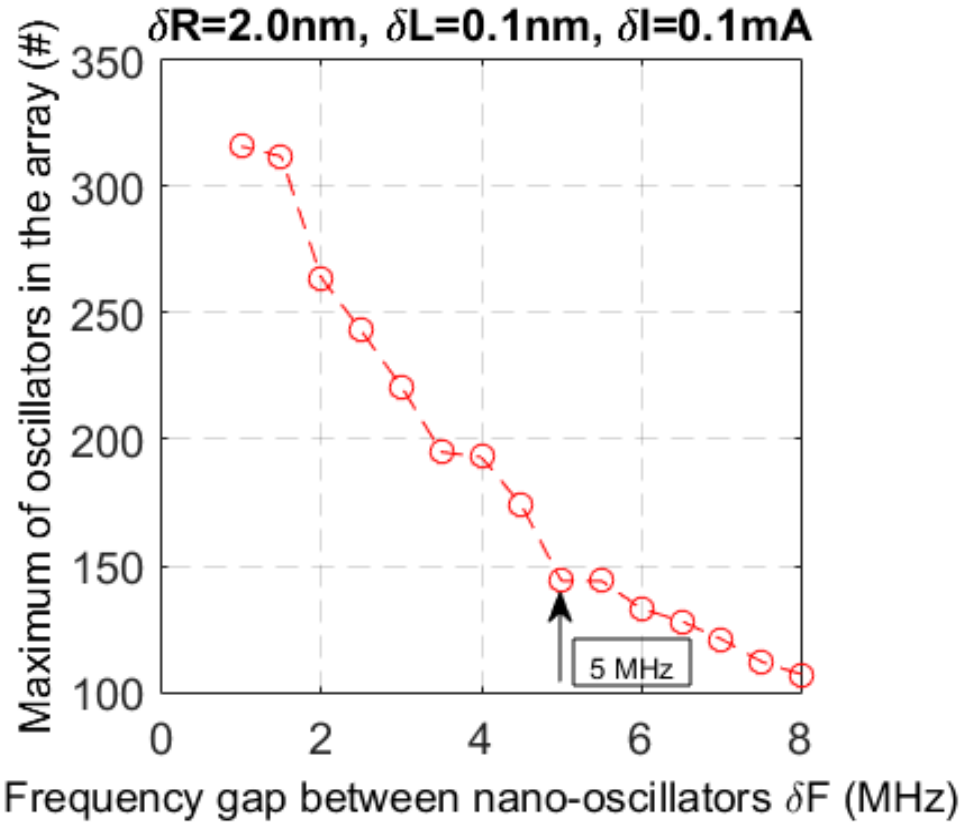
Perspectives: RF deep learning with spintronic nanodevices



Arrays of more than 300 spin-torque nano-oscillators can be built to obtain such synchronization state maps

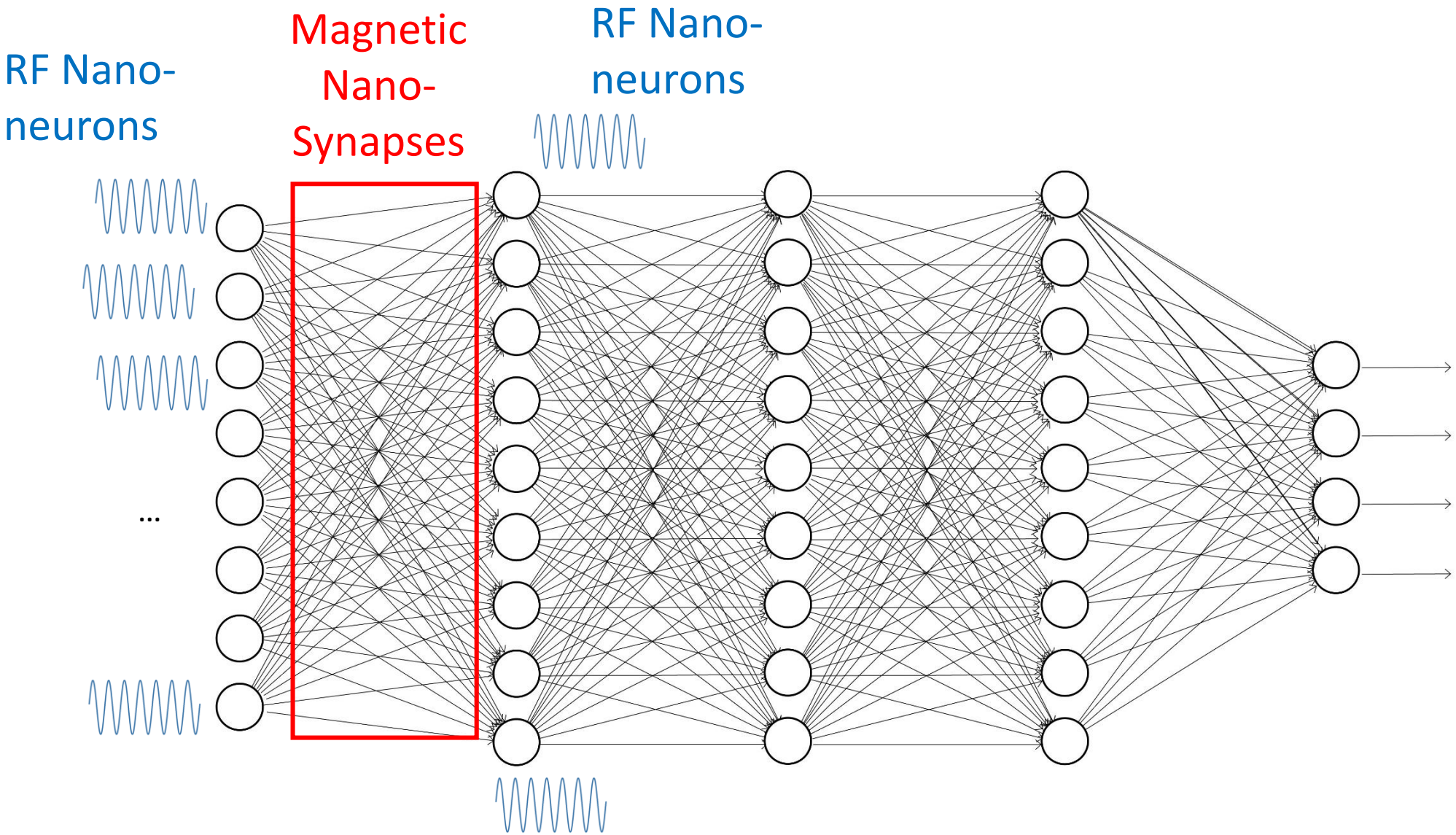
Simulated synchronization states for 100 nano-oscillators





P. Talatchian et al, in preparation

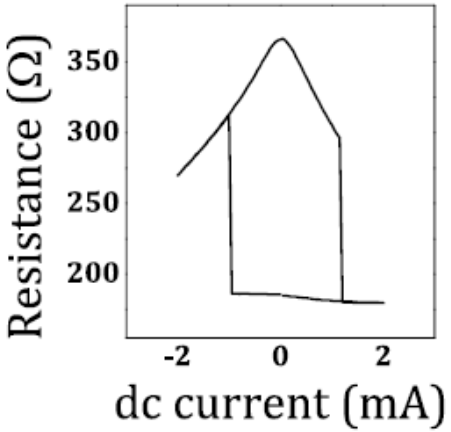
Perspectives: RF deep learning with spintronic nanodevices



Spintronics is multifunctional: we can create new devices

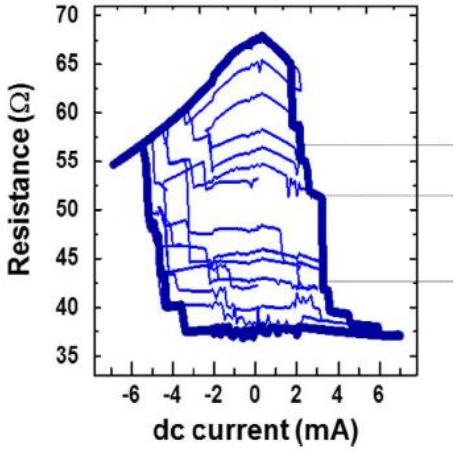
Binary memories

Multiple materials for synapses



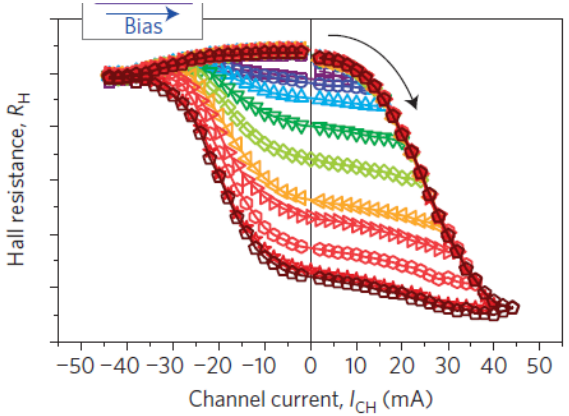
Ma, Endoh *et al* 2016 *Jpn. J. Appl. Phys.* **55** 04EF15

Ferromagnets

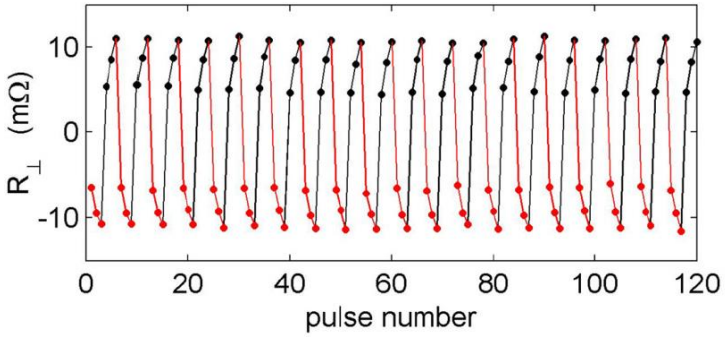


S. Lequeux, **JG** et al *Sci. Rep*. 6:31510 (2016)

Antiferromagnets



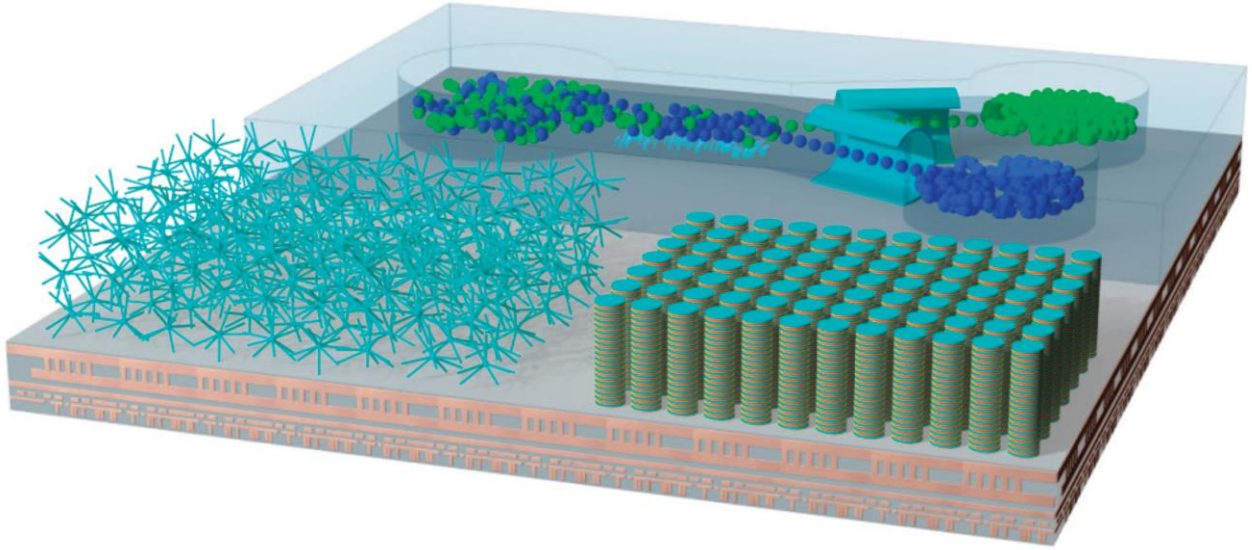
S. Fukami et al, *Nat. Mater.* 15, 535 (2016)



P. Wadley et al, *Science* (2016)

Multiple control means: **spin torques, spin-orbit torques, magneto-elastic, magneto-electric effects**

Spintronics nanodevices can emit solitons, magnons and microwaves, and go 3D for neuromorphic computing !



A. Fernandez- Pacheco et al, Nature Com 8:15756 (2017)

J. Grollier et al, PIEEE 104, 2024 (2016)
J. Torrejon et al, Nature 547, 428 (2017)
A. Mizrahi et al, Nature Com. 9:1533 (2018)
M. Romera et al Nature 563, 230 (2018)