Training of a neural network to model the MYRRHA LEBT for reliability improvements

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Outline

Introduction

- The MYRRHA project
- Low energy beam transport line

Machine learning

- Training databases
- Network performances
- Transferability

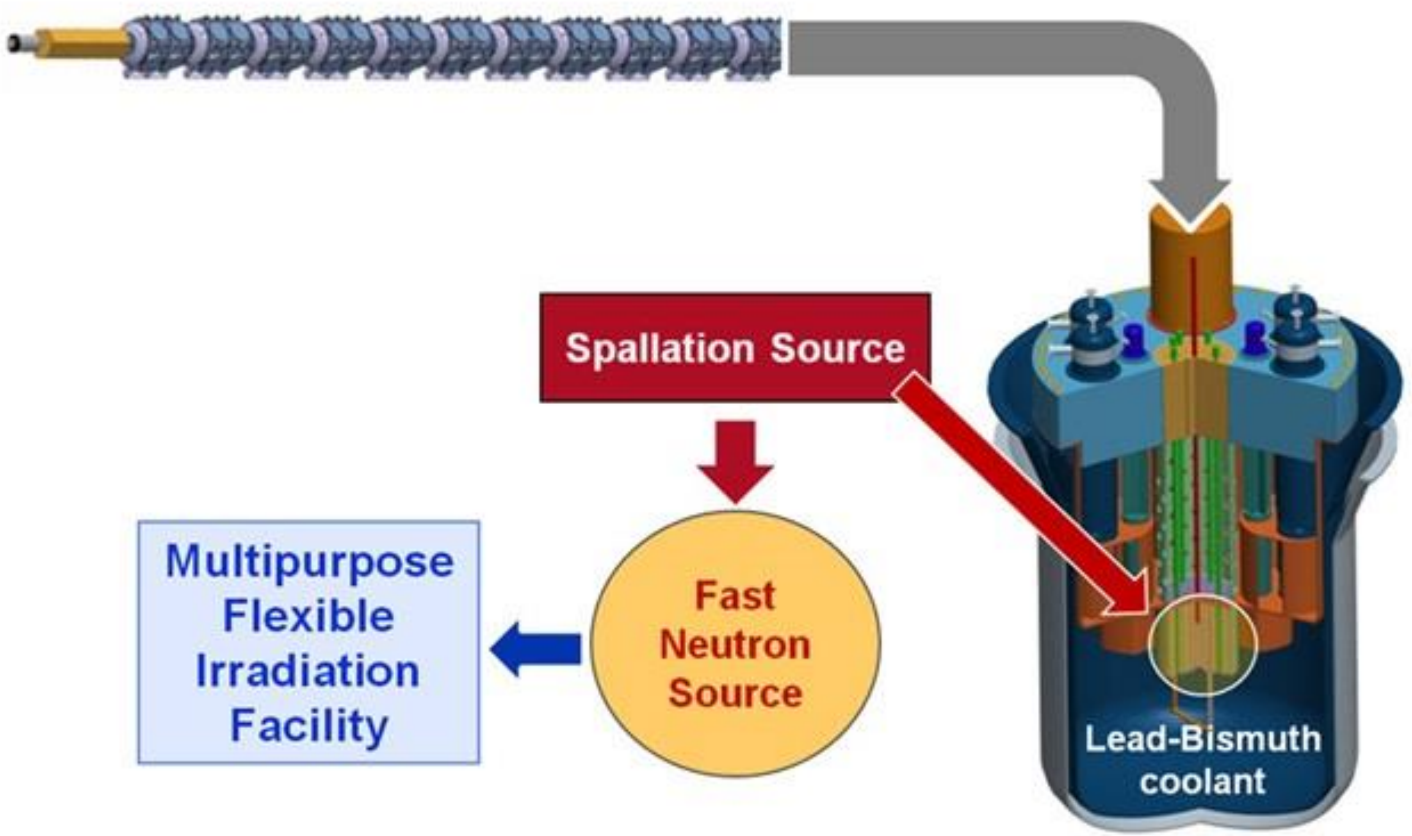
Conclusion & Prospects

MYRRHA

Multi-purpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications

Accelerator
(600 MeV - 4 mA proton)

Reactor
- Subcritical mode (65 -100 MWth)
- Critical mode (~100 MWth)

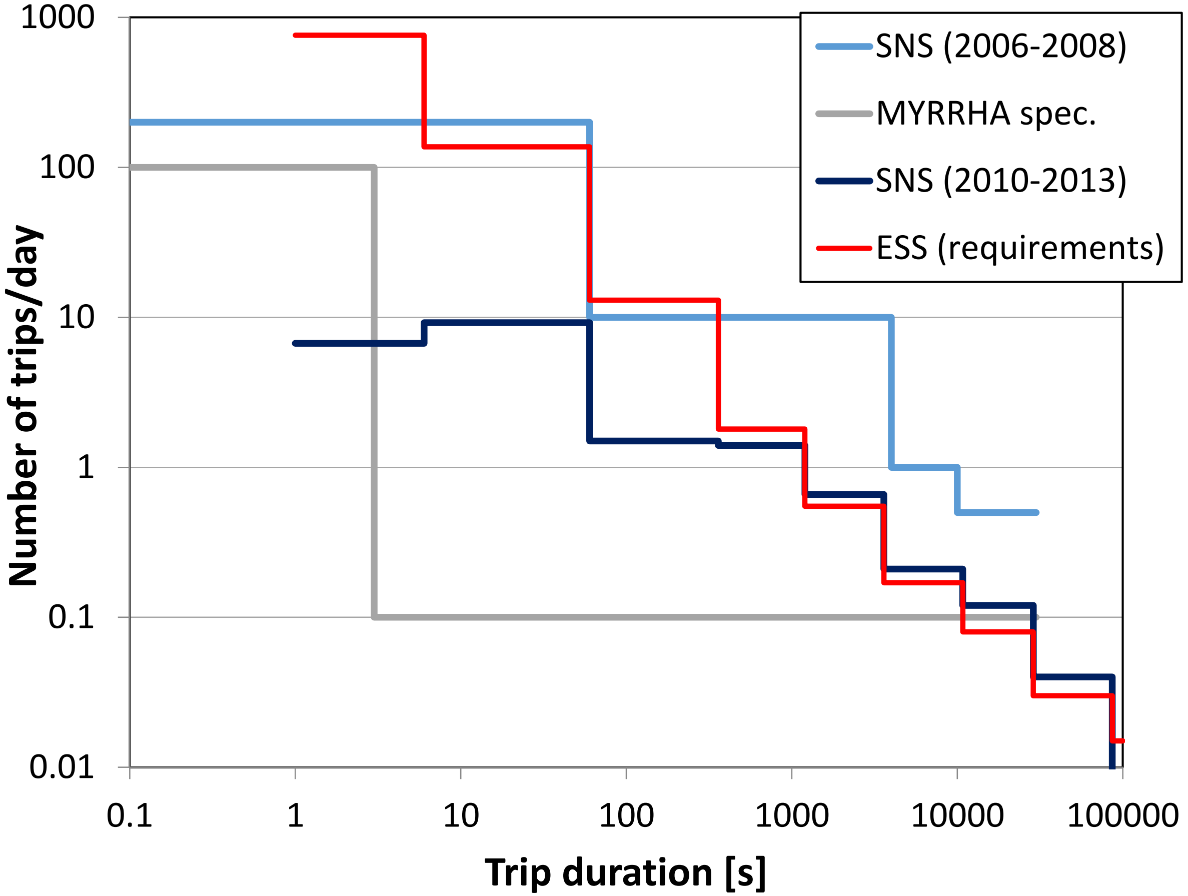


MYRRHA requirements

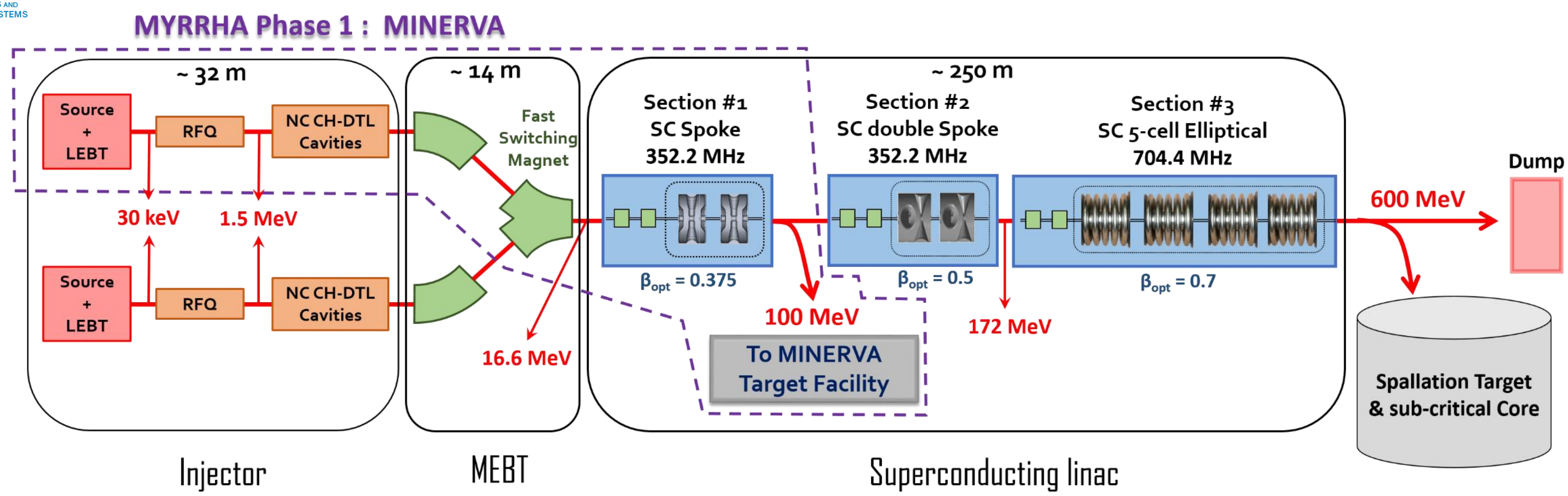
High power proton beam (up to 2.4 MW)

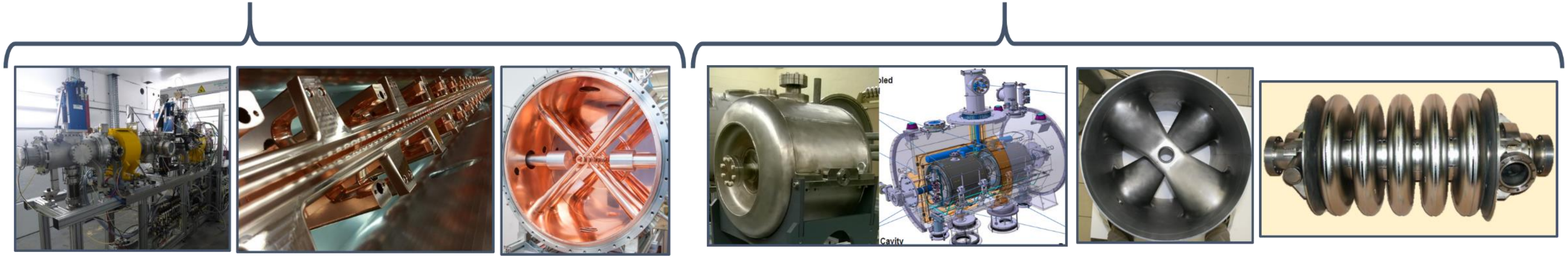
Proton energy	600 MeV
Peak beam current	0.1 to 4.0 mA
Repetition rate	1 to 250 Hz
Beam duty cycle	10^{-4} to 1
Beam power stability	< ± 2% on a time scale of 100ms
Beam footprint on reactor window	Circular ∅85mm
Beam footprint stability	< ± 10% on a time scale of 1s
# of allowed beam trips on reactor longer than 3 sec	10 maximum per 3-month operation period
# of allowed beam trips on reactor longer than 0.1 sec	100 maximum per day
# of allowed beam trips on reactor shorter than 0.1 sec	unlimited

Extreme reliability

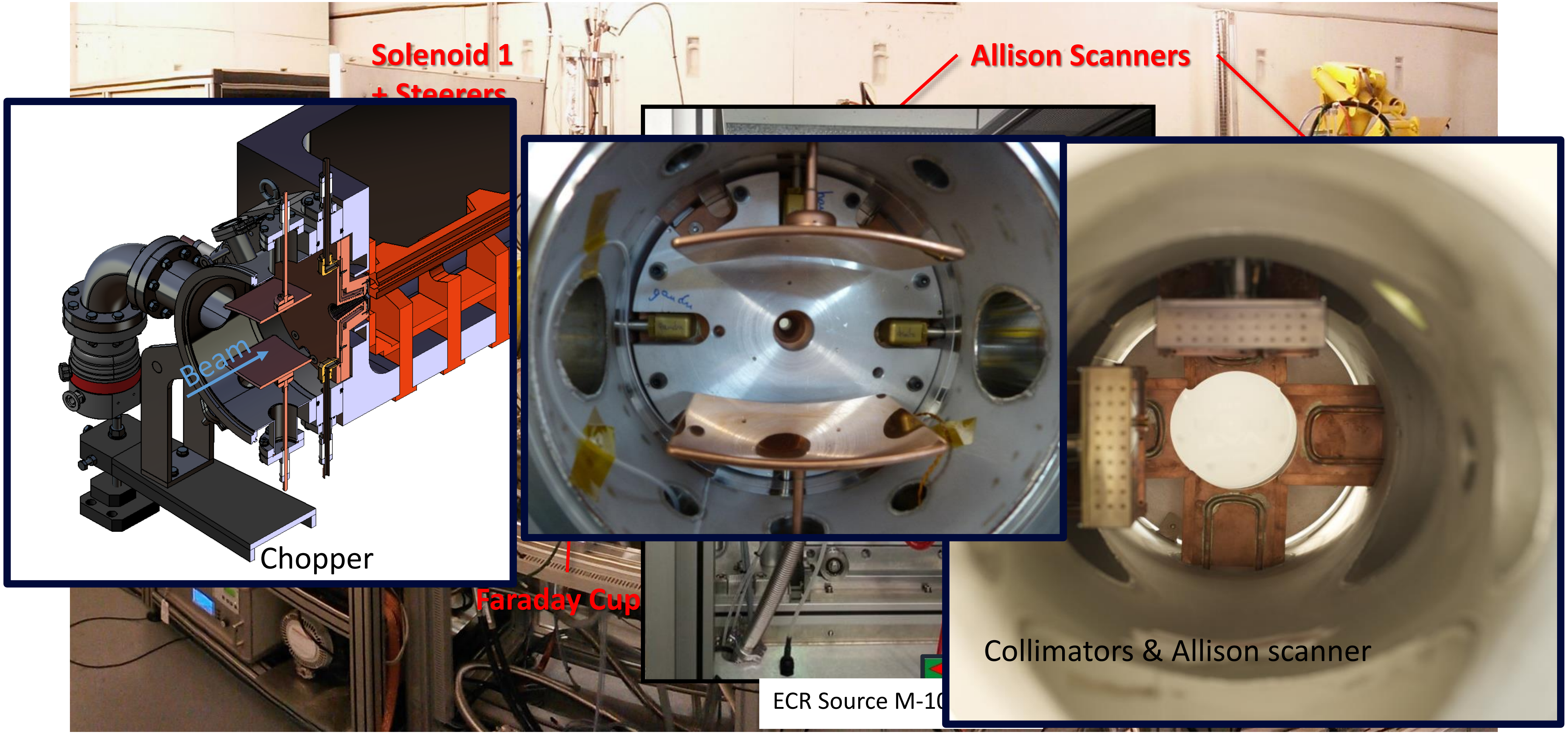


MYRRHA schematics





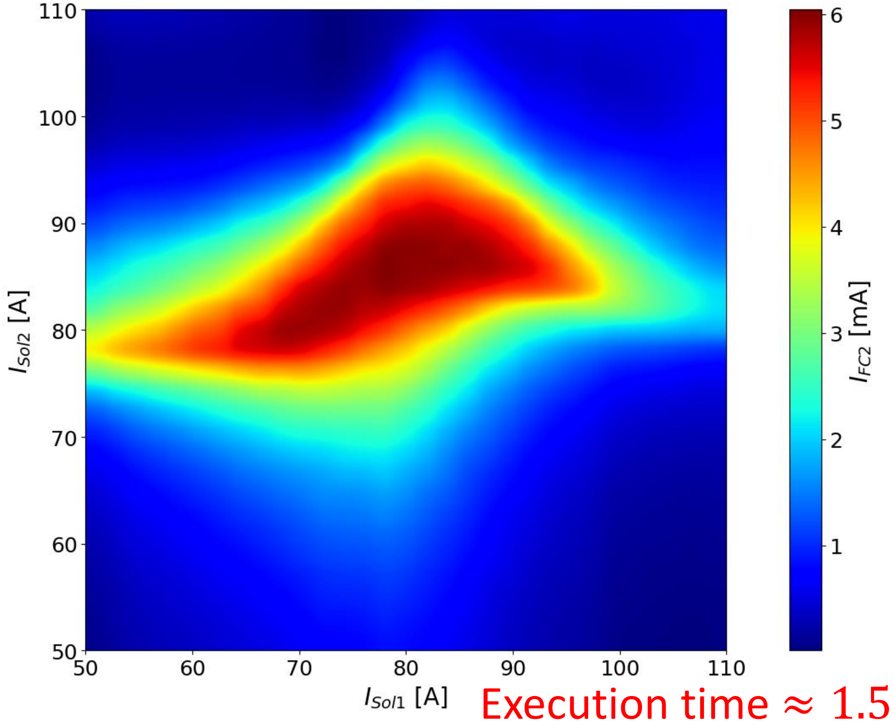
Low Energy Beam Transport Line



Transmission maps: experimental & simulated

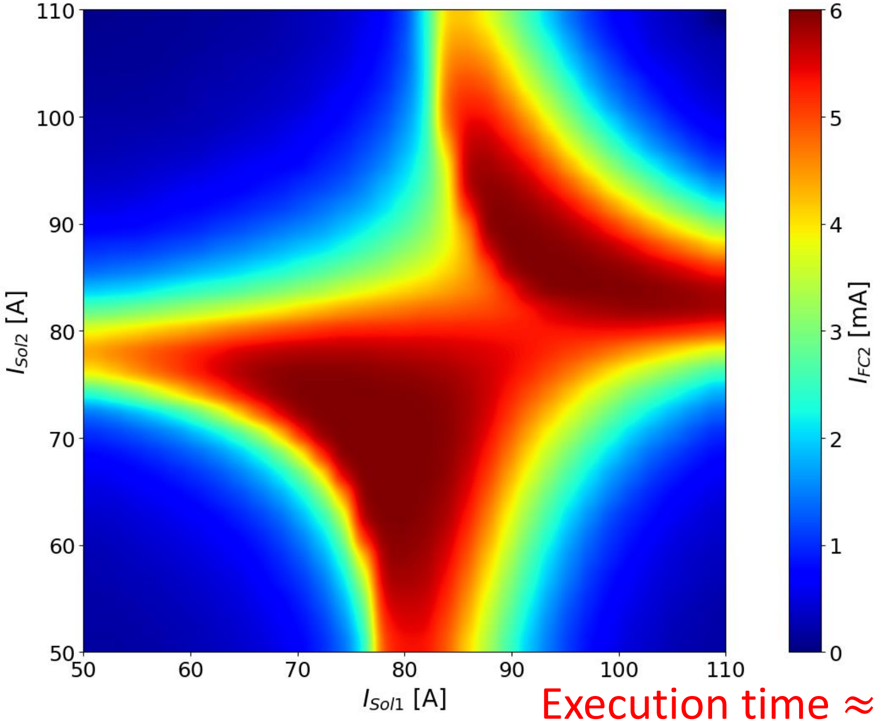
Beam current transmitted through the LEBT as a function of the solenoids focusing or the steering strength (current applied in the coils)

- $I_{Sol1}, I_{Sol2} \in [50, 110]$ A, $stepsize = 2$ A
- $I_{source} = 8$ mA
- $P = 2 \times 10^{-5}$ mbar
- $I_{St3} = 1$ A, $\mathrm{I_{St4}} = -0.5$ A



Execution time ≈ 1.5h

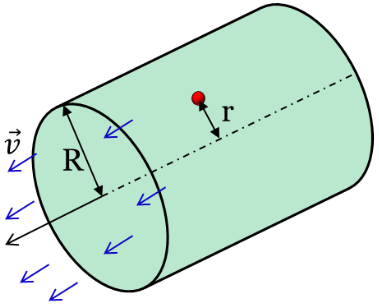
- $I_{Sol1}, I_{Sol2} \in [50, 110]$ A, $stepsize = 2$ A
- $I_{source} = 6$ mA
- $Space\ charge\ compensation = 99\%$
- $I_{St3} = 0$ A, $\mathrm{I_{St4}} = 0$ A



Execution time ≈ 10 min – 4h

Space charge effect

- Defocusing effect : Coulomb repulsion of charged particles inside the beam
- 2 contributions (Lorentz):
  - Electrostatic : repelling Force
  - Magnetic : attractive Force (charged particles in movement)

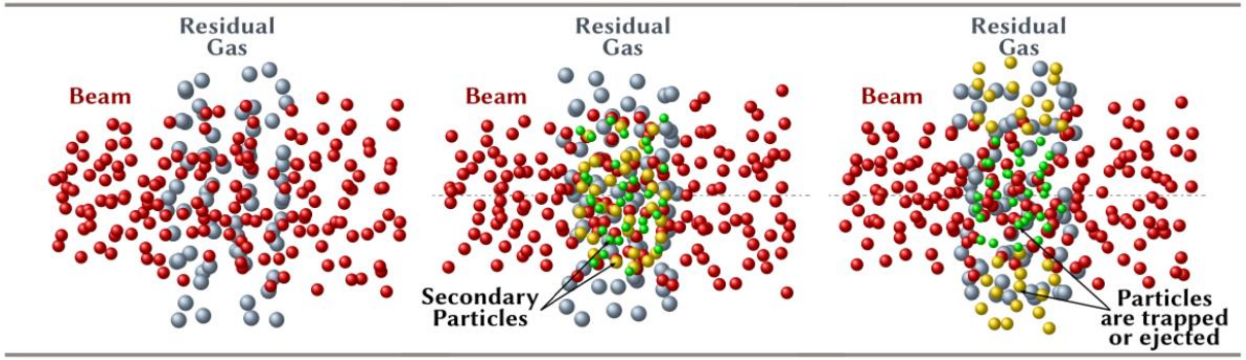


Radial force seen by one particle of a continuous (DC) cylindrical and homogenous beam

$$F_r = \frac{(1-\beta_L{}^2)}{\beta_L} \frac{qI}{2\pi\,\varepsilon_0\,c} \cdot \frac{r}{R^2}\ (\mathrm{r} < \mathrm{R})$$

β_L : reduced speed
ε_0 : vacuum permittivity
q : *charge*
I : beam current

- **Complex phenomena, difficult to model, depends on many parameters :** influence of the vacuum chamber walls, beam transverse and longitudinal distribution, different species/ions, residual gas interaction, etc.



Courtesy of N. Chauvin

- A solution to compensate the beam diverging effect in the LEBT :

→ Use the Ionisation of the residual gas in the vacuum chamber.

Machine Learning

- Objectives

  Fast control and tuning for different linac beam modes (peak current, duty cycle)

- Why?

  Classic simulation are slow

  Classic simulation don’t reproduce experiments accurately

- How?

  Training of an experimental model using supervised learning

Neural Network

An artificial neuron

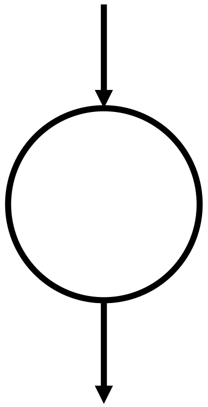
Input **X**

Weights **W**

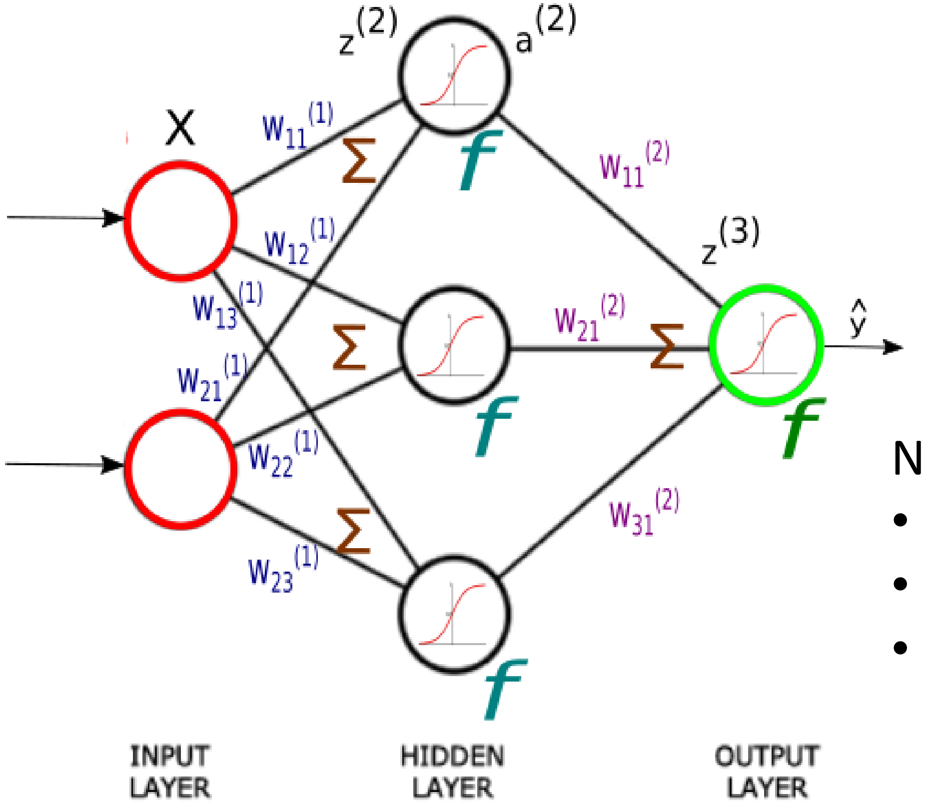
Bias b

Activation function f

Activation a



Output $a = f(\boldsymbol{WX} - b)$

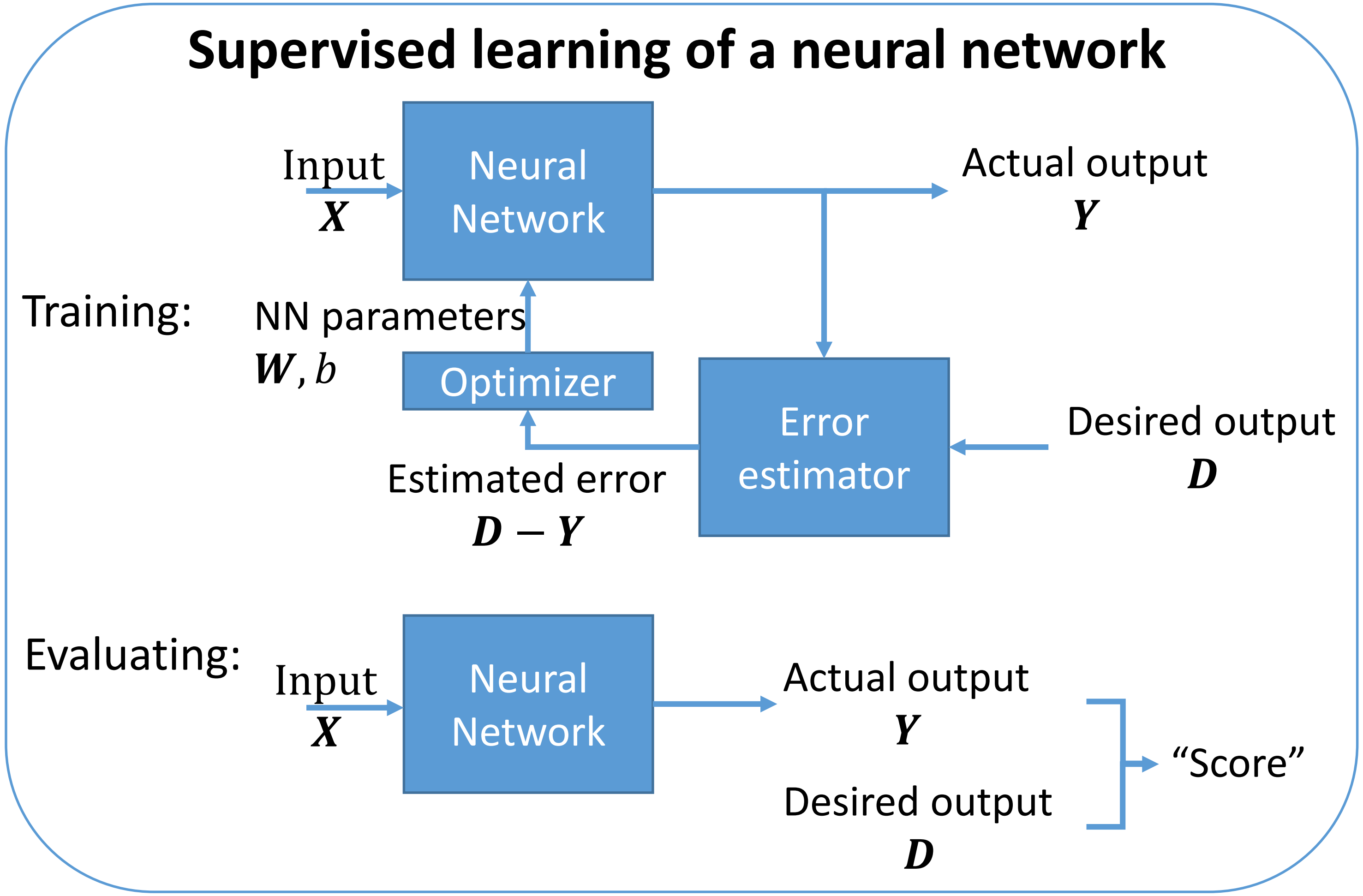


Network caracteristics:

- Dense
- ReLu (hidden layers)
- Sigmoid (output layer)

Can fit any continuous function

Supervised Learning



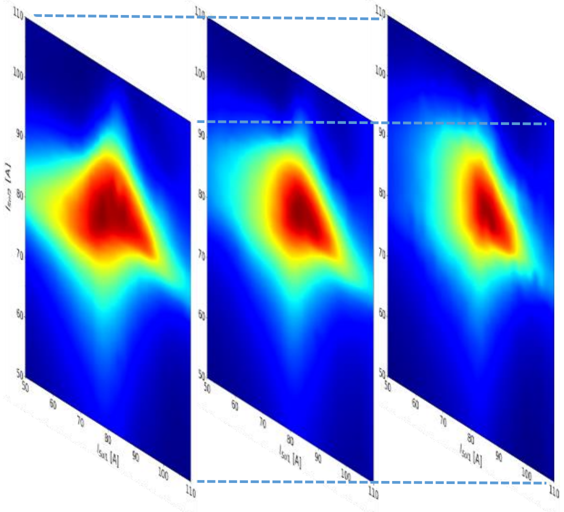
Parameters

- Learning rate: from 0.1 down to 0.001
- Error estimator: MSE
- Optimizer: SGD

Dataset

MYRRHA (SCK*CEN, Belgium)

- ~20000 measurements



Slices at different slits extensions

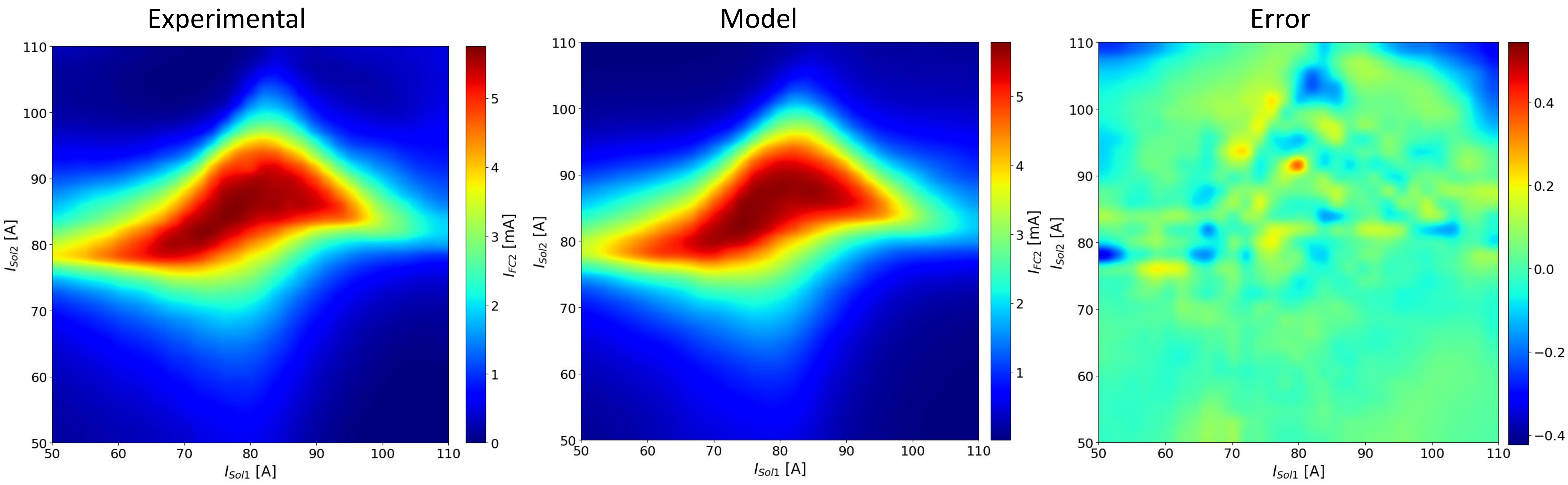
19 “slices” with solenoids
6 “slices” with steerers

→ Dataset
- 60% → Training data
- 20% → Evaluation data
- 20% → Validation data

Input				Desired output
Current in steerer x4 [A]	Current in solenoid x2 [A]	Collimator opening x1 [m]	Pressure gauge x3 [bar]	Current in FC2 [A]

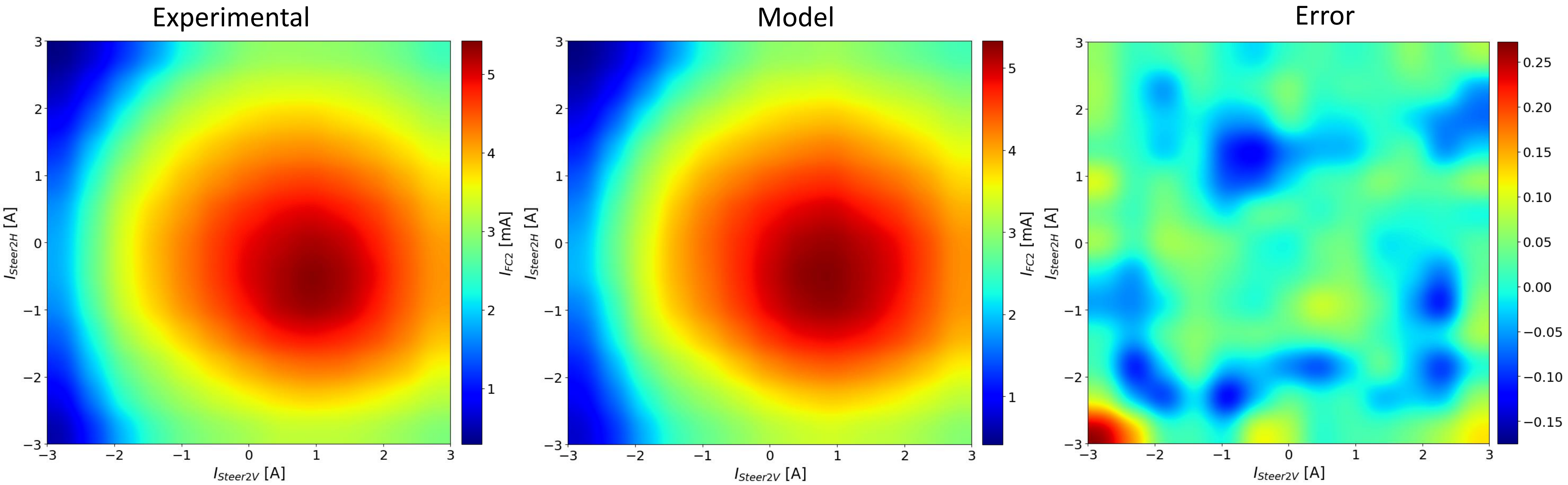
➔model $f(I_{st1}, I_{st2}, I_{st3}, I_{st4}, I_{so1}, I_{so2}, r_{coll} | p_1, p_2, p_3) = I_{FC2}$

Model output

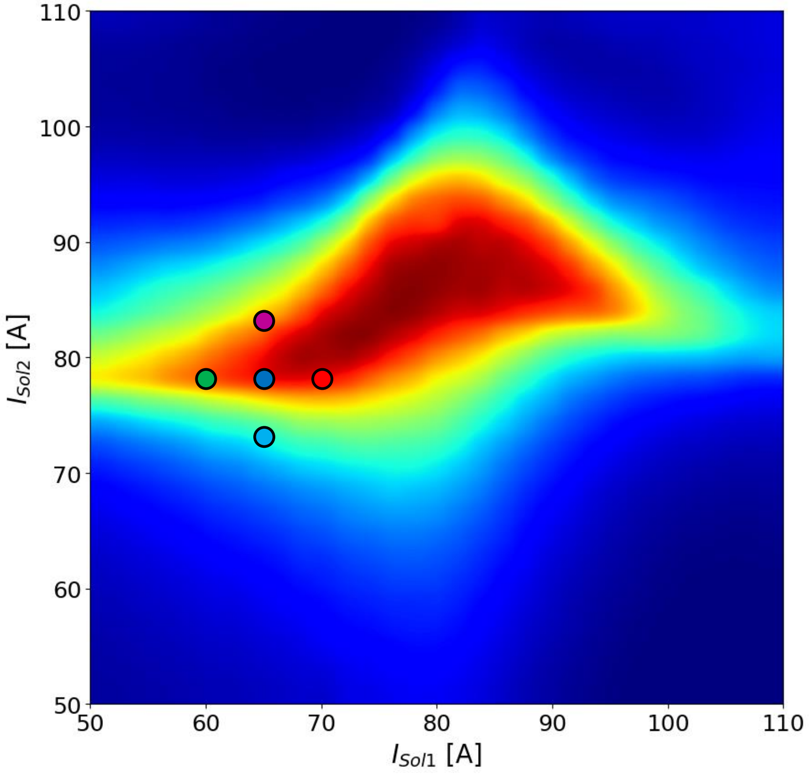


Execution time ≈ 1 ms

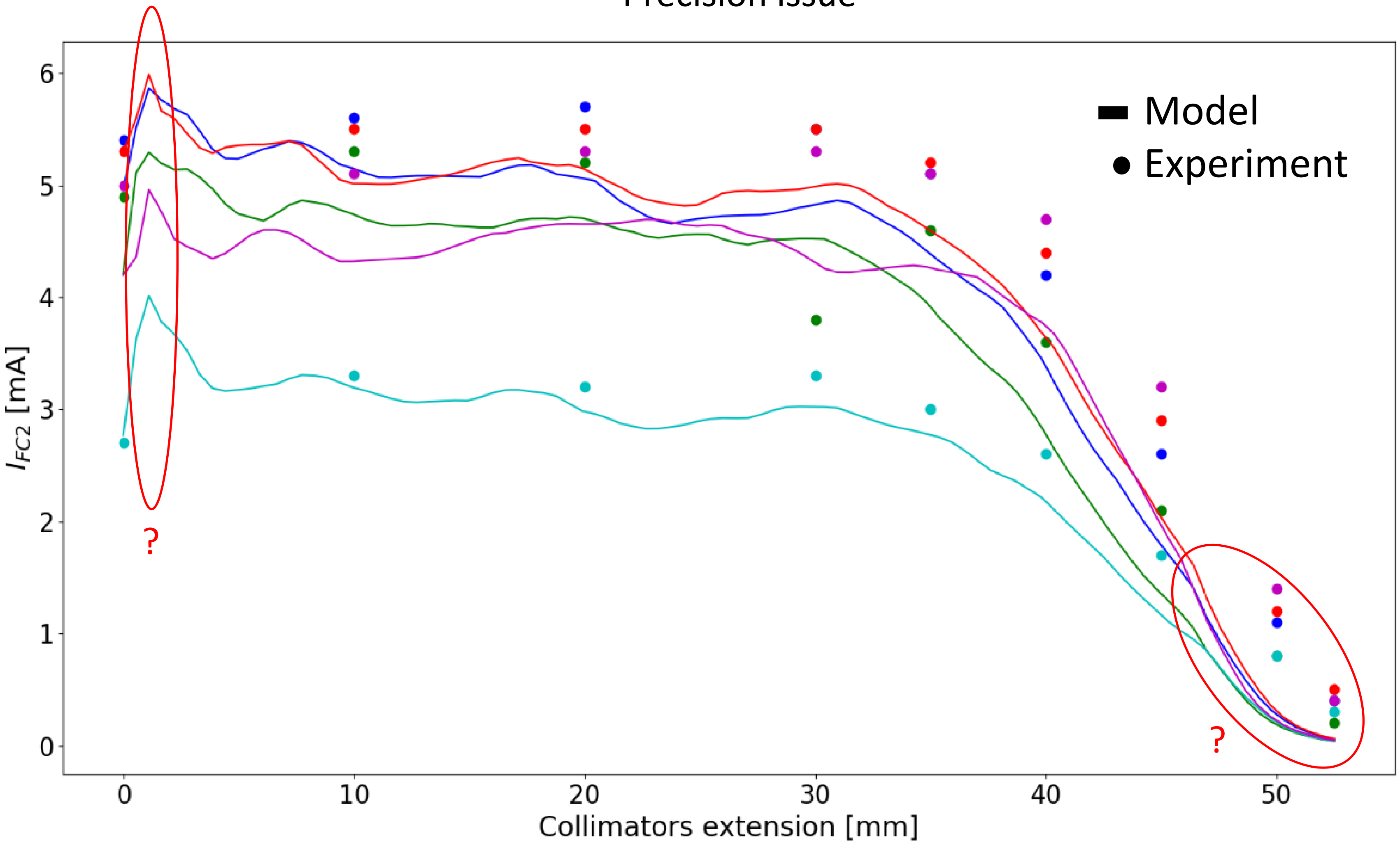
Model output



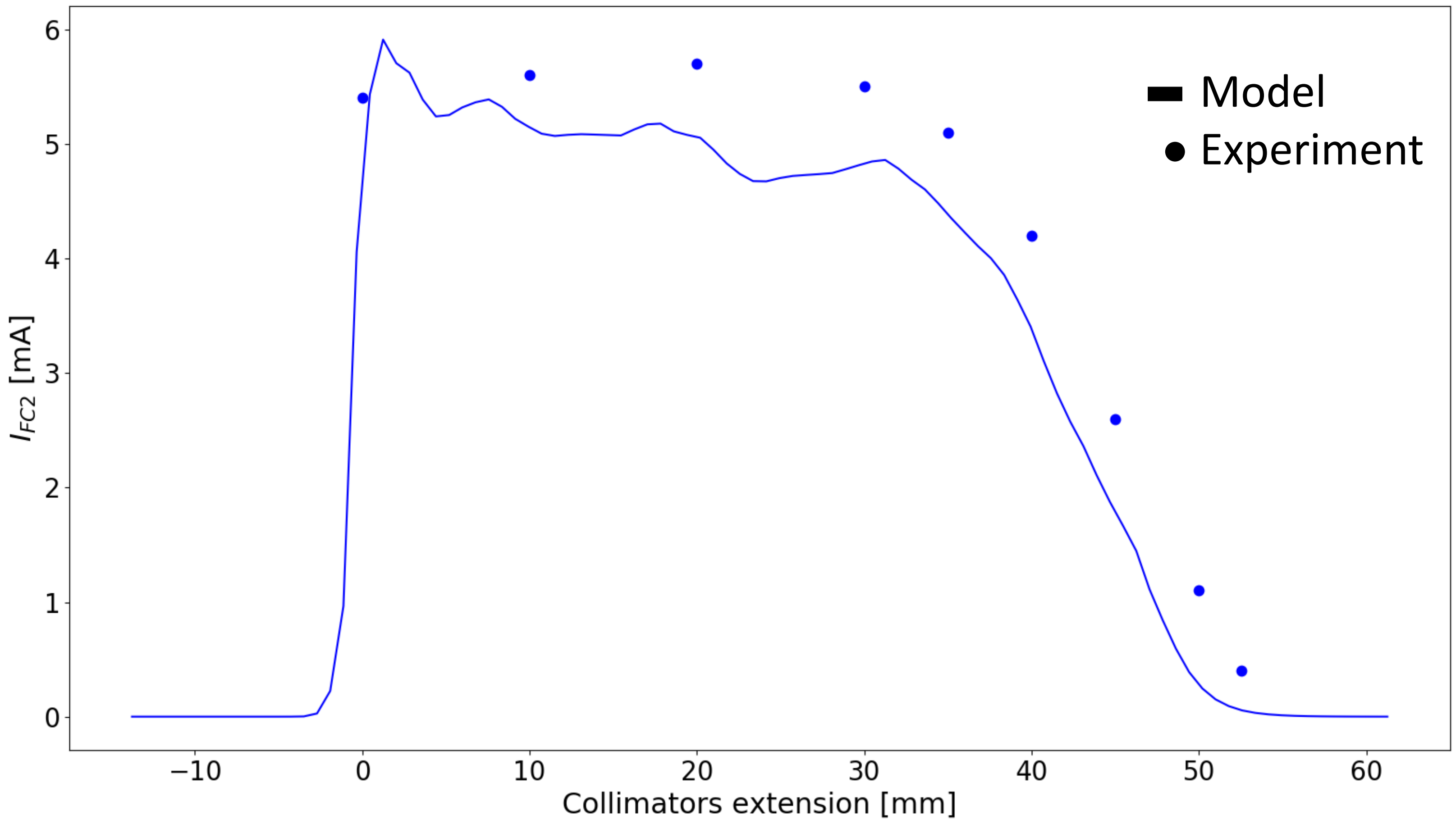
Model output : Identified issues & improvements



Precision issue



Model output : Identified issues & improvements



➔Issue comes from continuity

How to improve ?

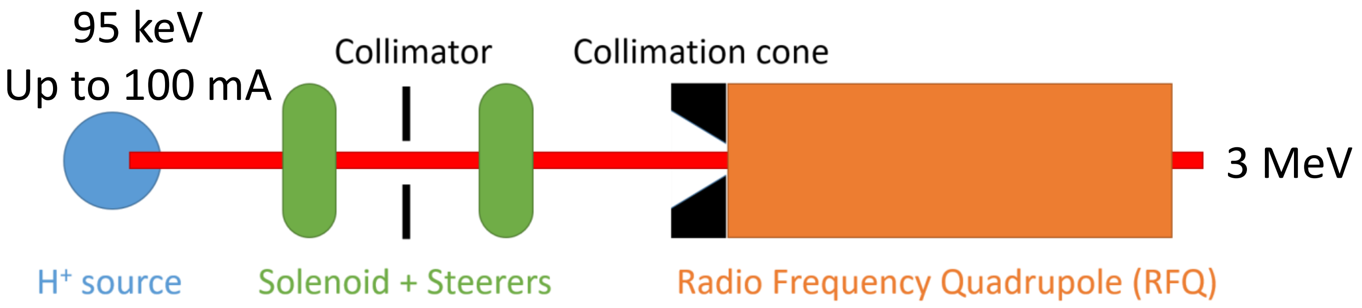
More training data !

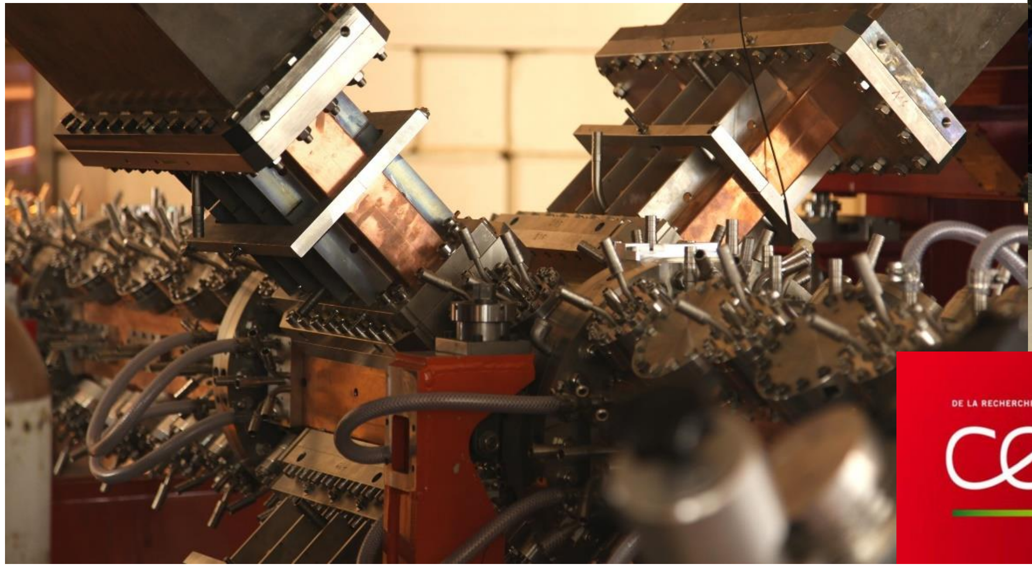
Simulation or Measurements

RFQ prospect: IPHI collaboration

Cycle utile ~0.4% x 50 mA x 3 MeV ≅ 600 W

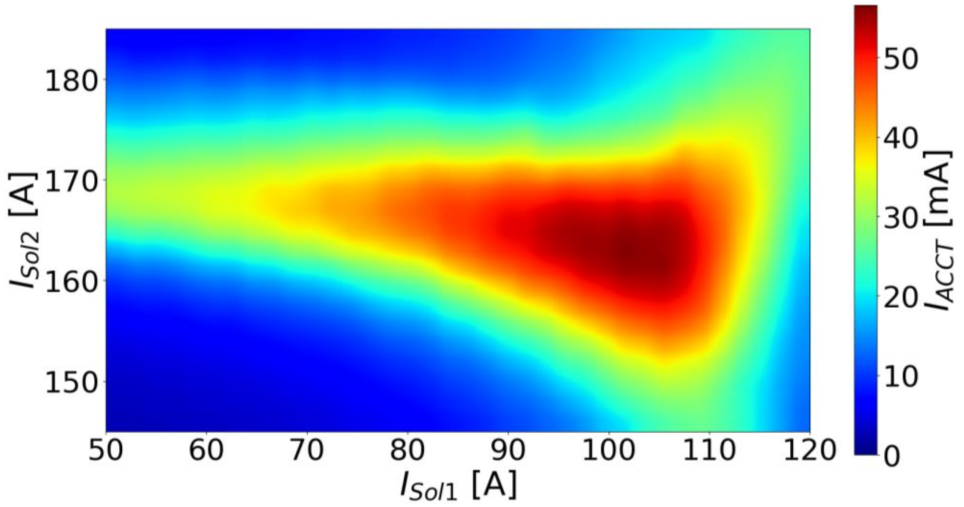
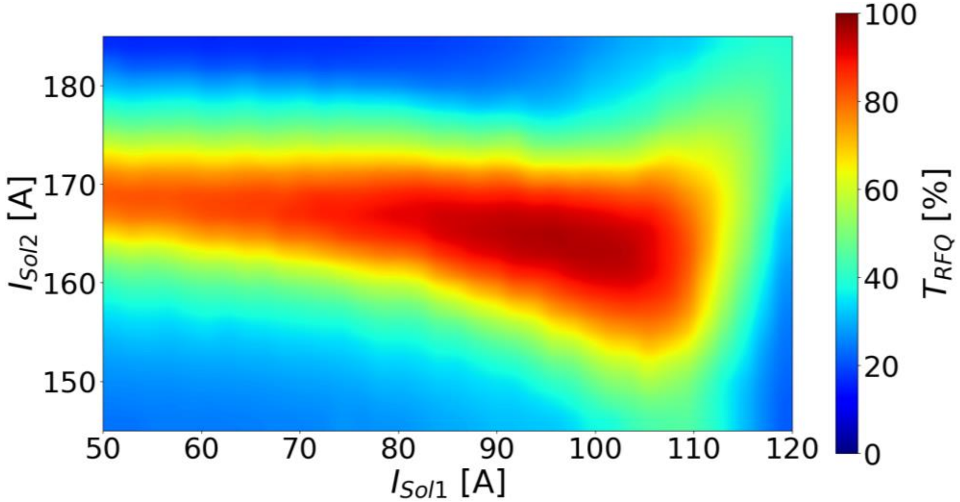
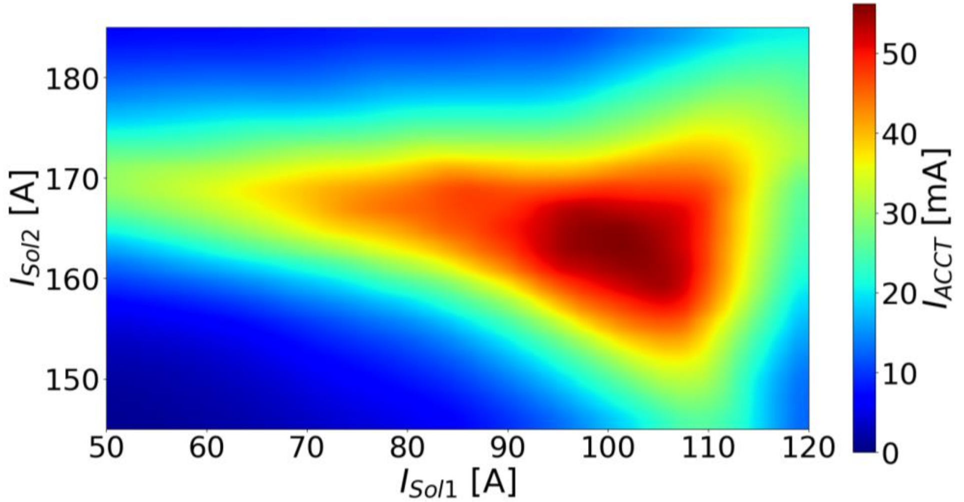
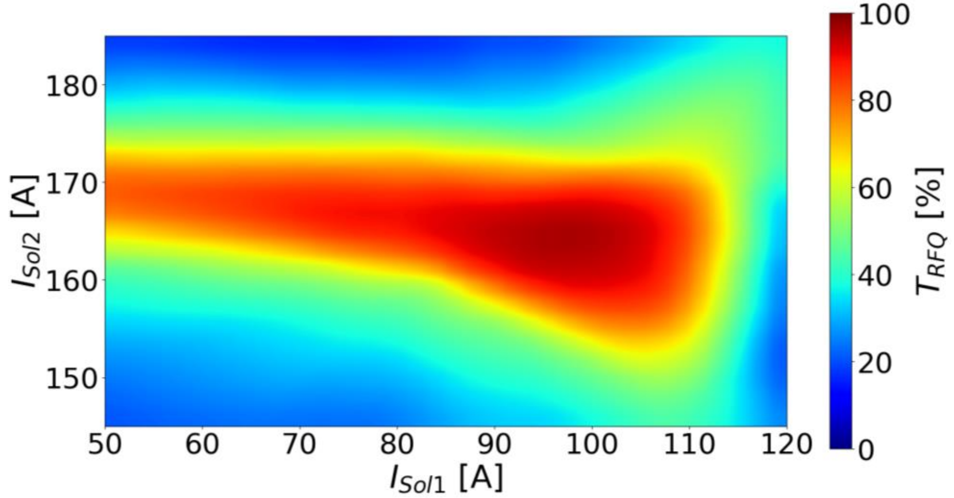
Same configuration as MYRRHA (LEBT + RFQ)





IPHI @ CEA Saclay

RFQ prospect: IPHI collaboration

	RFQ output current	RFQ transmission
Experimental		
Model		

Conclusion & prospects

- Machine Learning model
  - Training of an experimental model is possible
  - Improvement to be made
    - Optimize training: solve over fit issues
    - Optimize neural network (minimize training/execution time): #neurons, #layers, …
- Alternative
  - Particle Swarm Optimization
- Prospects
  - Training of a neural network controller
  - From desired current and RFQ transmission ➔ solenoid settings
  - Applications to SC cavities fast fault-recovery


рахмат
danke
謝謝
ngiyabonga
teşekkür ederim
Баярлалаа
спасибо
thank you
gracias
dank je
tapadh leat
хвала
asante
manana
mochchakkeram
bedankt
dziękuje
go raibh maith agat
obrigado
sukriya
kop khun krap
grazie
arigatō
takk
dakujem
trugarez
мерси
terima kasih
감사합니다
ευχαριστώ
merci
hvala
maururu
köszönöm
mahalo
paldies
blagodaram
misaotra
matondo
enkosi
rahmet
xiexie
diolch
dhanyavadagalu
shukriya
najis tuke
tanemirt
gracies
sulpay
ありがとう

Models performances in numbers

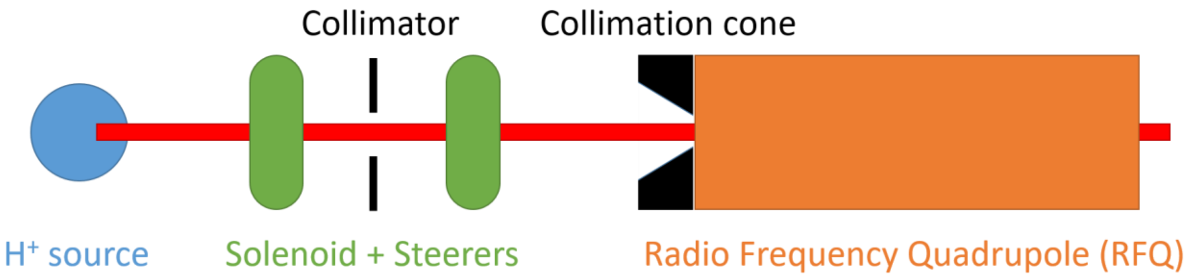
- Execution time ~10 µs

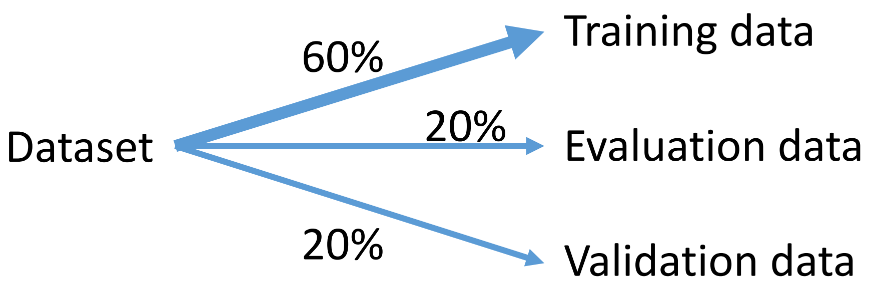
$$RMSE = \sqrt{\frac{\sum_{y_i}\left(y_i^{true} - y_i^{model}\right)^2}{N_{y_i}}}$$

- Quality evaluation: RMS error

	MYRRHA	IPHI	
Outputs	Beam current [mA]	Beam current [mA]	RFQ transmission [%]
RMSE on training dataset	0.09	0.66	1.25
RMSE on validation dataset	0.10	0.79	1.62
RMSE on test dataset	0.10	0.81	1.65
RMSE on whole dataset	0.09	0.72	1.42

RFQ prospect: IPHI collaboration



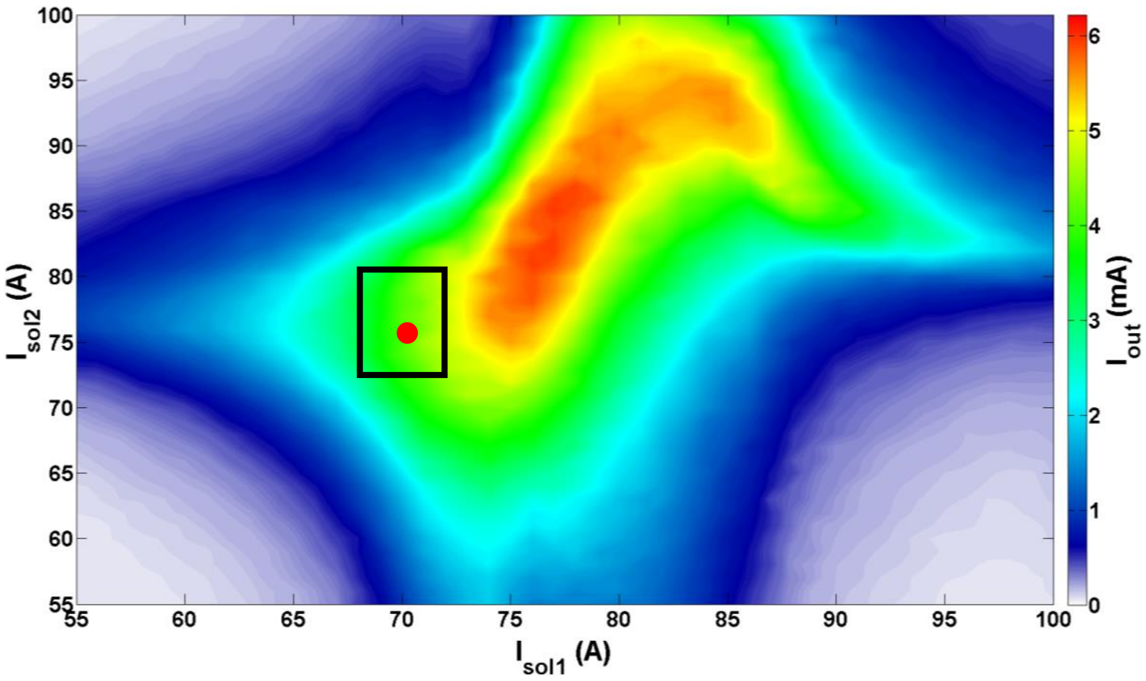


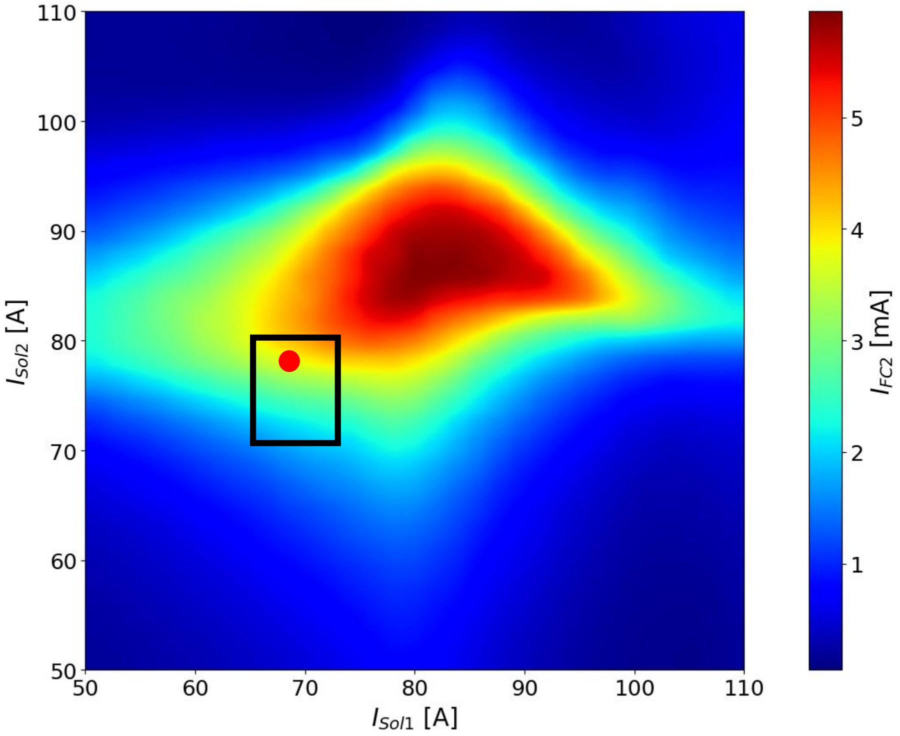
IPHI (CEA Saclay, France)

- ~8000 measurements

Input			Desired output	
Current in solenoids [A]		Collimator opening [m]	Beam current output [mA]	Transmission [/]
I_{sol1}	I_{sol2}	r_{coll}	$I_{Beam,out}$	T_{RFQ}

Comparison Grenoble-LLN



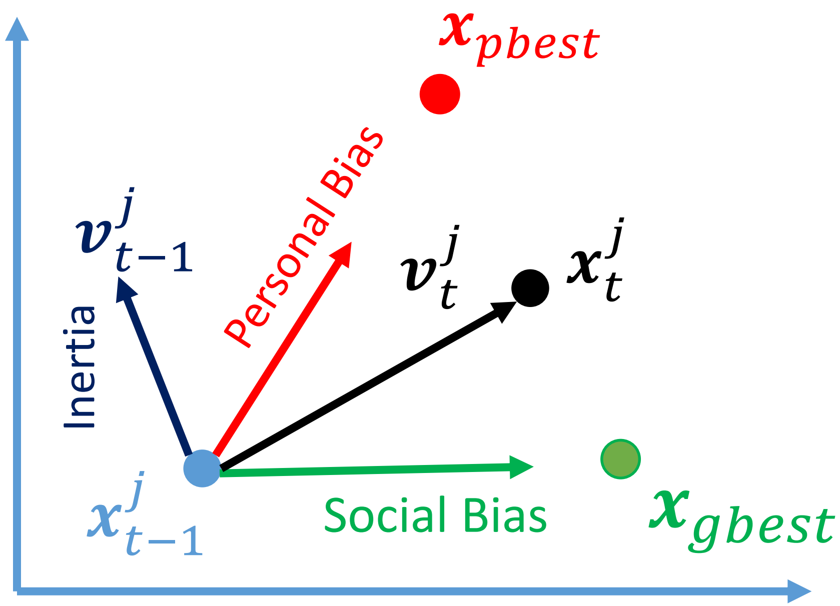


- I_{source} = 9 mA
- P = 2.4 10^{-5} mbar
- Collimator aperture : 37 mm
- Steerers settings inside solenoid 2 :
  - $I_{steererH}$ = 0.5 A
  - $I_{steererV}$ = -2 A

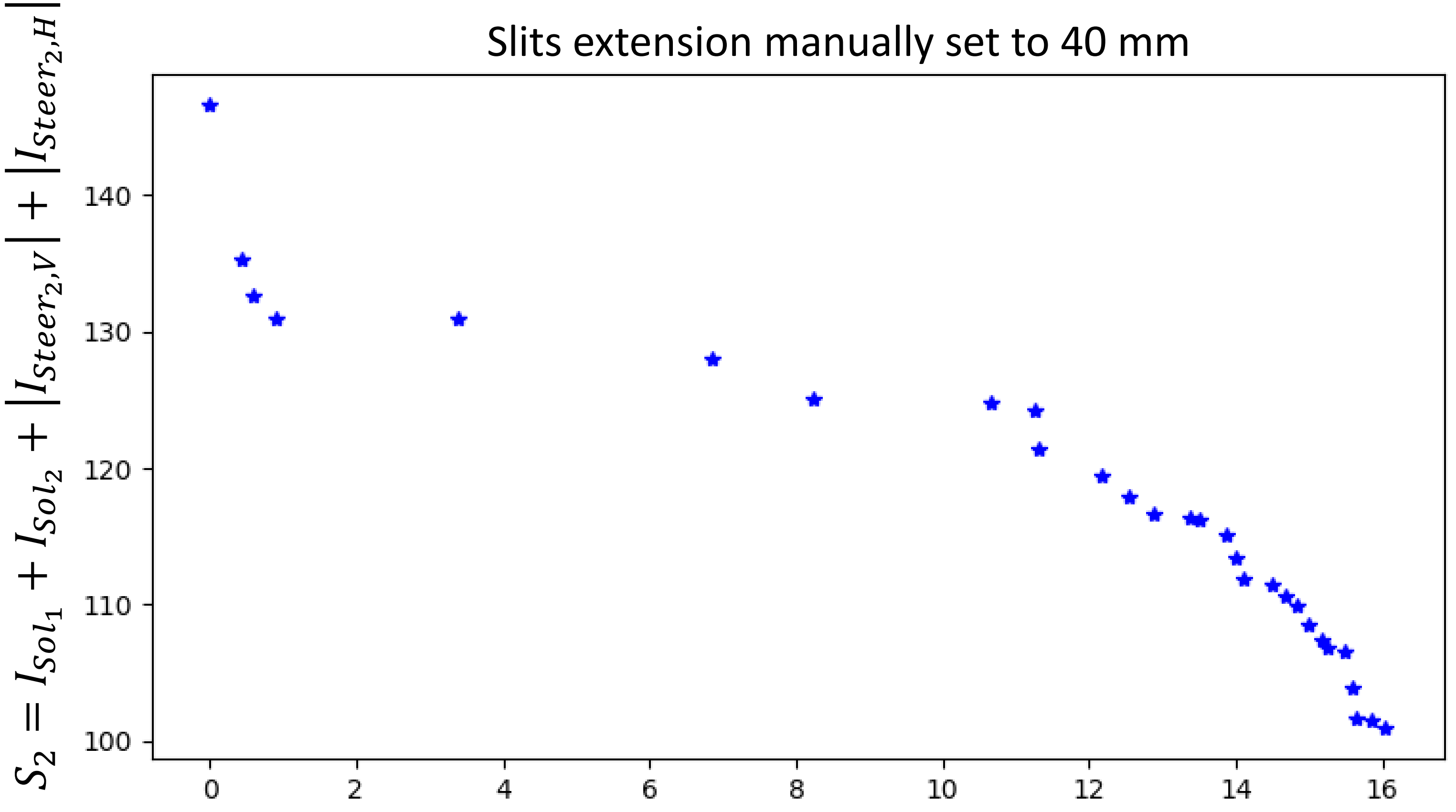
- $I_{source} = 8$ mA
- $P = 1.9 \times 10^{-5}$ mbar
- $I_{Steer2H} = -0.5$ A, $I_{Steer2V} = 0.75$ A
- Collimator extension = 40 mm

Particle Swarm Optimization

- Metaheuristic algorithm



Particles are potential solutions of the optimization problem (≠particles in physics)



Score 1 $= (I - I^{target})^2$ with $I^{target} = 4.2\ mA$

First test !

Improvements to be made…