



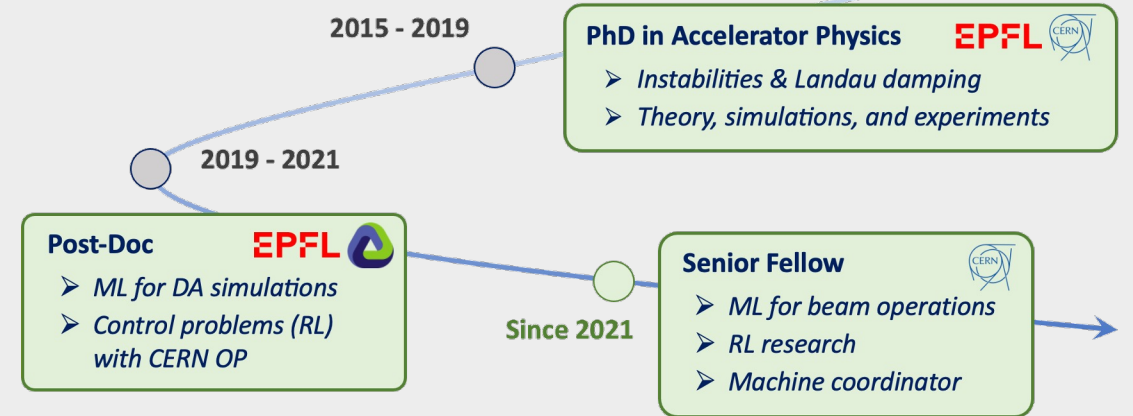
## Michael Schenk

Accelerator Physicist

Fellow in Data Science for Beam Operations

✉ [michael.schenk@cern.ch](mailto:michael.schenk@cern.ch)

in <https://www.linkedin.com/in/m-schenk/>



## RL projects & interests

- **2019:** first RL steps on LEIR together with Simon
- **Now**  
Sample-efficient RL with quantum Boltzmann machines trained on D-Wave hardware
- **Future**
  - Continue N. Madysa's LEIR Schottky RL project
  - Hierarchical RL: student's project

## Other ML / control experience

- Adaptive sampling / Bayesian exploration
- Conditional GANs
- Clustering
- Automatic tune adjustment using numerical optimizers

# Free energy based RL (FERL)

## RL with quantum Boltzmann machines

### Q-learning

Various function approximators for  $Q(s, a)$

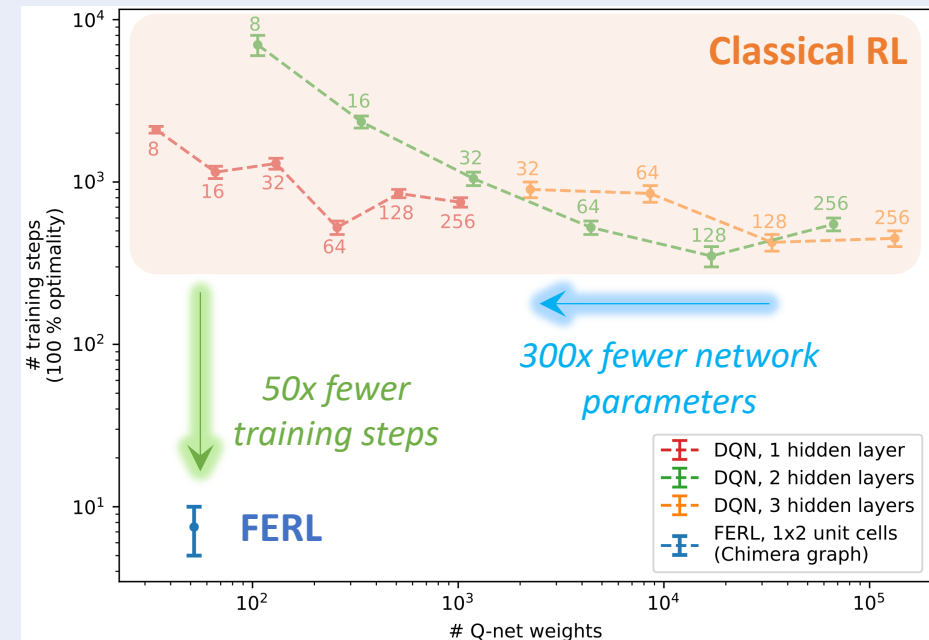
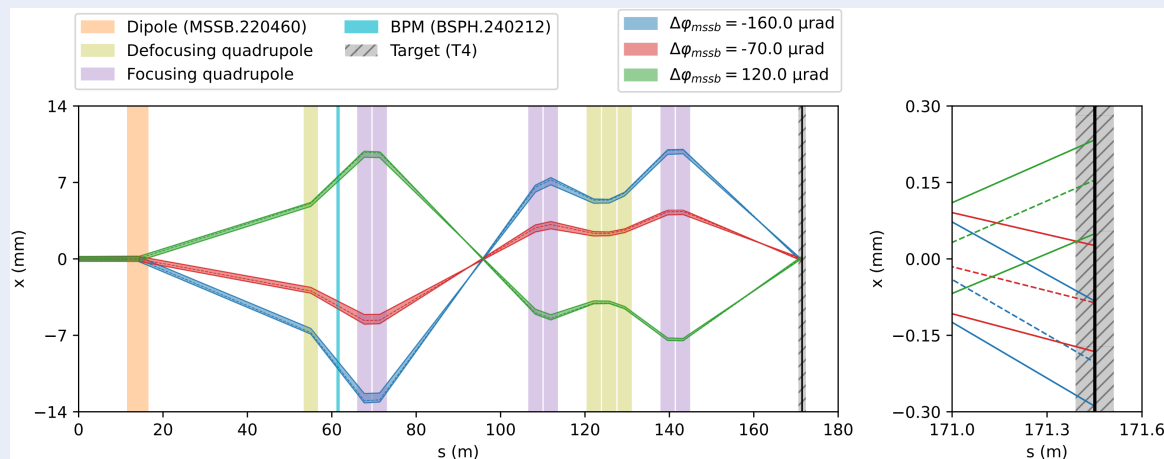
- **Traditionally:** look-up table
- **DQN:** feed-forward neural net
- **FERL:** quantum Boltzmann machine (QBM)

### Why FERL

- **Better learning efficiency?**
  - ➡ more **cost-effective** for beam operations
- **No FERL algorithm exists for continuous control**

### 1D beam steering

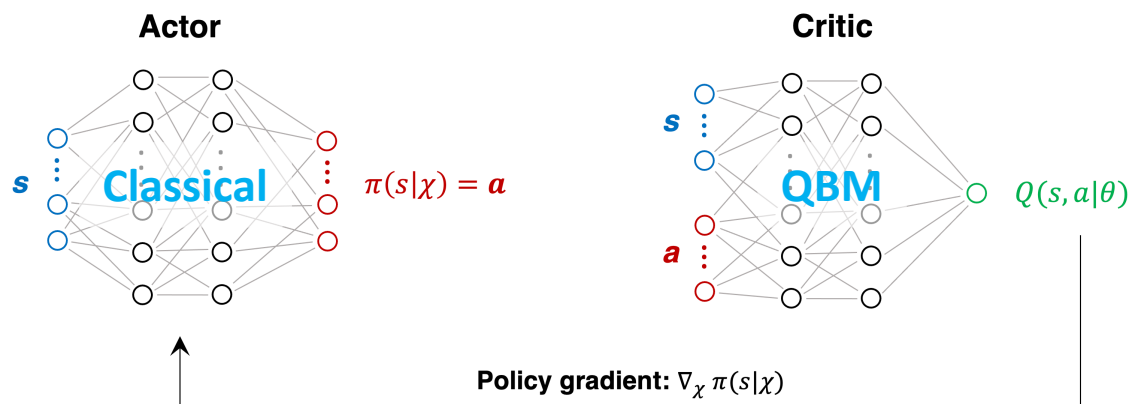
SPS North Area transfer line



# Free energy based RL (FERL)

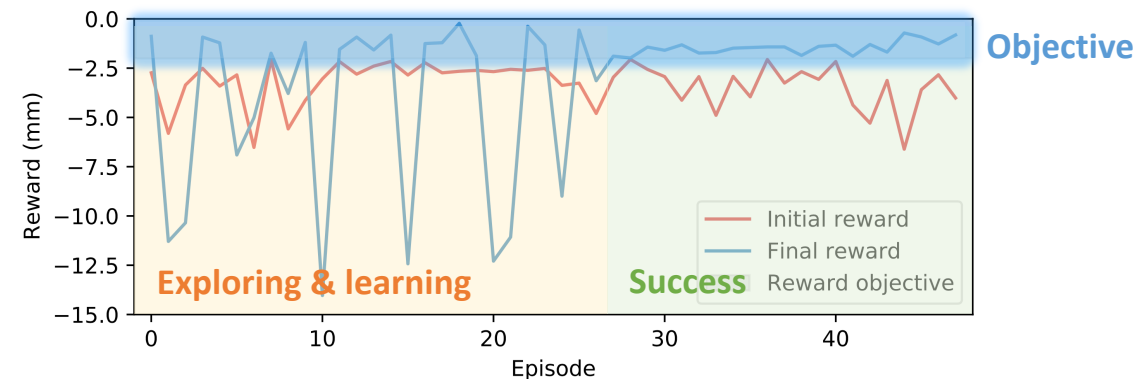
## RL with quantum Boltzmann machines

- Inspired by classical actor-critic scheme, developed a hybrid algorithm for continuous state-action space  
*Intuition: if critic learns more efficiently, can provide more valuable feedback early on during training*
- Trained on D-Wave quantum annealer and tested on CERN's AWAKE beam line



### Training our algorithm on a quantum computer

Trajectory steering on simulated AWAKE e- beam line



AWS Service Charges		\$2,805.51
▼ Braket		\$2,337.88
▼ US West (Oregon)		\$2,337.88
Amazon Braket CompleteTask		\$98.08
\$0.00019 per-shot for D-Wave-2000Q in US West (Oregon) Region	516,209.000 Quantum-Shot	\$98.08
Amazon Braket Task		\$2,239.80
\$0.30 per-task for D-Wave-2000Q in US West (Oregon) Region	7,466.000 Quantum-Task	\$2,239.80

