Real-Time Implementation of the Neutron/Gamma discrimination in an FPGA-based DAQ MTCA platform using a Convolutional Neural Network

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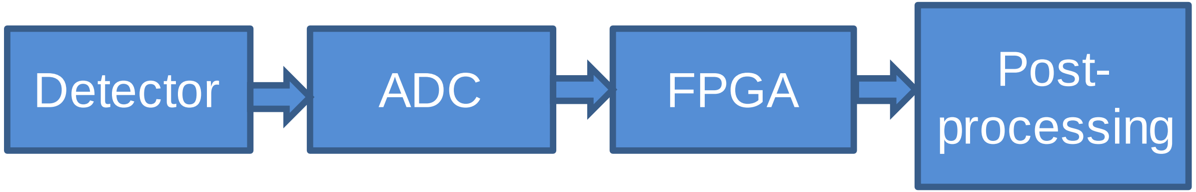
Outline

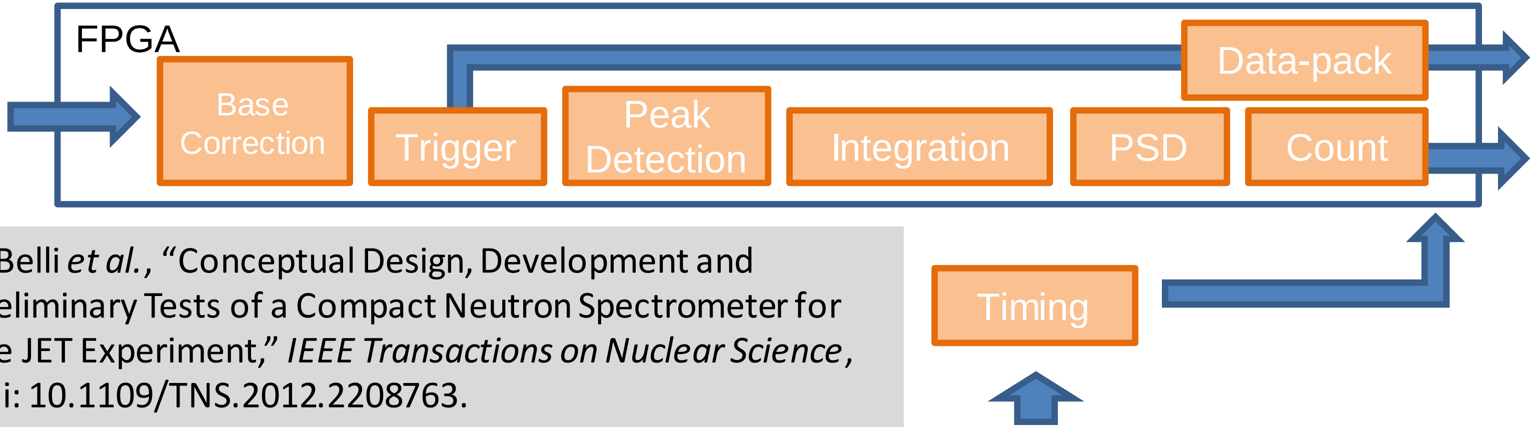
- Context on Neutron-Gamma discrimination
- Objective
- 1D Convolutional Neural network
- Implementation
- Results
- Conclusions

Context on Neutron-gamma discrimination

- Architecture of **Traditional FPGA-based DAQ systems**



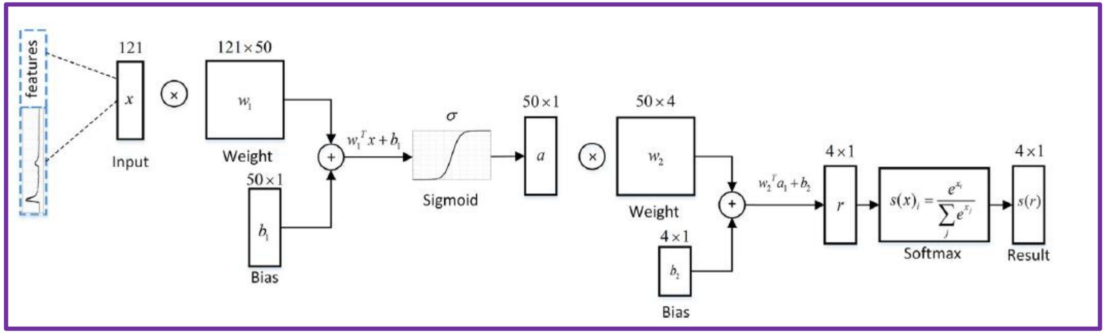
- Example of FPGA Neutron gamma discrimination in JET



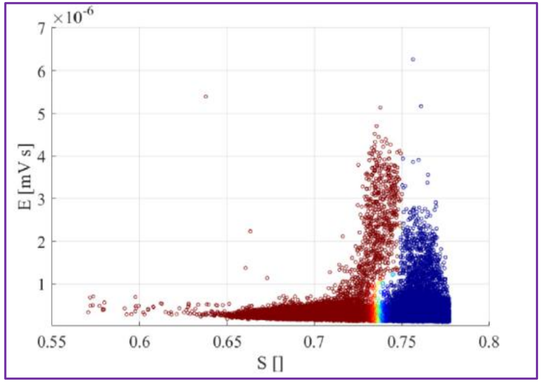
F. Belli *et al.*, "Conceptual Design, Development and Preliminary Tests of a Compact Neutron Spectrometer for the JET Experiment," *IEEE Transactions on Nuclear Science*, doi: 10.1109/TNS.2012.2208763.

Context on Neutron-gamma discrimination

- Extensively researched topic.
- Traditionally integration over different intervals.
- Latest techniques involve Machine learning
- Fusion datasets cannot be easily split (Complex problem, specially for low Energy)



Multi Layer perceptron developed by [C. FU]



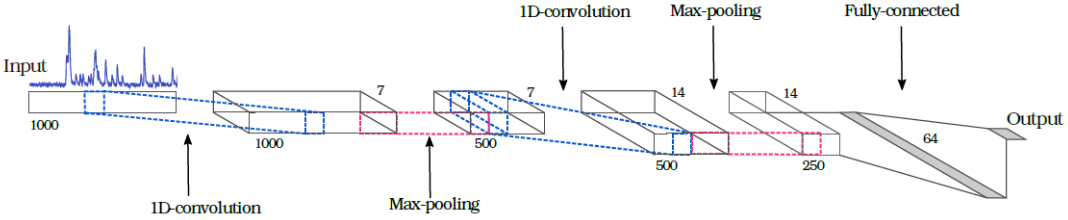
Classification of Gama-Neutron suing SVM
Reproduced from [Gelfusa]. JET Pulse no. 90653

C. Fu, A. et al, "Artificial neural network algorithms for pulse shape discrimination and recovery of piled-up pulses in organic scintillators," *Annals of Nuclear Energy*, doi: 10.1016/j.anucene.2018.05.054

M. Gelfusa *et al.*, "Advanced pulse shape discrimination via machine learning for applications in thermonuclear fusion," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, doi: 10.1016/j.nima.2020.164198

Context on Neutron-gamma discrimination

- Machine learning methods:
  - Signal and feature MLP
  - Support Vector machines
  - CNN
- Each with different advantages.
- Implemented a model using the successful CNN (very popular in image processing).
  - Very good results for pattern recognition.
  - Requires more than just 2 classes for more real signal classification.

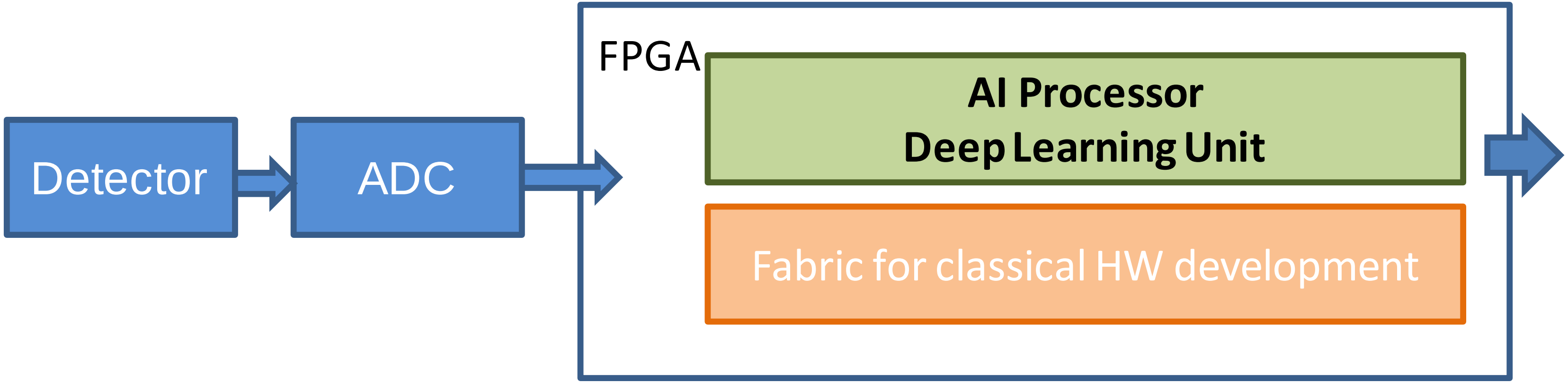


Reproduced from [A. Vacheret]

A. Vacheret, R. Taylor, D. Saunders, S. Kleinegesse, and J. Griffiths, "Pulse Shape Discrimination and Exploration of Scintillation Signals Using Convolutional Neural Networks," Machine Learning: Science and Technology, 2020, Accessed: Sep. 30, 2020. [Online]. Available

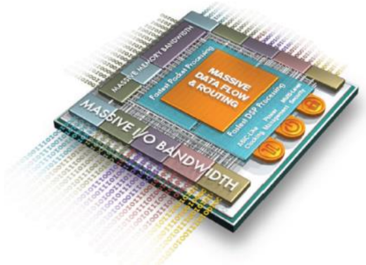
Context on Neutron-gamma discrimination

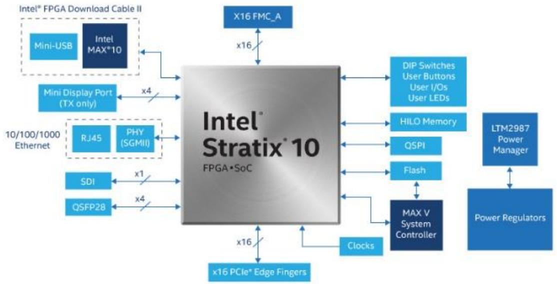
- What can we change by a NN ? → Classification problem
- What is the architecture of this NN ? → Many choices
- What are the advantages ? → Potentially better results
- What are the drawbacks ? → Black box
  → Intensive computing



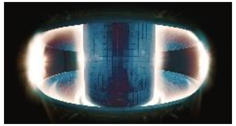
Objective

- Traditional FPGA or SoC: Hard to develop. HDL
- New trends in FPGA technologies: promoting the use of High-level languages (HLS) or OpenCL
- New Heterogeneous Hardware platform: FPGA + ARM Cores **+** AI cores, ACAPs. Tensor cores, with ADCs
- Much more raw computing power than traditional approach.
- Industry interest in AI.

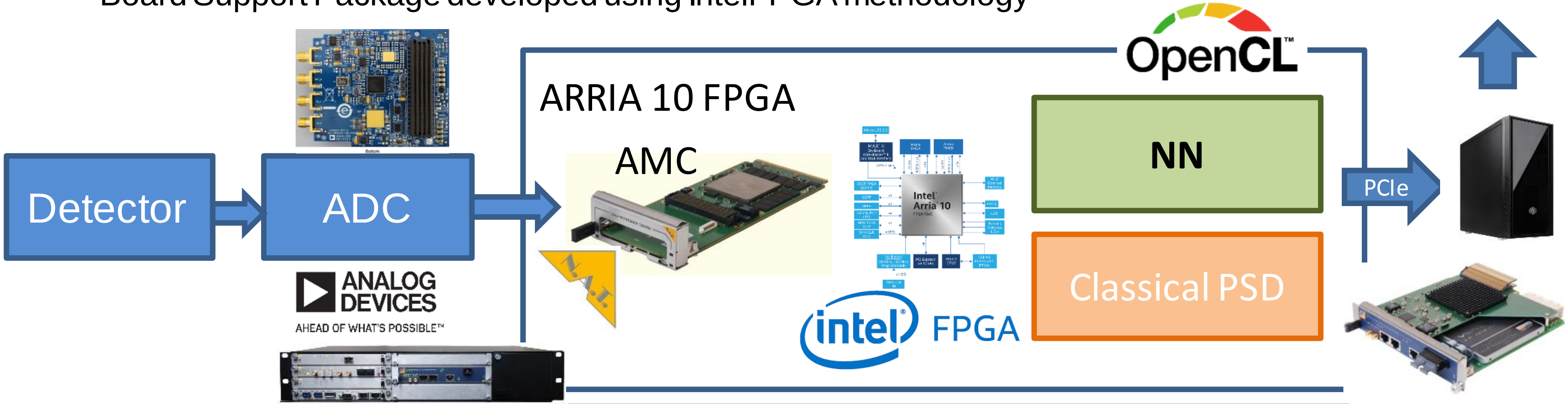




Objective



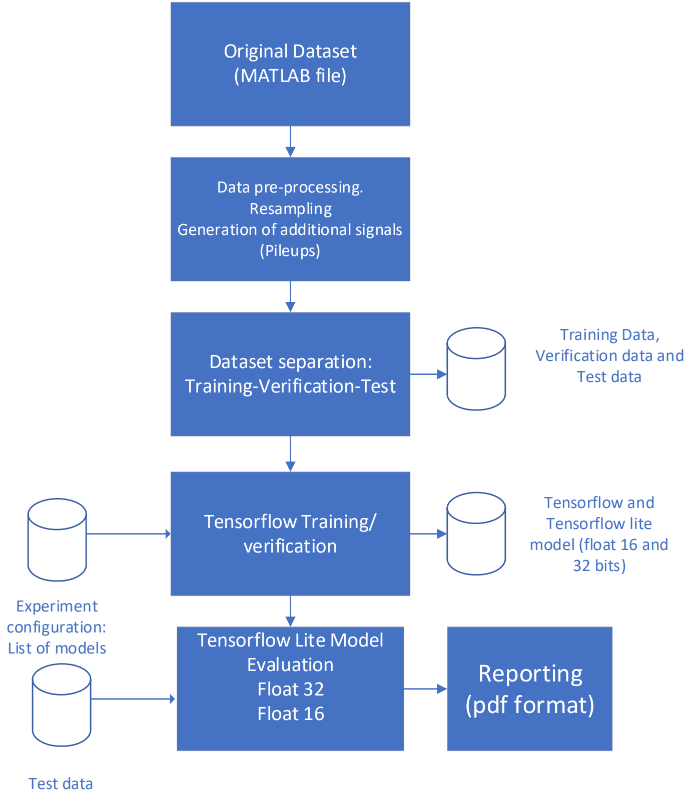
- Evaluate the implementation of a prototype using MTCAtechnology and ITER CODAC Core environment (RHEL)
  - Use of commercial AMC module and FMC ADC (NAT and Analog Devices)
  - Integration with EPICS
- Hardware development using OpenCL C like programming (custom CNN Neural network).
- Board Support Package developed using IntelFPGA methodology



M. Astrain et al, "A methodology to standardize the development of FPGA-based high-performance DAQ and processing systems using OpenCL," *Fusion Engineering and Design*, doi: 10.1016/j.fusengdes.2020.111561

Convolutional Neural network

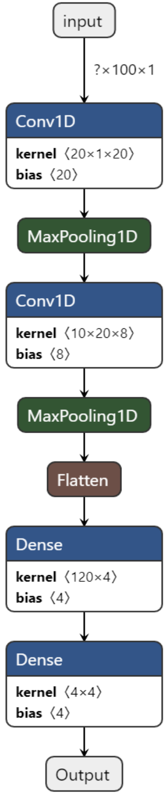
- Using 1D CNN
- JET Pulse no. 90653, re-sampled to 250MS/s
- Generate Pile-ups from pulses
- 33% split data train-verification-test
- Modeled for float 32 and 16 (Quantization did not provide useful results yet)
- Created in a python environment using:
  - Anaconda, python 3.8,tensoflow(keras) and tensorflow-lite



C. Fu, A. et al, "Artificial neural network algorithms for pulse shape discrimination and recovery of piled-up pulses in organic scintillators," *Annals of Nuclear Energy*, doi: 10.1016/j.anucene.2018.05.054

1D Convolutional Neural Network

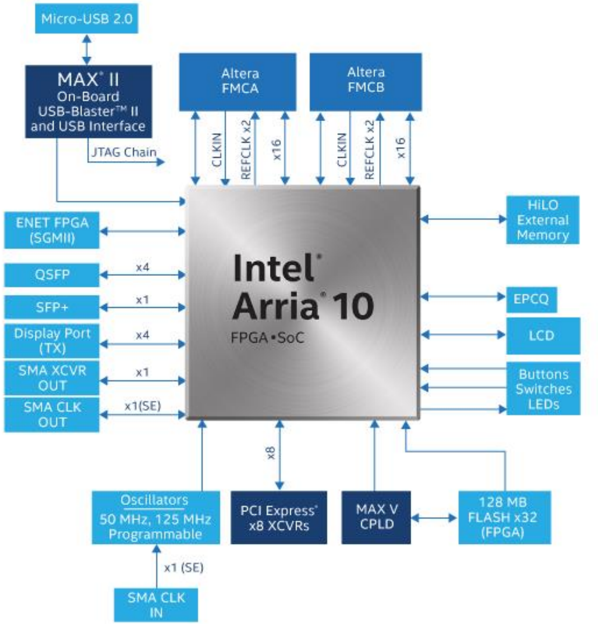
- Solution:
  - 7 Layers with 2532 weights
  - Accuracy of 99.5% in TensorFlow
  - Performance of 40 us in a desktop computer
- Advantages using CNN
  - More robust than MLP when there is a signal displacement
  - Automatic learning of features. The filters focus on different patterns, similar to the classic PSD techniques
- Disadvantage
  - Second CNN layer requires most part of computational resources
  - Data re-ordering required for calculations (implies accessing to memory resources in the FPGA. This slows the solution)



Netron Representation

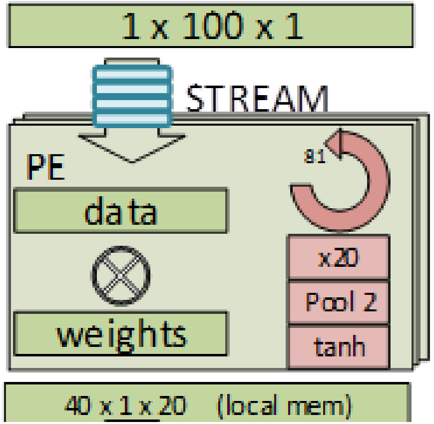
FPGA Implementation (ARRIA 10)

- Complete NN implementation using OpenCL (float32)
- Board Support Package for OpenCL 17.1
- Utilizing hardened floating-point variable-precision digital signal processing (DSP) blocks.
- 1D CNN can fit the inference parameters inside the FPGA RAM blocks (avoiding use of external DRAM)
- External access to DRAM is minimized (global memory)
- Data streams from FMC I/O board



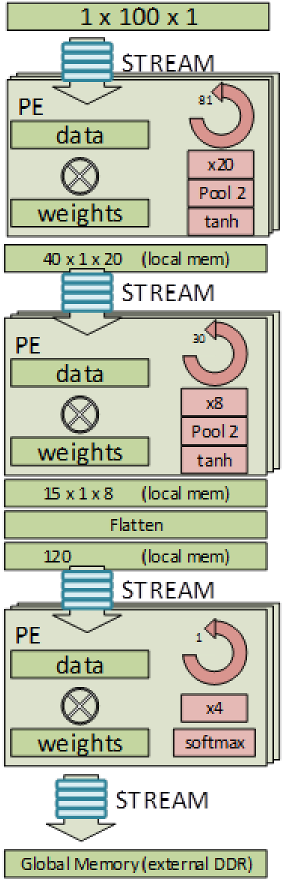
FPGA Implementation

- Processing elements in the FPGA take data streams
- ML Convolution operations:
  - Calculate the dot product and accumulate (weights)
  - Add offset (bias)
- Weights and data between layers is streamed to M20K blocks.
- Activations of (tanh) neuron are costly in computing
  - But ReLu operations where unsuccessful in training
- Replication of the Processing Elements enables parallelization



Results

- 2532 weights CNN 32bit float.
- 150MHz kernel clock frequency.
- 40% area usage.
- Low DSP usage (higher parallelization potential!).
- 250us processing time, 4k event/s working with internal RAM blocks.
- Maximum error in the classification with the test signals of 0.8% (gamma), 0.9% (neutron), 2.5% (close pileup), and 1.1% for each class.
- Moving to an Intel-FPGA Stratix device could achieve around 25k events/s (this is under development!).



Conclusion

- Modern state-of-the-art Machine Learning methods where applied to the n/g discrimination problem using JET Pulse no. 90653.
- 1DCNNs are capable of achieving very high accuracies with very little knowledge about the signals.
- 1D implementations are simple enough to fit in the FPGA using OpenCL. The whole NN can be executed locally.
- Using OpenCL the NN can be ported to higher-performance solutions.
- Higher performance FPGAs might be able to achieve a real-time classification system with around 25kevent/s

Acknowledgement

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Thank you!

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