Validation and comparison of FPGA-based Real-Time Thomson Scattering data processing against offline analysis methods

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目录

CONTENTS

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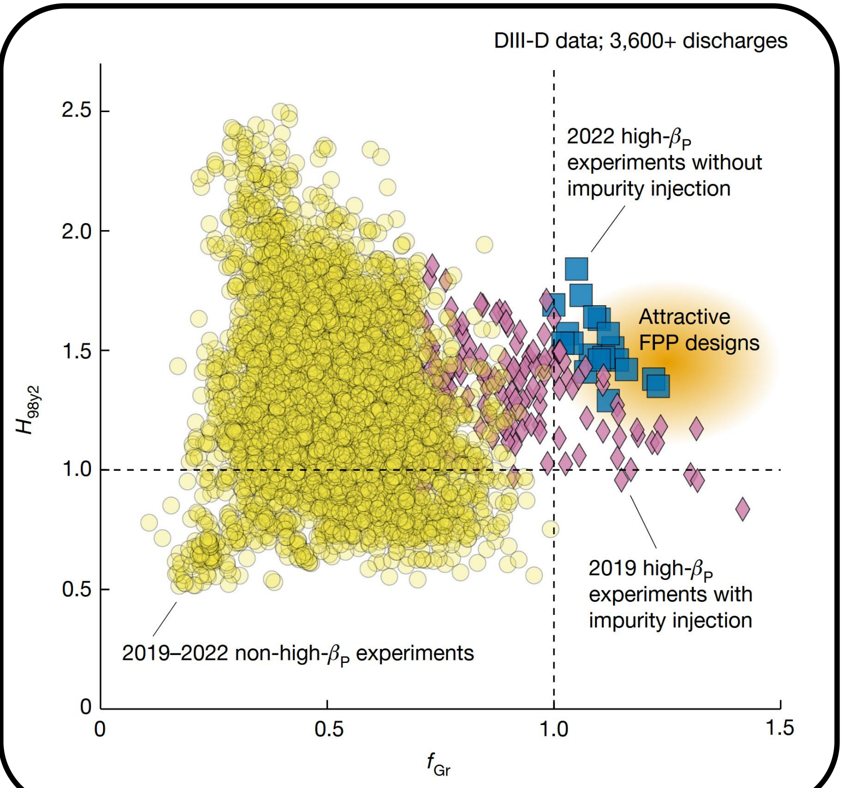
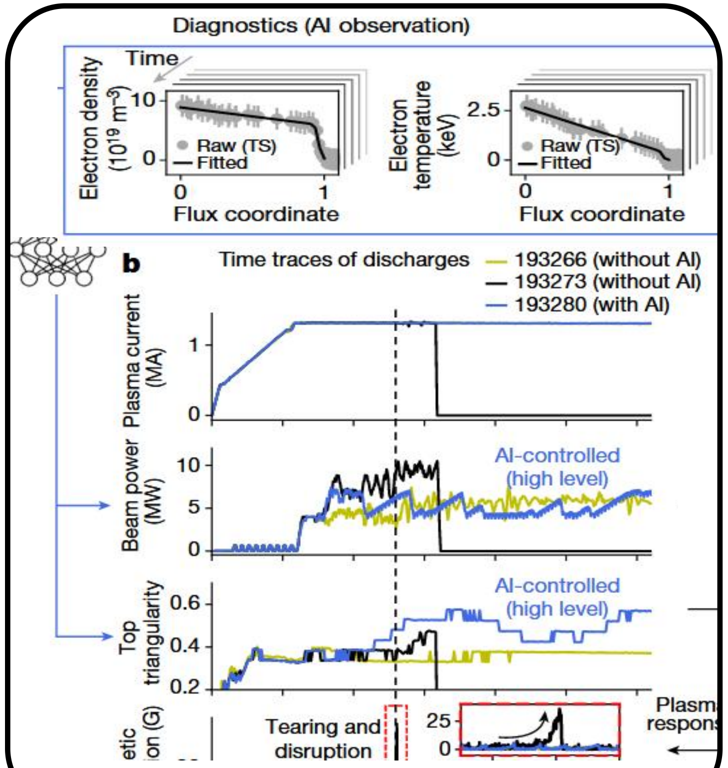
目录
CONTENTS

Background

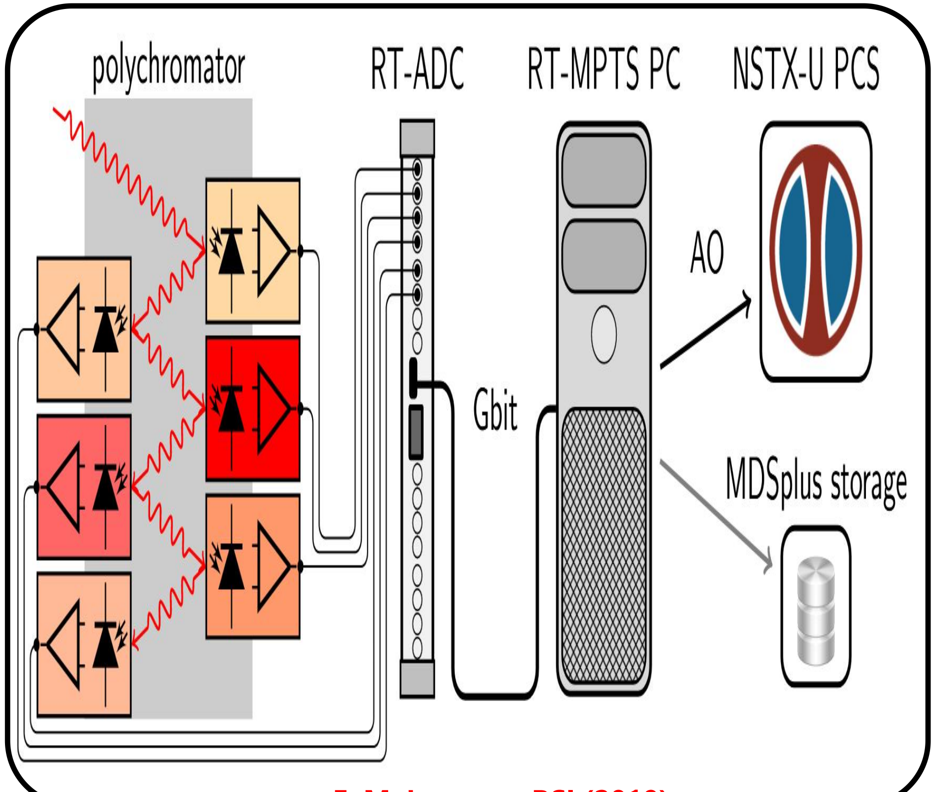
- Operate in high-density, high-confinement regimes;
- Advanced profile control needs real-time T_e and n_e;
- Compute must beat millisecond-level GPU latency;



Ding, S., Nature (2024)



Jaemin Seo,, Nature (2024)



F. M. Laggner, RSI (2019)

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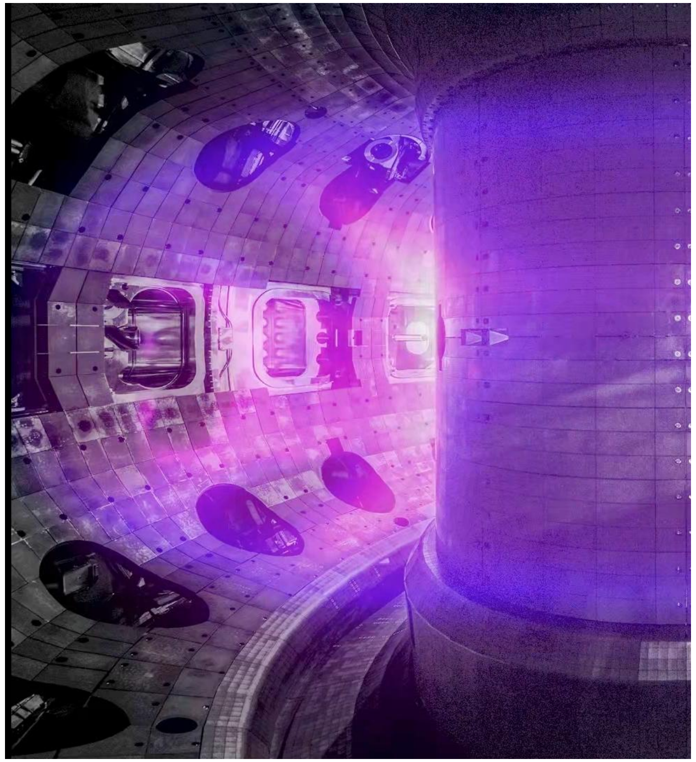
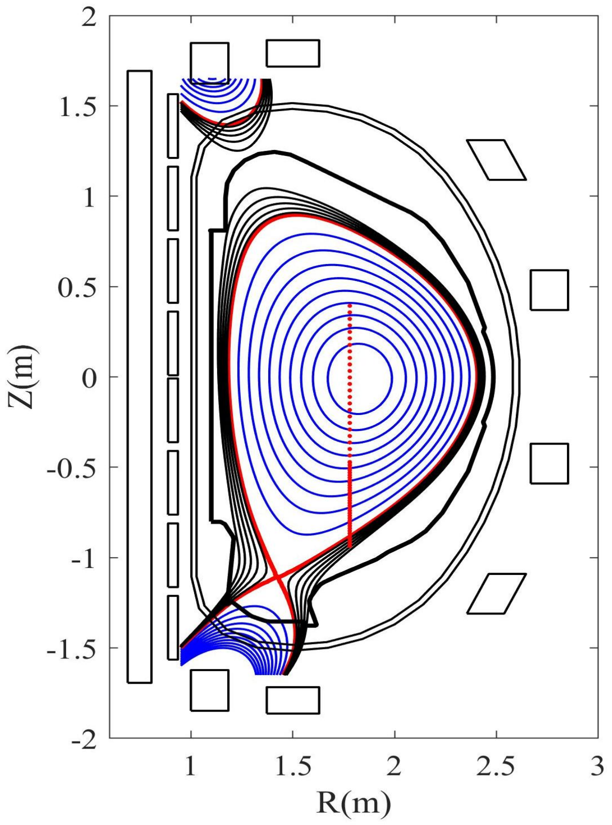
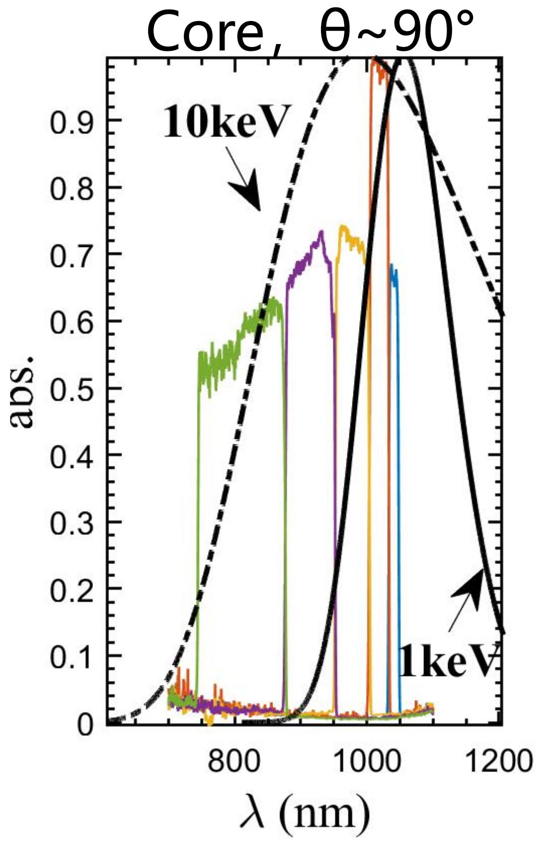
目录
CONTENTS

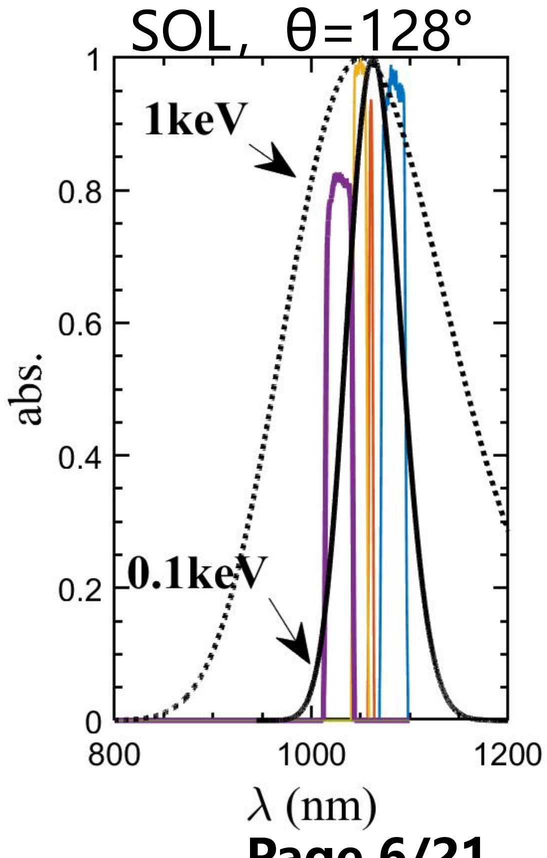
Design Basis

- On HL-3 in Spring 2025, the Thomson scattering system used a vertical laser beam with 60 spatial points
- Covering T_e=0.1–10 keV and n_e of 5×10^{18} m^{-3}—2×10^{20} m^{-3};
- A 1064nm@2J Nd:YAG laser enabled 30 Hz temporal and 1–2 cm spatial resolution.



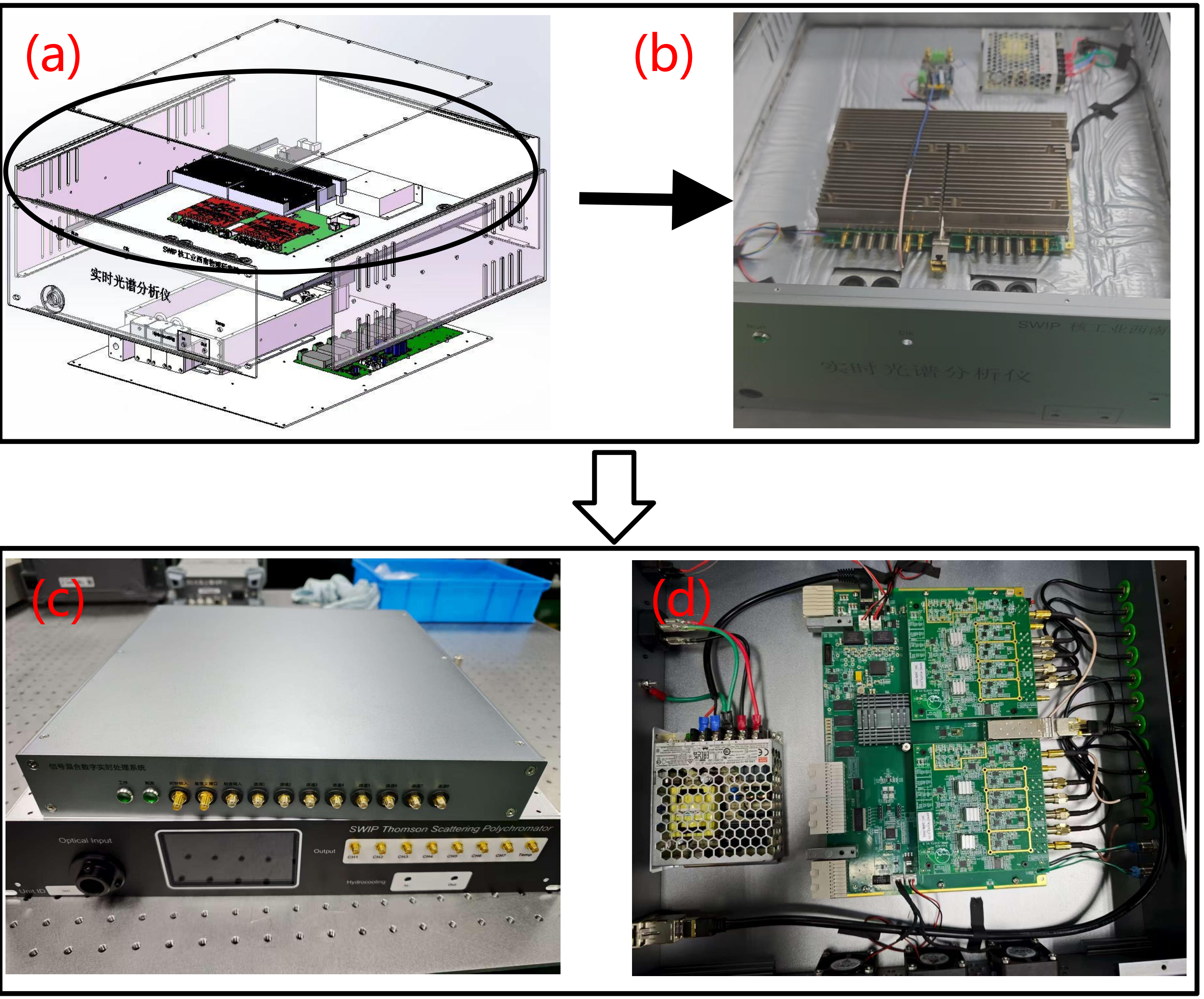


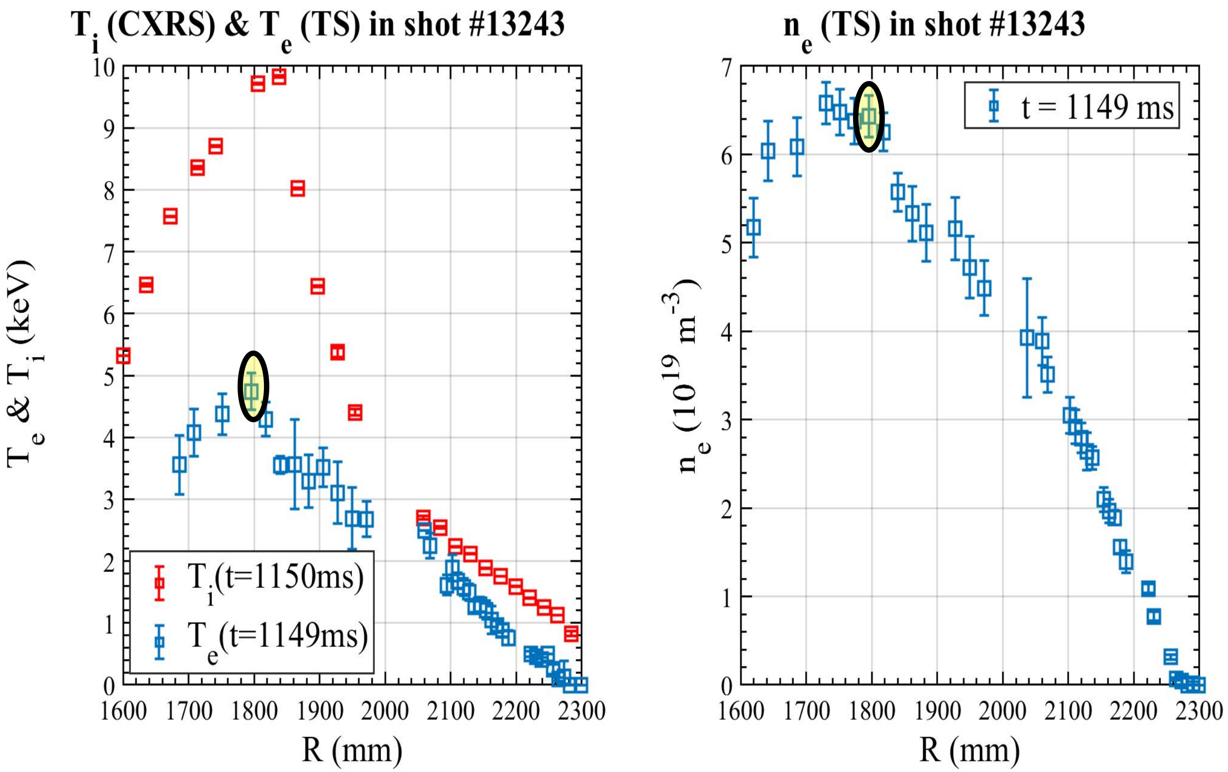




Design Basis

- RT-TS was developed and validated on the existing polychromator.
- Core spatial points were selected to support disruption prediction.



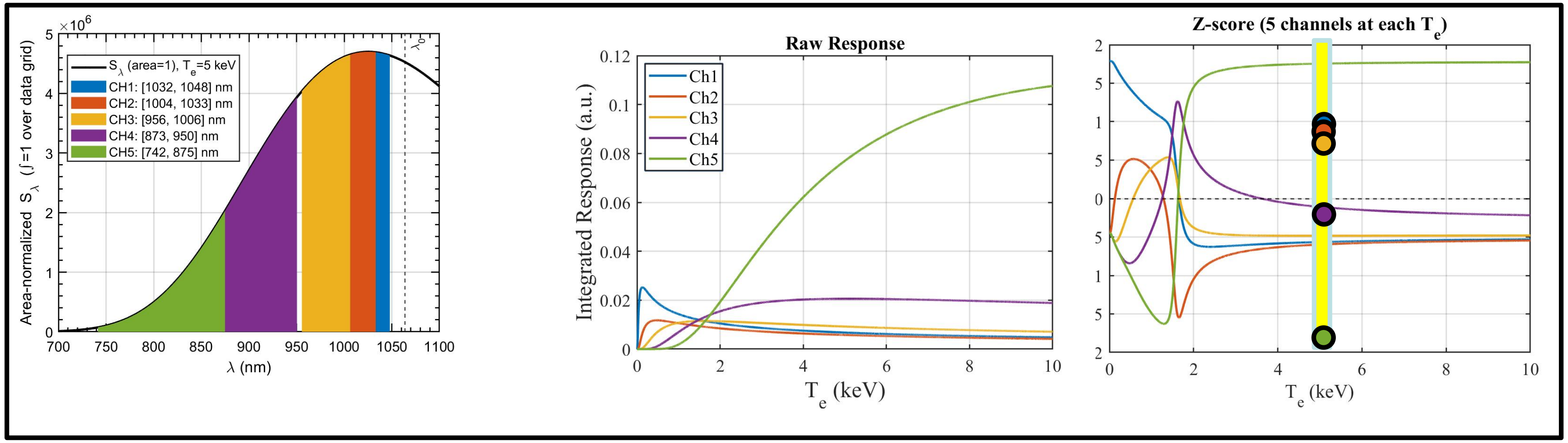


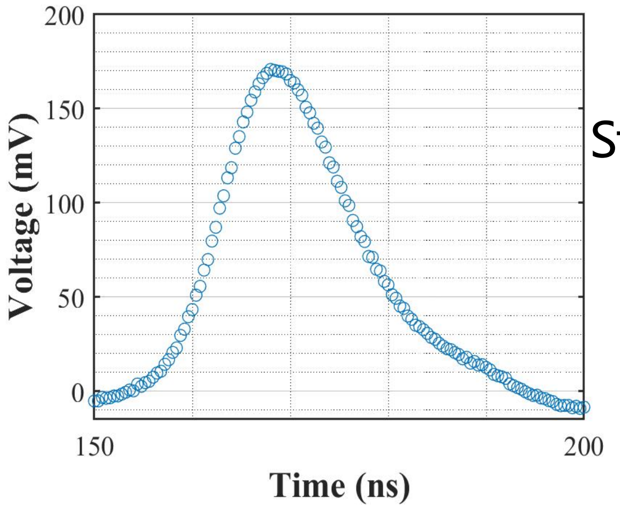
目录

CONTENTS

Implementation Process

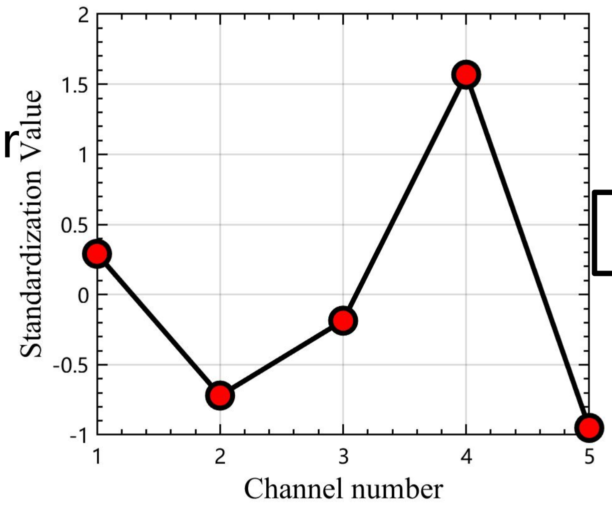
Calculate Te
- Waveform Integration
- Integral Extraction
- Normalization
- Least-Squares Table Lookup





Integration
StandardScaler

$$X = \frac{X_i - \mu}{\sigma}$$



least squares

Ch1 → CH5

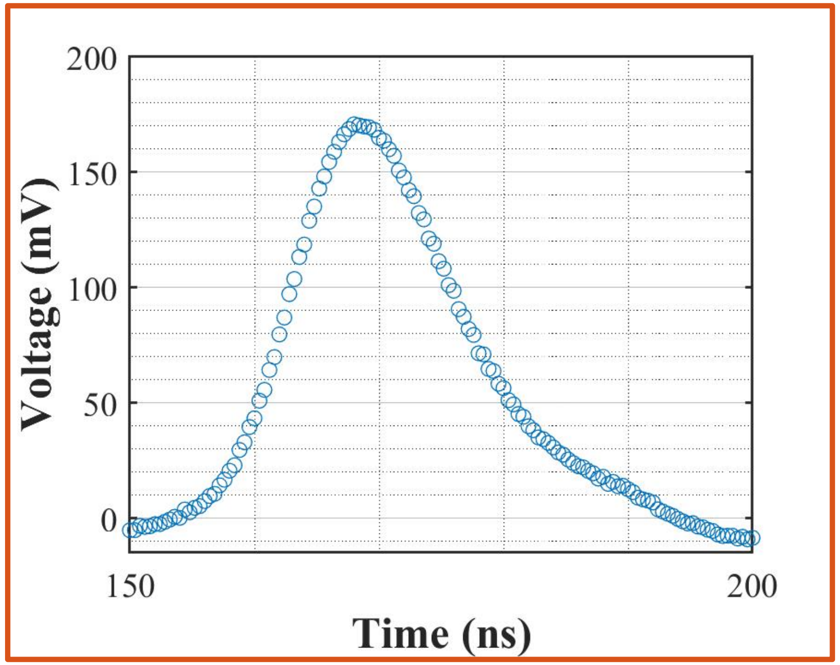
0 ↓ 10KeV

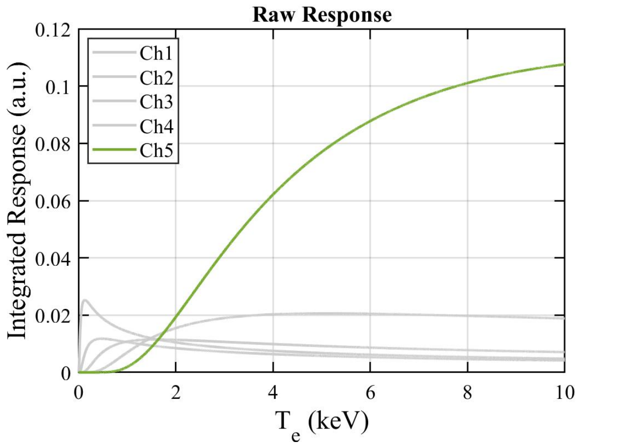
	1	2	3	4	5
1	-0.7663	-0.6340	-0.5263	0.3008	1.6258
2	1.5919	-0.8651	-0.7627	-0.2418	0.2777
3	1.7648	-0.6115	-0.5703	-0.3823	-0.2006
4	1.7792	-0.5498	-0.5299	-0.4080	-0.2915
5	1.7835	-0.5146	-0.5177	-0.4211	-0.3301
6	1.7855	-0.4839	-0.5160	-0.4318	-0.3538
7	1.7864	-0.4530	-0.5195	-0.4422	-0.3717

5×5001

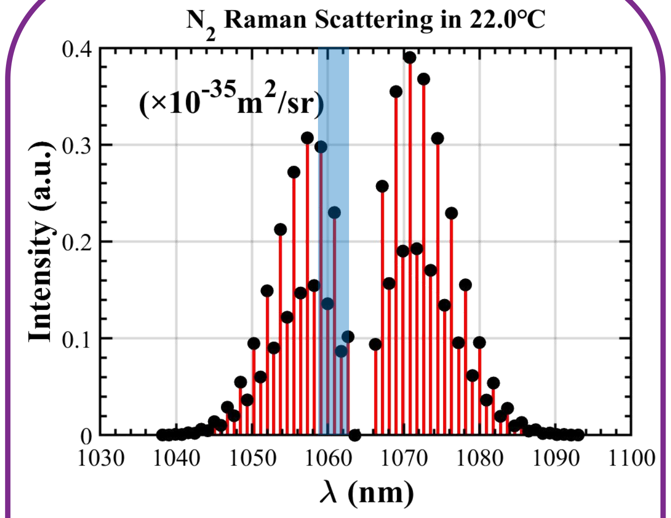
Implementation Process

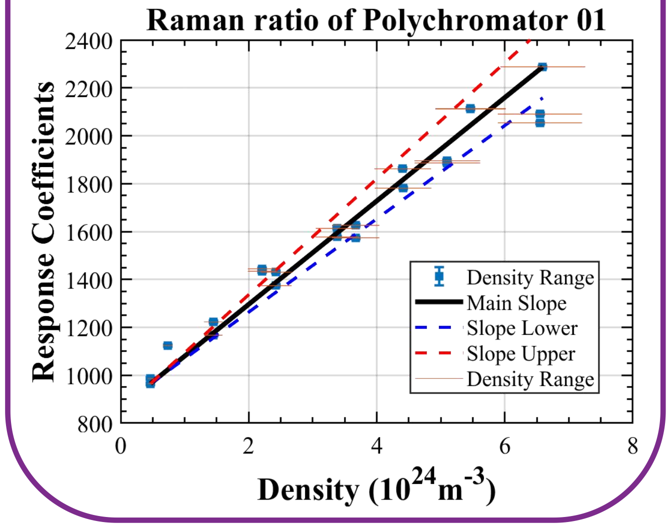
$$n_{e,i} = S_{i,TS} \bullet \left(\frac{\sum \sigma_{Raman}(\lambda_i) \bullet R(\lambda_i)}{\sigma_{TS} \bullet \int f_{i,TS}(T_e) \bullet R(\lambda_i) d\lambda} \right) \bullet \frac{1}{\partial_i} = \frac{S_{i,TS}}{\int f_{i,TS}(T_e) \bullet R(\lambda_i) d\lambda} \bullet \left(\frac{\sum \sigma_{Raman}(\lambda_i) \bullet R(\lambda_i)}{\sigma_{TS} \bullet \partial_i} \right)$$





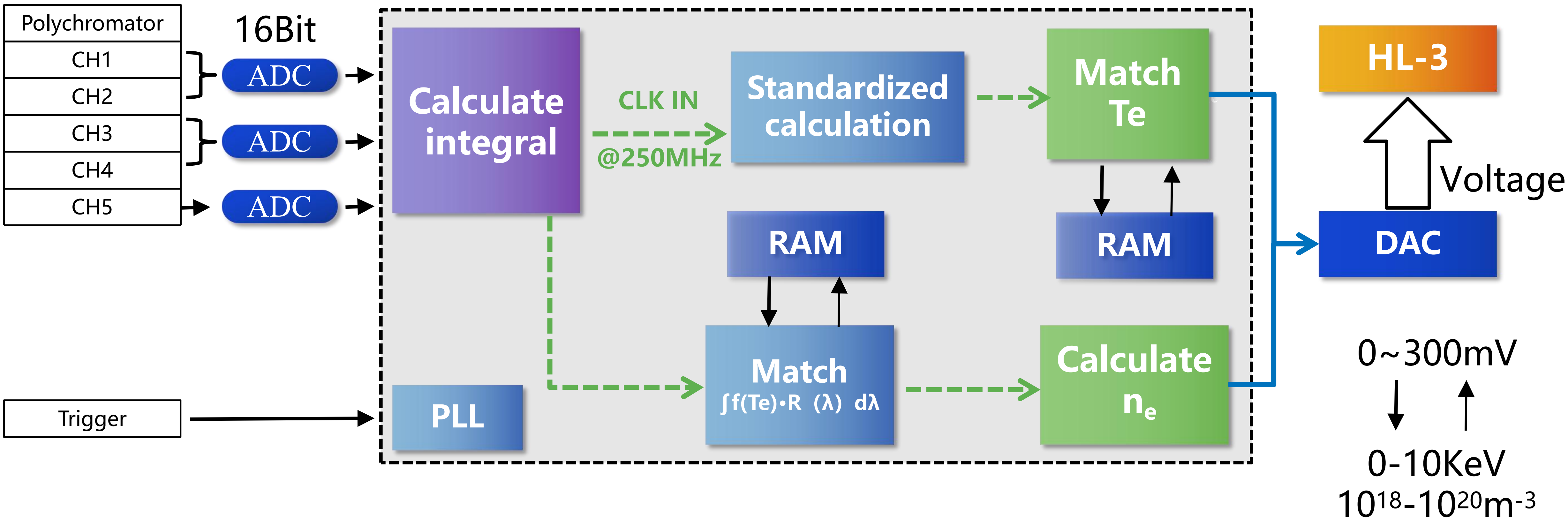
	1	2	3	4	5	6	7
1	1	2	3	4	5	6	
2	2.3369...	1.9768	1.8850...	5.9993...	4.8788...	1.9992...	5.5265





Implementation Process

- The acquired raw signals are baseline-subtracted before integration over the scattering time window.;
- The calculated T_e&n_e are then mapped linearly to the DAC by the FPGA.;



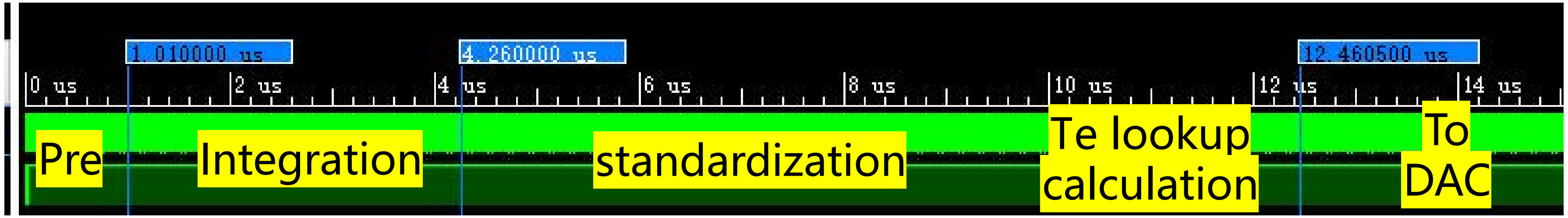
目录

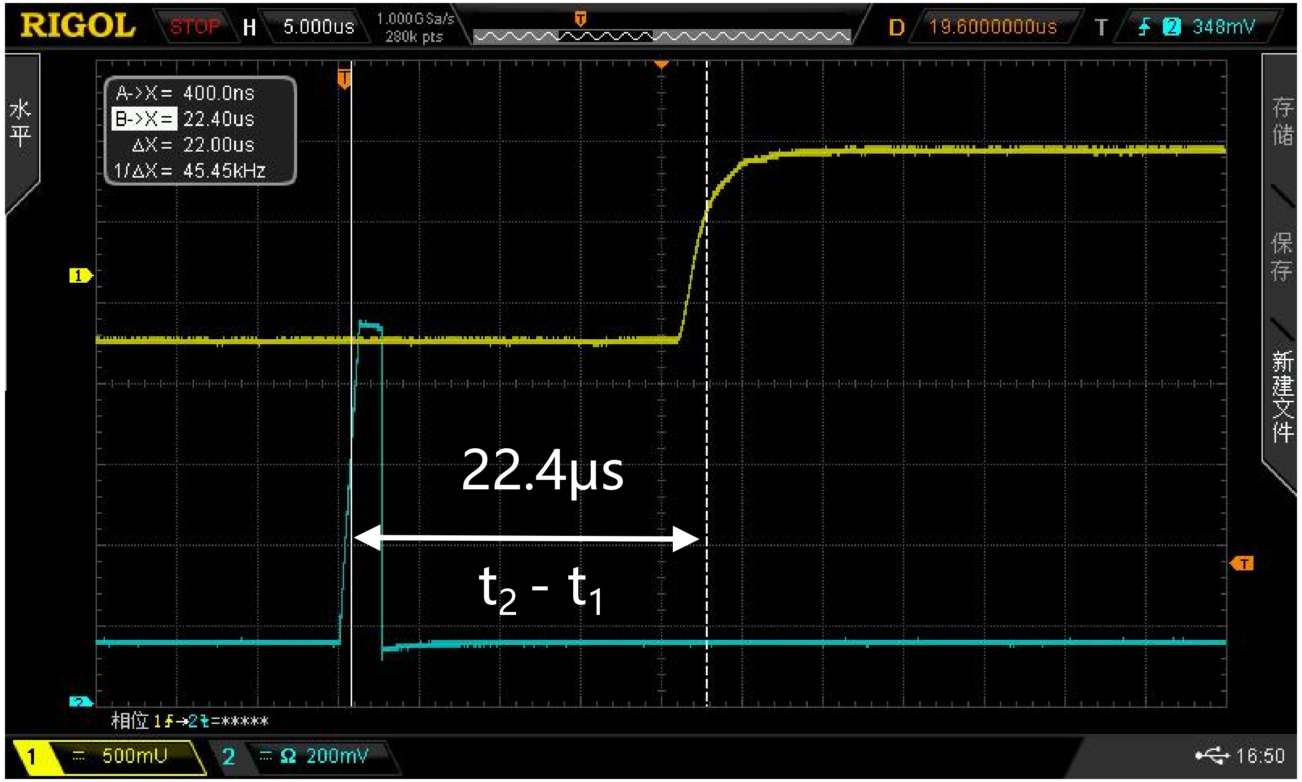
CONTENTS

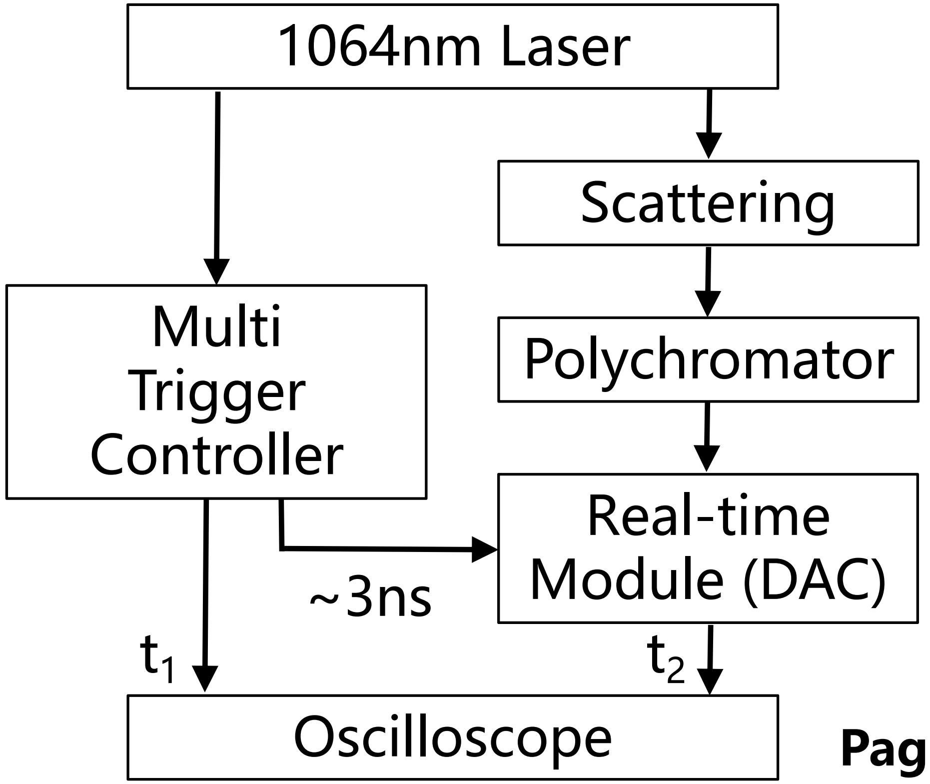
Results and Validation

■ The simulated FPGA computation of T_e takes about 12.46 μs, while oscilloscope measurements show a trigger-to-result latency of about 22.4 μs.

Vivado2018
Simulating the computation takes time：

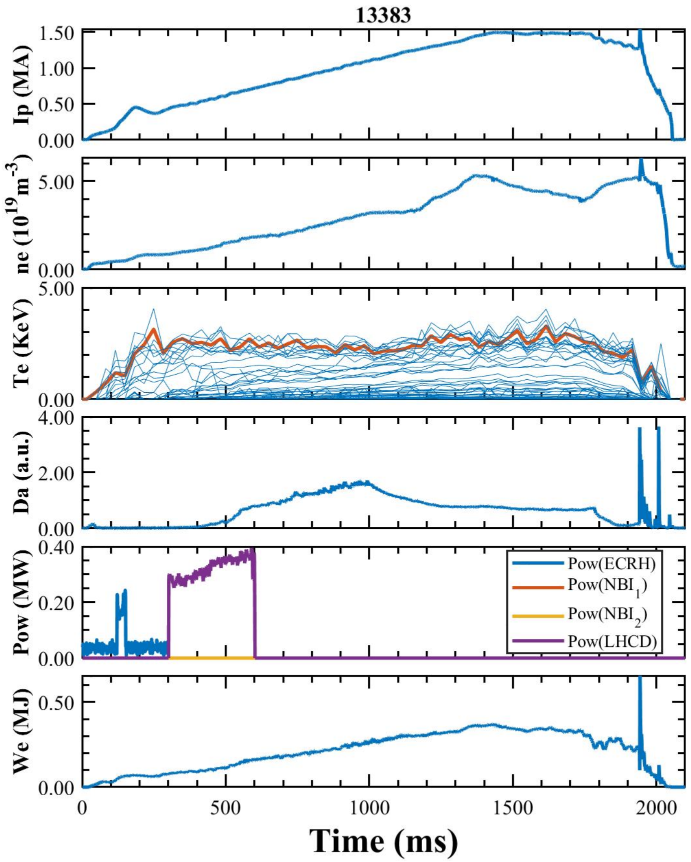


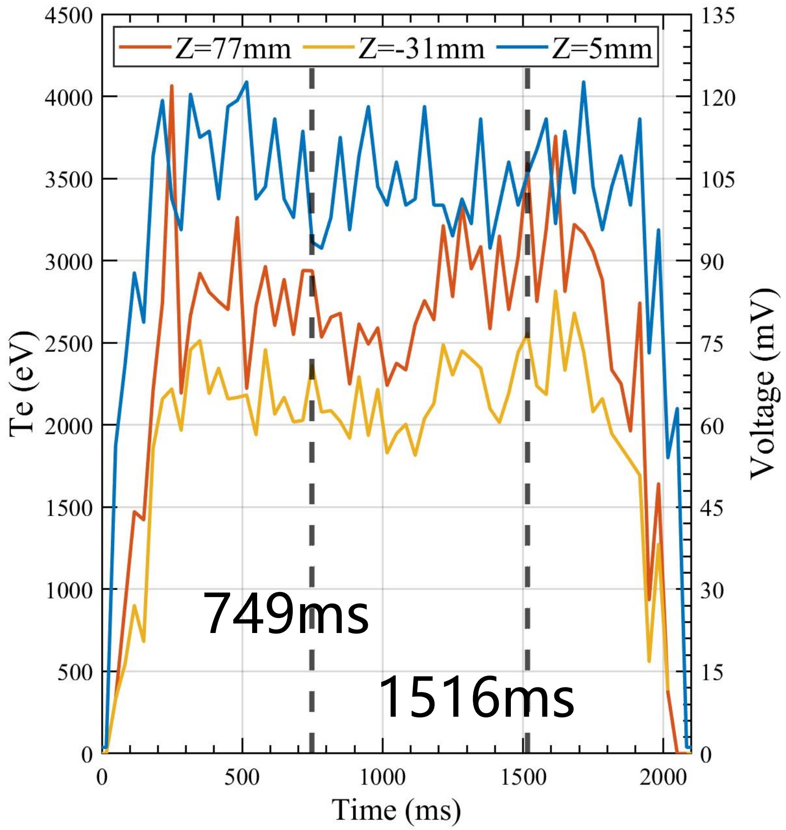


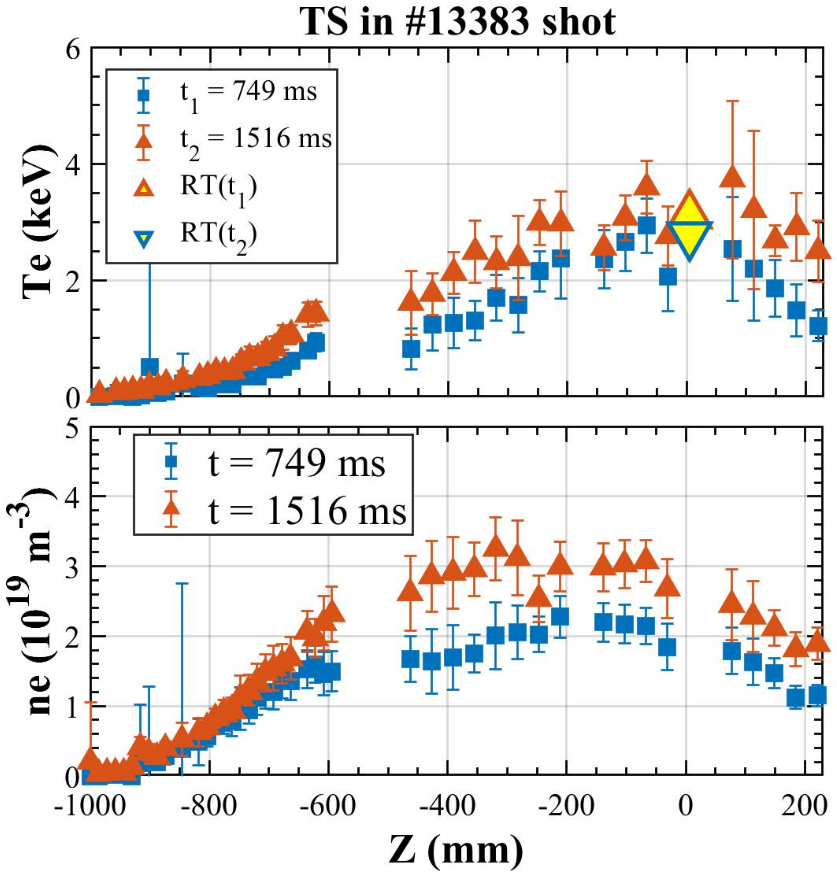


Results and Validation

- The time evolution of T_e is consistent with that of neighboring channels.
- After conversion from mV to eV, the profile features are fairly consistent.



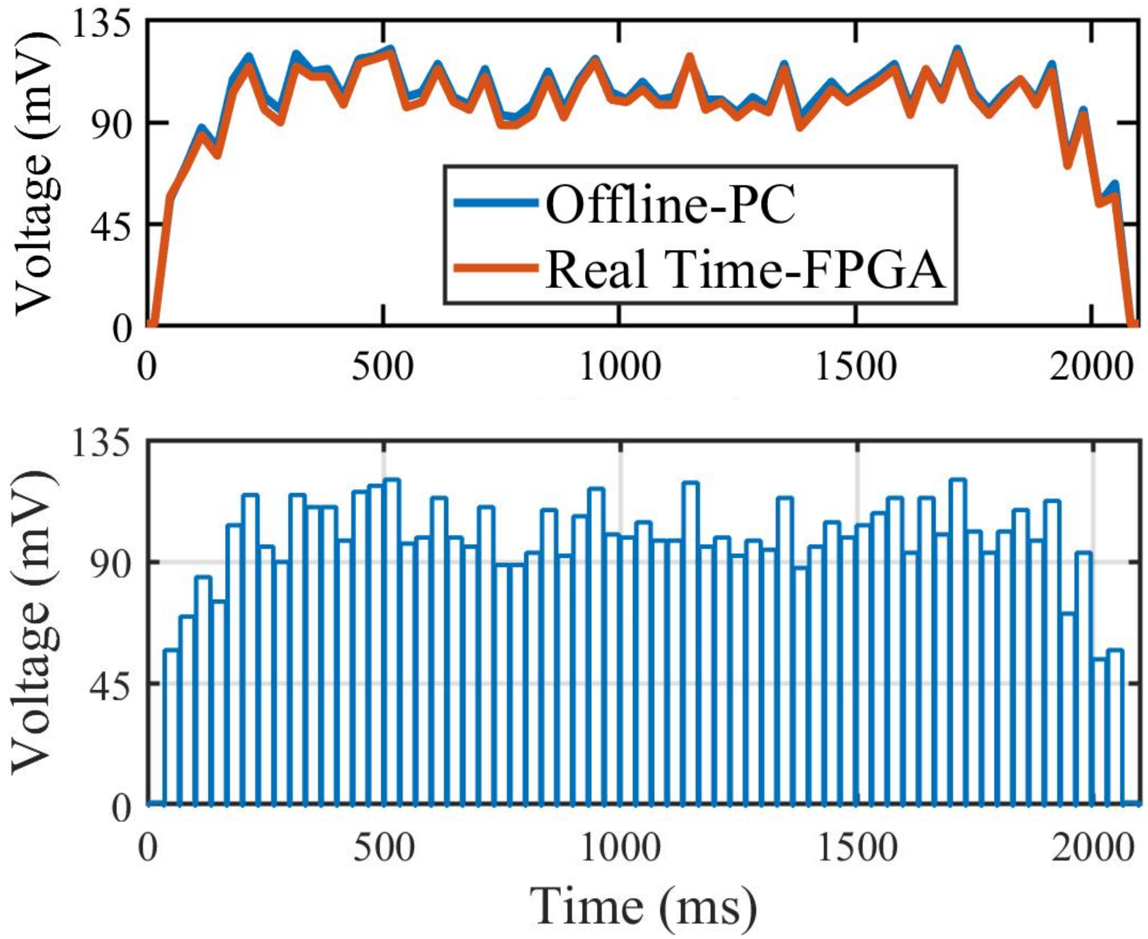


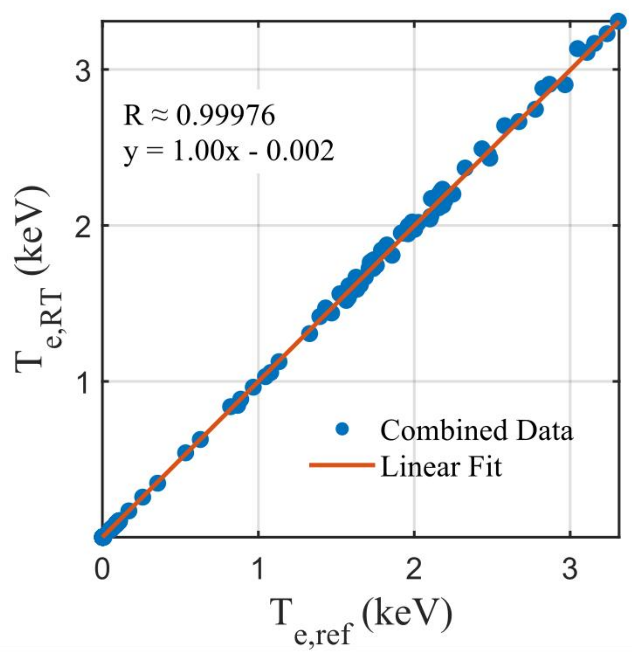


Note: Due to cable transmission constraints, only the real-time T_e results.

Results and Validation

- The data recorded by the real-time module were recalculated on a Offline-PC, yielding results consistent with those from the FPGA.
- The real-time DAC outputs an analog signal, with each computed result held at a flat-top level for 30 ms.



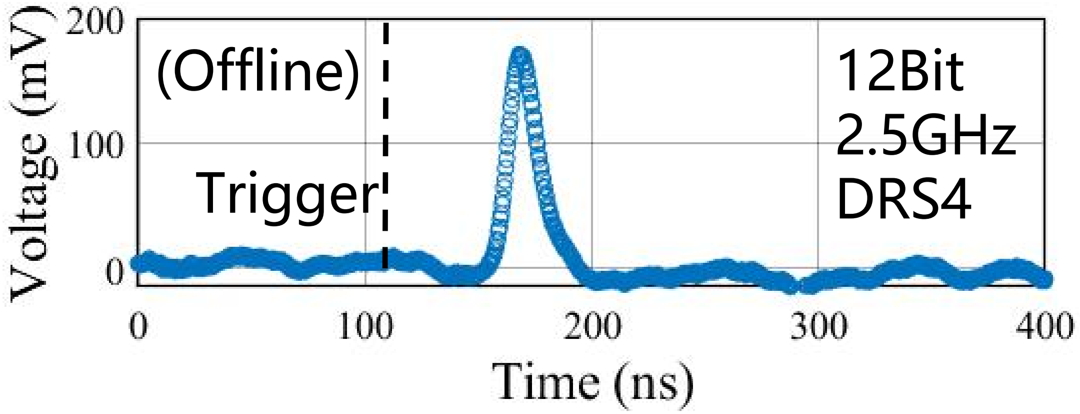


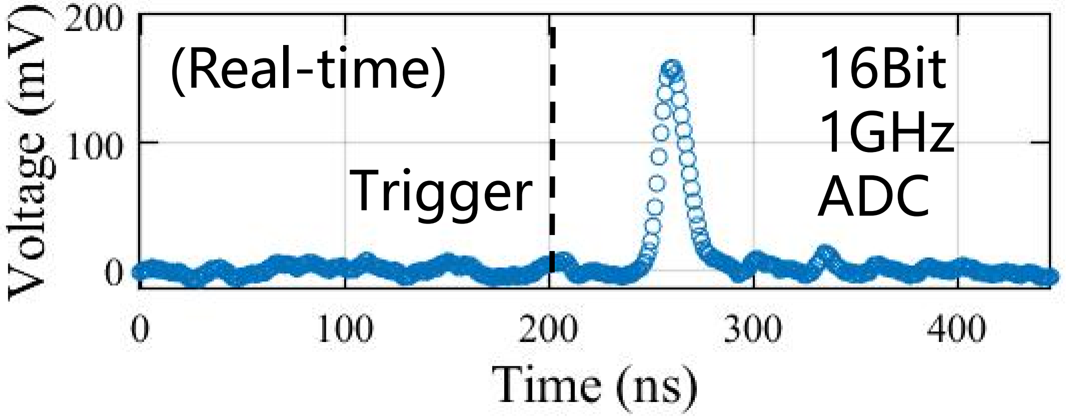
Note: The DAC voltage output is affected by environmental noise.

Results and Validation

- The calculation accuracy is mainly determined by the fidelity of the raw signals.
- The polychromator output ranges from 0 to 500 mV with a pulse width of ~20 ns.
- Under the same noise conditions, ACQ of real-time module provides superior performance.

0-500mV
FWHM~20ns

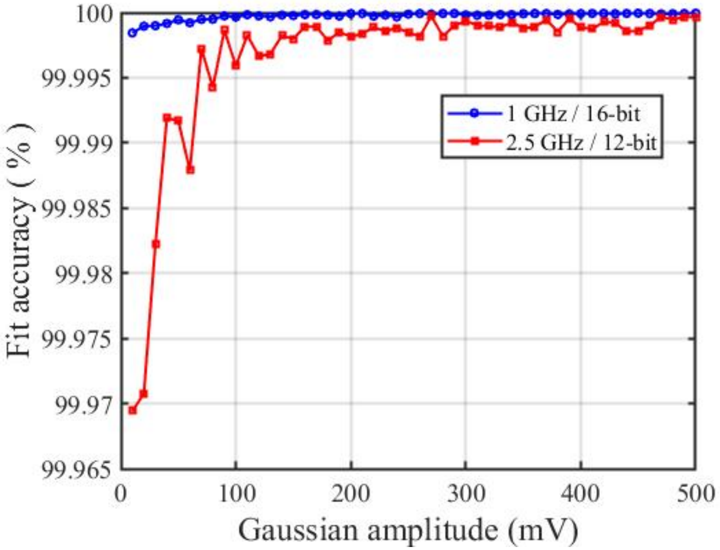




$$y_{true}(t) = A_0 \exp\left[-\frac{(t-t_0)^2}{2\sigma^2}\right]$$

$$NRMSE = \frac{\sqrt{\frac{1}{N}\sum_k \left(y_{fit}(t_k) - y_{true}(t_k)\right)^2}}{A_0}$$

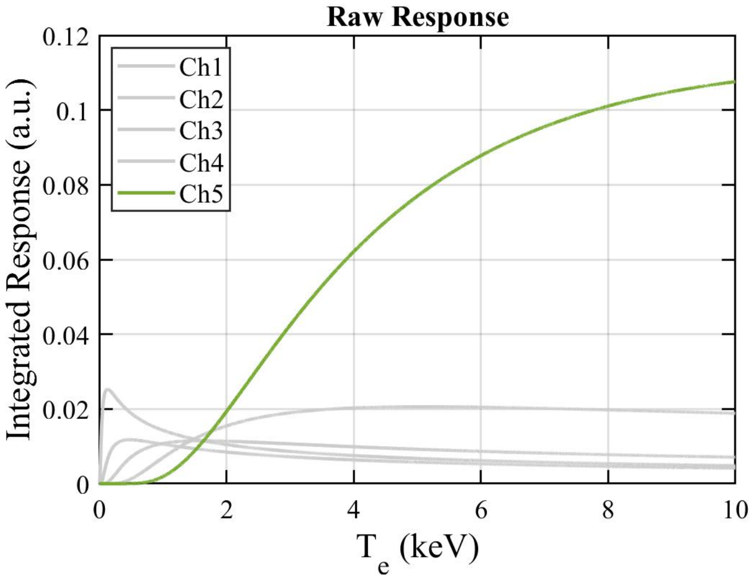
$$Fit\_Accurary(\%) = 100 \times (1 - NRMSE)$$

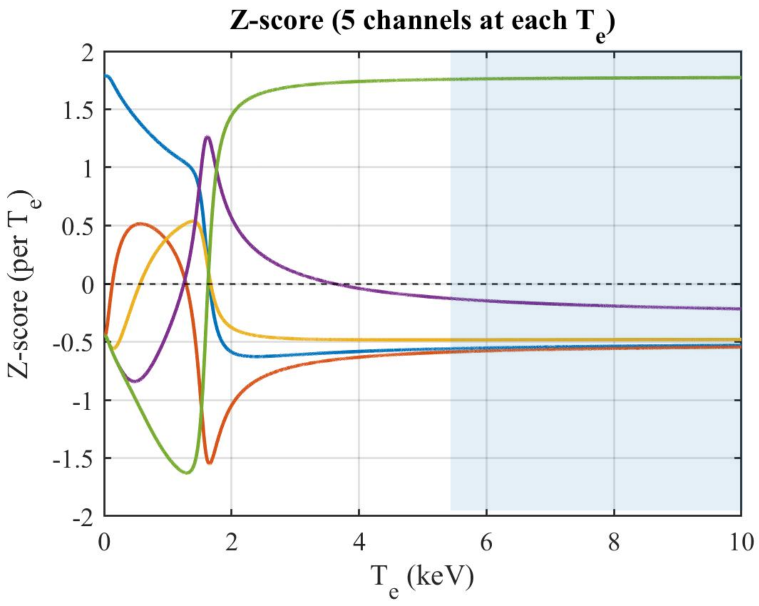


目录
CONTENTS

Limitations

- One channel used for density evaluation are not suitable for the table-lookup method.
- With the 5-channel polychromator, lookup bias becomes significant for Te~10KeV;
- A higher-precision DAC is needed, with output range extended to 10 V.

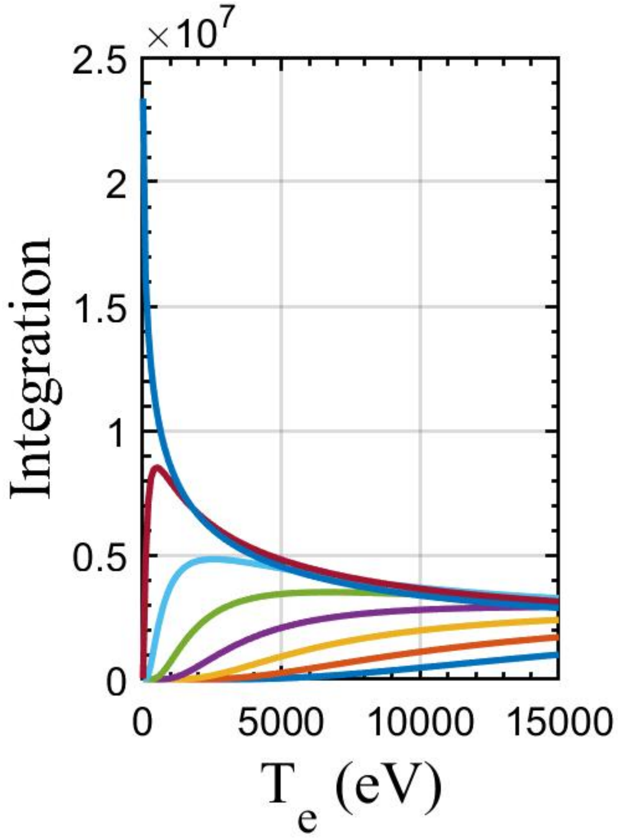


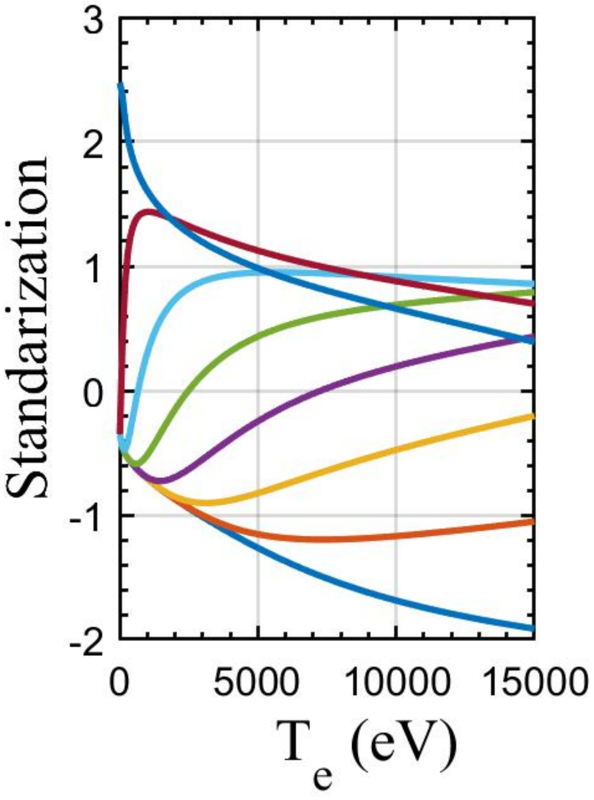


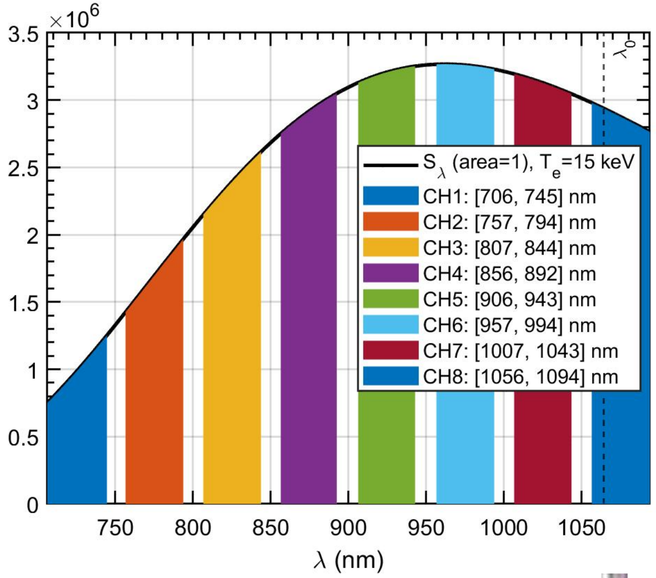
0~300mV		0~10V
1×5001	⇨	1×5001
↓ ↑		↓ ↑
0-10KeV		0-10KeV
10^{18}-10^{20}m^{-3}		10^{18}-10^{20}m^{-3}
0.03mV/eV		1mV/eV
0.03mV/10^{17}m^{-3}		1mV/10^{17}m^{-3}

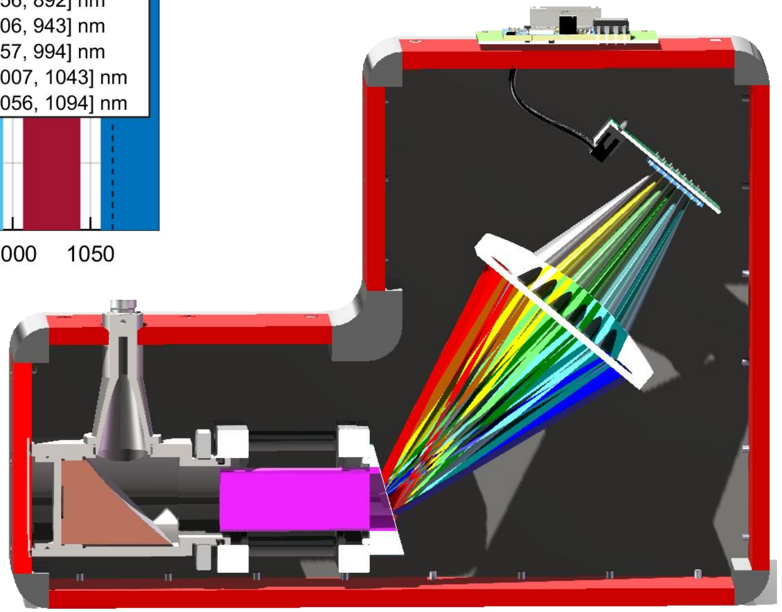
Development Plan

- To access higher HL-3 operating regimes (10–15 keV), develop an 8-channel polychromator.
- For density lookup, add a spare channel and select computation based on SNR or validity range.









Summary And Outlook

Summary

1. Real-time T_e computation was developed and validated at a single spatial point.
2. The real-time processing runs on a FPGA;
3. software emulation shows a T_e compute time of ~12.4 μs, and the instrument's trigger-to-TTL output latency is ~22.4 μs.
4. The real-time results track the experimental T_e evolution, and raw data acquired during real-time operation, when recomputed offline, achieve a 99.91% correlation with the FPGA outputs.

Outlook

1. To improve output accuracy, a higher-precision DAC with an extended 10 V range is required.
2. To enhance core T_e accuracy on HL-3, an 8-channel polychromator optimized for the 10–15 keV range should be developed.
3. For robust n_e evaluation, multiple channels should be incorporated into the computation.

Thanks

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