AI4EIC workshop summary

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EIC-Beam AI WG meeting

July 28, 2026

AI4EIC workshops: 2021 — 2025

- 1st AI4EIC (virtual), Sep 7-10, 2021, Center for Frontiers in Nuclear Science, Stony Brook, NY
- 2nd AI4EIC, Oct 10- 14, 2022, William & Mary, Williamsburg, VA
- 3rd AI4EIC, Nov 28-Dec 1, 2023, Catholic University of America, Washington, D.C.
- Joint Session between AI4EIC and Streaming Readout, Dec 2-4, 2024, Streaming Readout Workshop SRO-X
- 4th AI4EIC, Oct 27-Oct 30, 2025, IAIFI/MIT, Boston, MA

1st AI4EIC: AI for Accelerator Design – Todd Satogata, Yue Hao

Motivation

- EIC design requires balancing many competing objectives including luminosity, beam stability, dynamic aperture, beam-beam effects, cooling, and engineering constraints.
- Traditional optimization becomes computationally prohibitive because of nonlinear beam dynamics and large parameter spaces.

AI opportunities

- Surrogate models to replace expensive beam dynamics simulations
- Bayesian optimization and Gaussian Processes for accelerator parameter optimization
- Neural networks and XGBoost for modeling machine performance
- Reduced-order models and feature extraction for high-dimensional parameter spaces

Early demonstrations

- Dynamic aperture prediction using surrogate models
- Beam-beam interaction modeling
- Machine tuning with LEReC/RHIC operational data
- AI-assisted luminosity prediction and parameter ranking

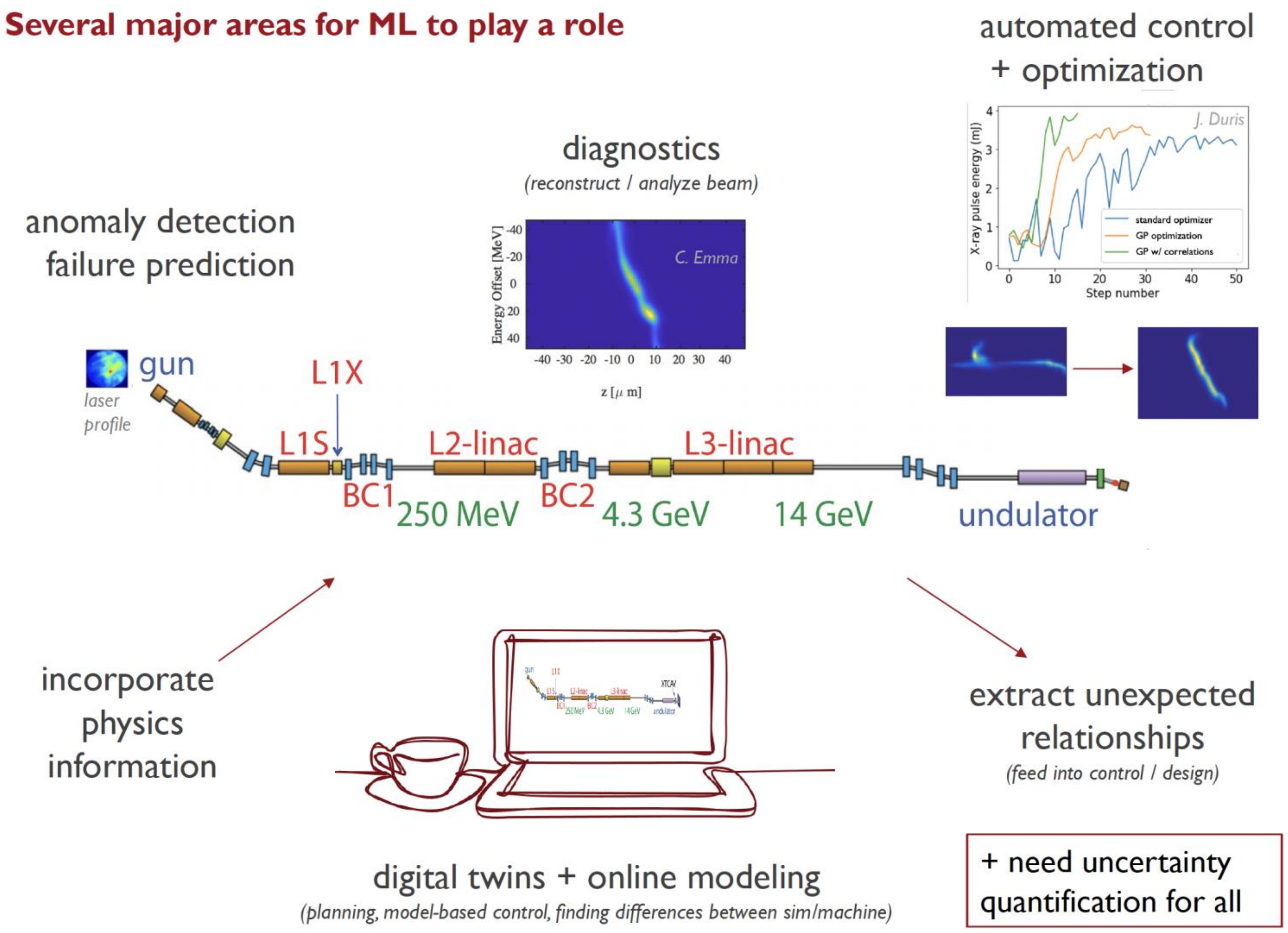
1st AI4EIC: Accelerator Control – Auralee Edelen

Motivation

- Accelerator control involves nonlinear, time-varying systems with hundreds of controllable variables and diagnostics.
- Manual tuning is costly and limits facility availability and scientific output.
- Fast, accurate machine models are needed for real-time decision making and automation.

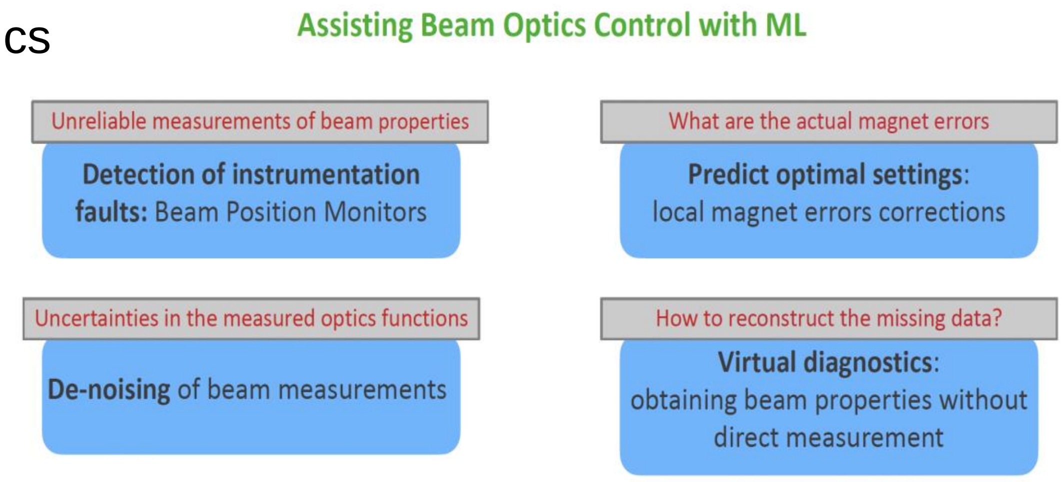
Emerging AI capabilities

- ML surrogate models & digital twins
- AI-assisted optimization
- Virtual diagnostics
- Machine health monitoring



2nd AI4EIC: ML for LHC – Elena Fol

- **Fault detection**
  - Automatic identification of faulty BPMs using Isolation Forest
  - Eliminated much of the manual data cleaning before optics analysis
- **Optics correction**
  - ML reconstructed quadrupole field errors from optics measurements
  - Enabled simultaneous correction of multiple interaction regions during LHC commissioning
- **Virtual diagnostics**
  - Predicted optics quantities without dedicated measurements
  - Reduced measurement time from minutes to seconds
- **Measurement enhancement**
  - Autoencoder-based denoising improved optics reconstruction
  - Reinforcement learning explored for future HL-LHC optics control



2^{nd} AI4EIC: AIML for Design – Todd Satogata

Established AI workflows

- Multi-objective genetic algorithms (MOGA) for accelerator component optimization
- Surrogate models for computationally expensive design studies
- Human-guided optimization remains essential near design singularities and engineering constraints

Emerging Community vision (2022)

- **End-to-end virtual accelerators and digital twins**
  - Integrated modeling across the full accelerator lifecycle
- **AI-enabled design ecosystem**
  - Physics-informed surrogate models
  - Advanced algorithms for nonlinear optimization
  - HPC-enabled large-scale design-space exploration
- **Open software and data infrastructure**
  - Community frameworks
  - Benchmark datasets
  - Sustainable software ecosystem

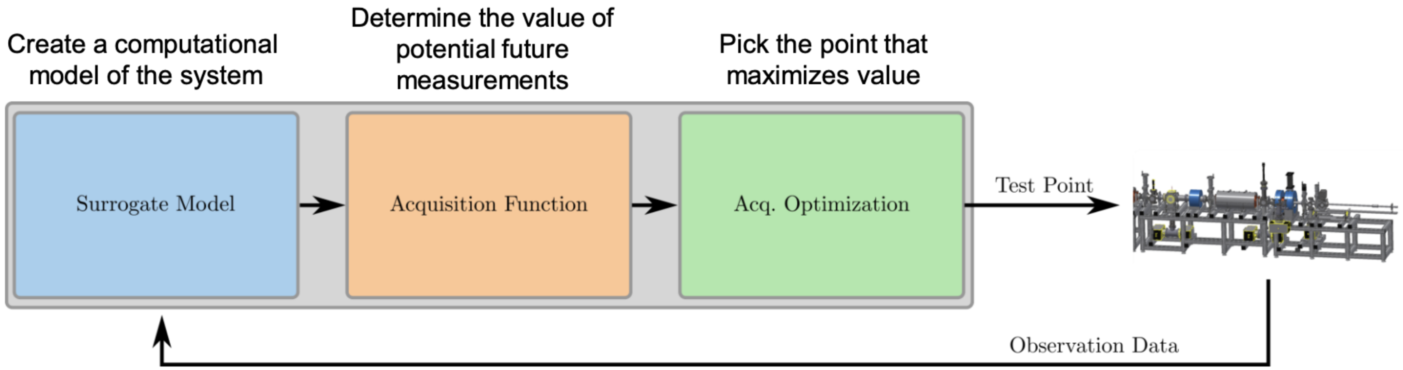
3rd AI4EIC: AI for Online Optimization and Accelerator Control

Talks

- Bayesian Optimization Techniques for Accelerator Control and Characterization – Ryan Roussel
- Machine Learning applications for collider luminosity maximization – Ji Qiang
- Reinforcement Learning applications at Jlab – Malachi Schram

Main Messages

- Bayesian optimization becoming the preferred online tuning algorithm
- Multi-objective optimization for machine performance
- Reinforcement learning beginning to be explored for sequential control
- Human-guided optimization transitioning toward autonomous optimization



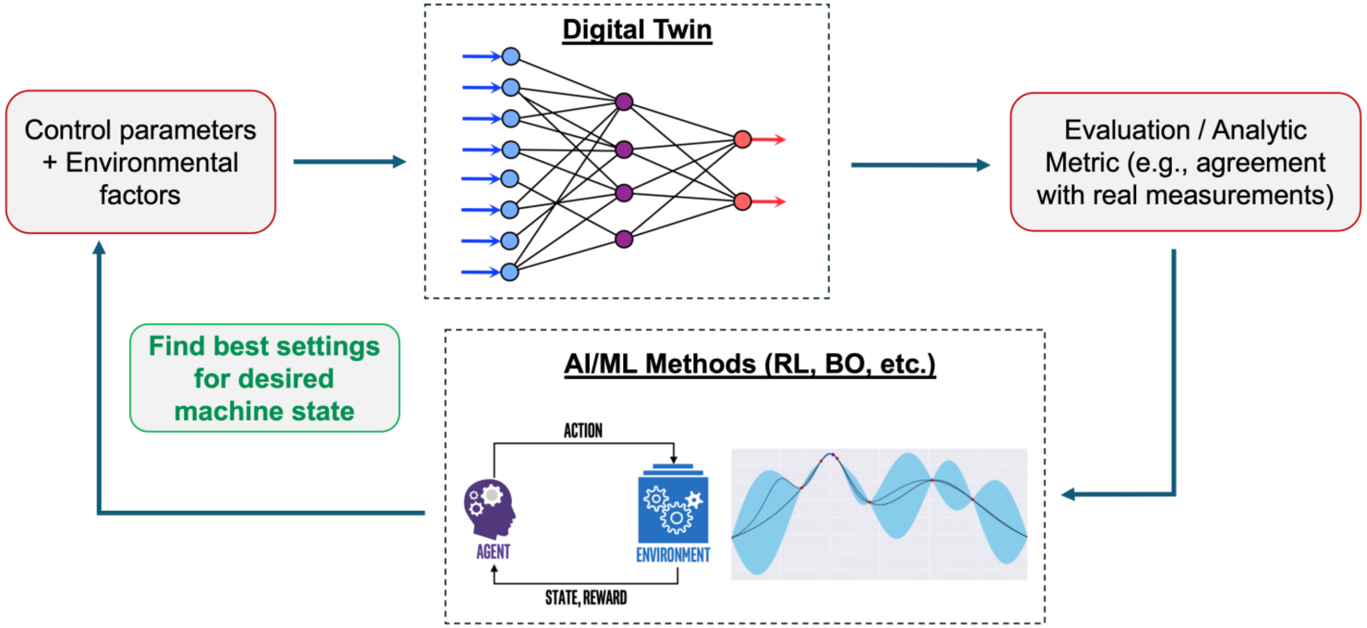
3rd AI4EIC: Digital Twins and Predictive Modeling

Talks

- Digital twin development and polarization optimization at BNL – Lucy Lin
- Beam Condition Forecasting at FACET-II – Matt Kilpatrick
- Uncertainty estimation at JLab – Malachi Schram

Main Messages

- Digital twins becoming operational tools rather than future concepts
- Predictive ML models forecasting future machine behavior
- Physics-informed models combined with uncertainty estimates
- Growing emphasis on trustworthy AI



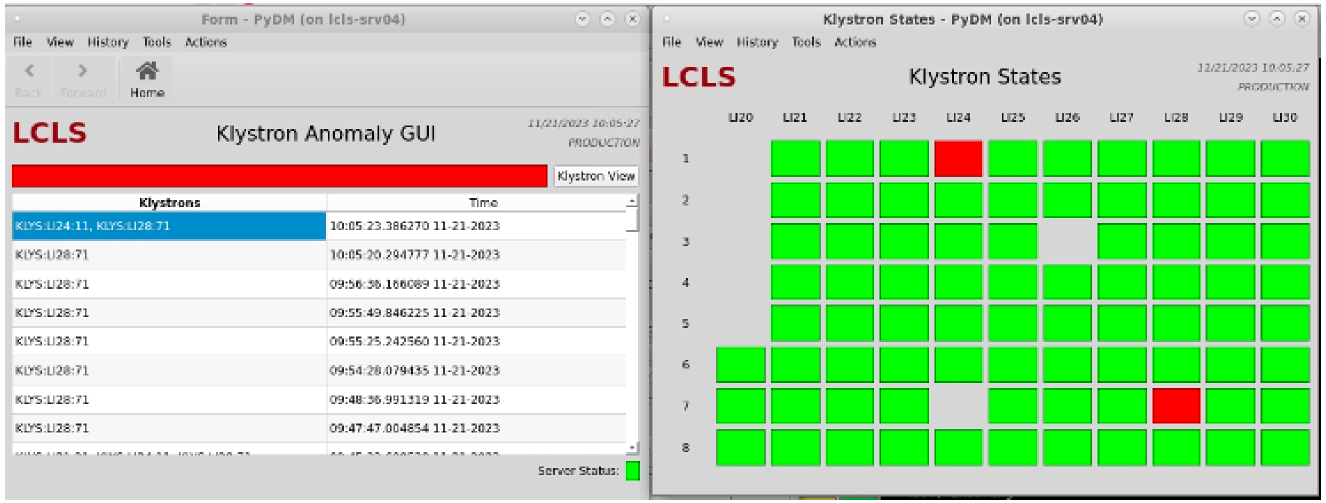
3rd AI4EIC: AI-enhanced Diagnostics and Beam Physics

Talks

- Anomaly detection at an X-ray FEL – Daniel Ratner
- Machine Learning to Improve Dynamic Aperture Estimates – Frederik Van der Veken

Main Messages

- ML extracting information from complex diagnostics
- Automatic anomaly detection
- Surrogate models accelerating expensive beam physics calculations
- AI supporting accelerator physics analysis in addition to control



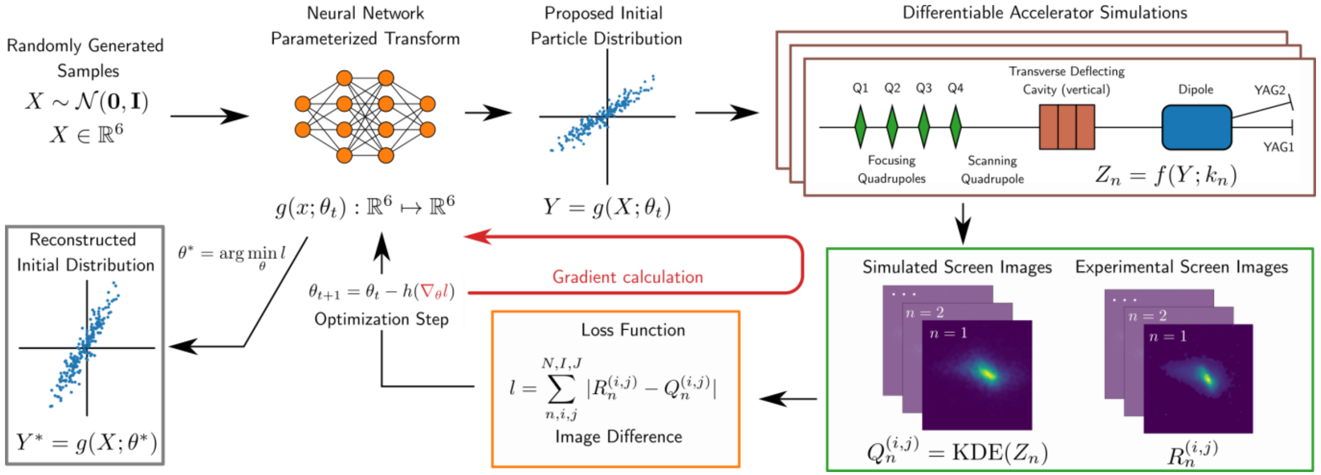
4th AI4EIC: Differentiable AI for Accelerator Modeling

Talks

- Explainable and Differential Reinforcement Learning for Multi-Objective Optimization – Kishansingh Rajput
- Differentiable beam dynamics codes – Chenran Xu
- Symplectic machine learning model for fast space-charge simulation – Jinyu Wan

Main Points

- Differentiable beam dynamics enables gradient-based optimization
- Physics-preserving ML (symplectic networks) improves simulation fidelity
- Explainable RL addresses multi-objective optimization while maintaining interpretability
- Shift from black-box surrogate models toward physics-aware AI



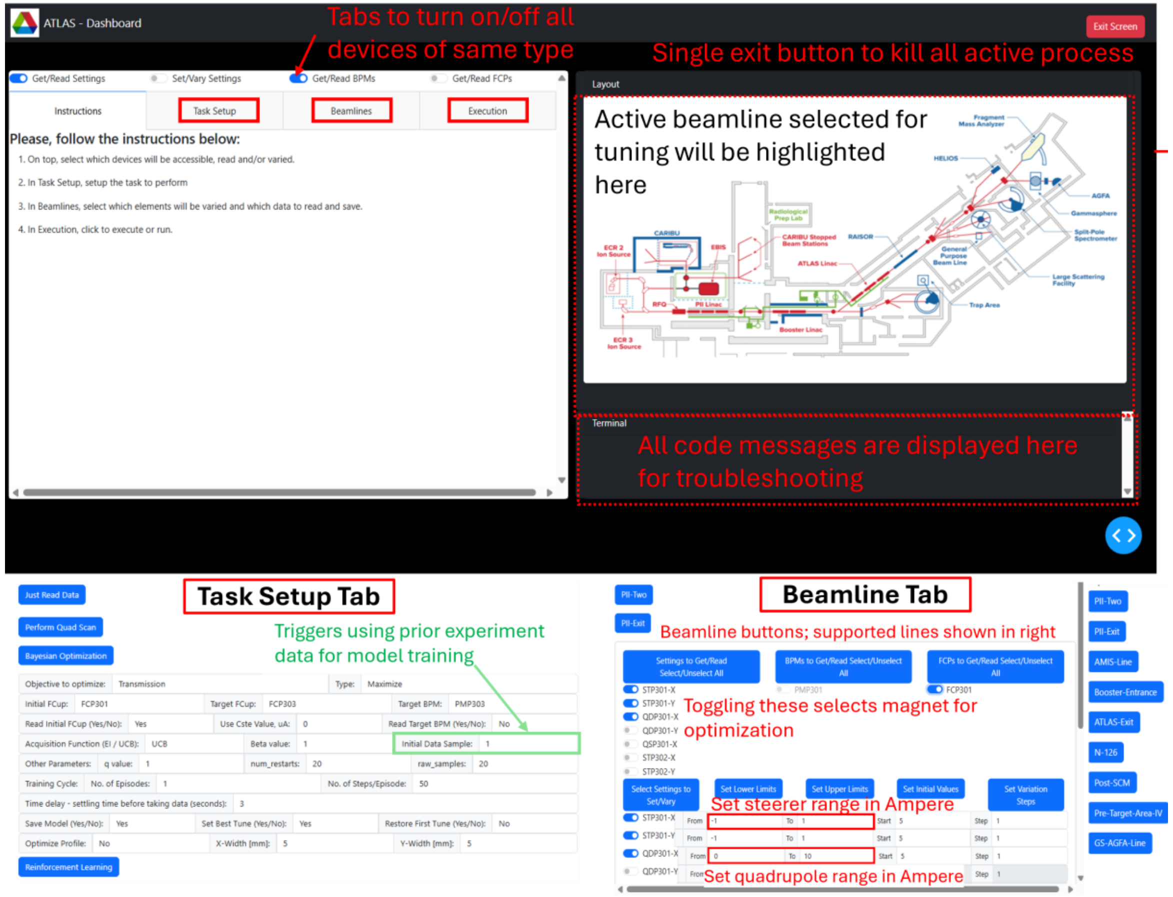
4^{th} AI4EIC: Digital Twins Development

Talks

- Framework for the Development of Virtual Accelerator Models – Adwaith Ravichandran
- ML-Accelerated Bayesian UQ – Christopher Kelly
- AI/ML for higher brightness and polarization – Eiad Hamwi
- Improved Ion Profile Monitor Measurements – Christopher Hall

Main Points

- Standardized frameworks for virtual accelerators
- Bayesian uncertainty quantification for trustworthy digital twins
- Digital twins supporting online optimization and control
- Improved diagnostics provide higher-quality inputs for AI models



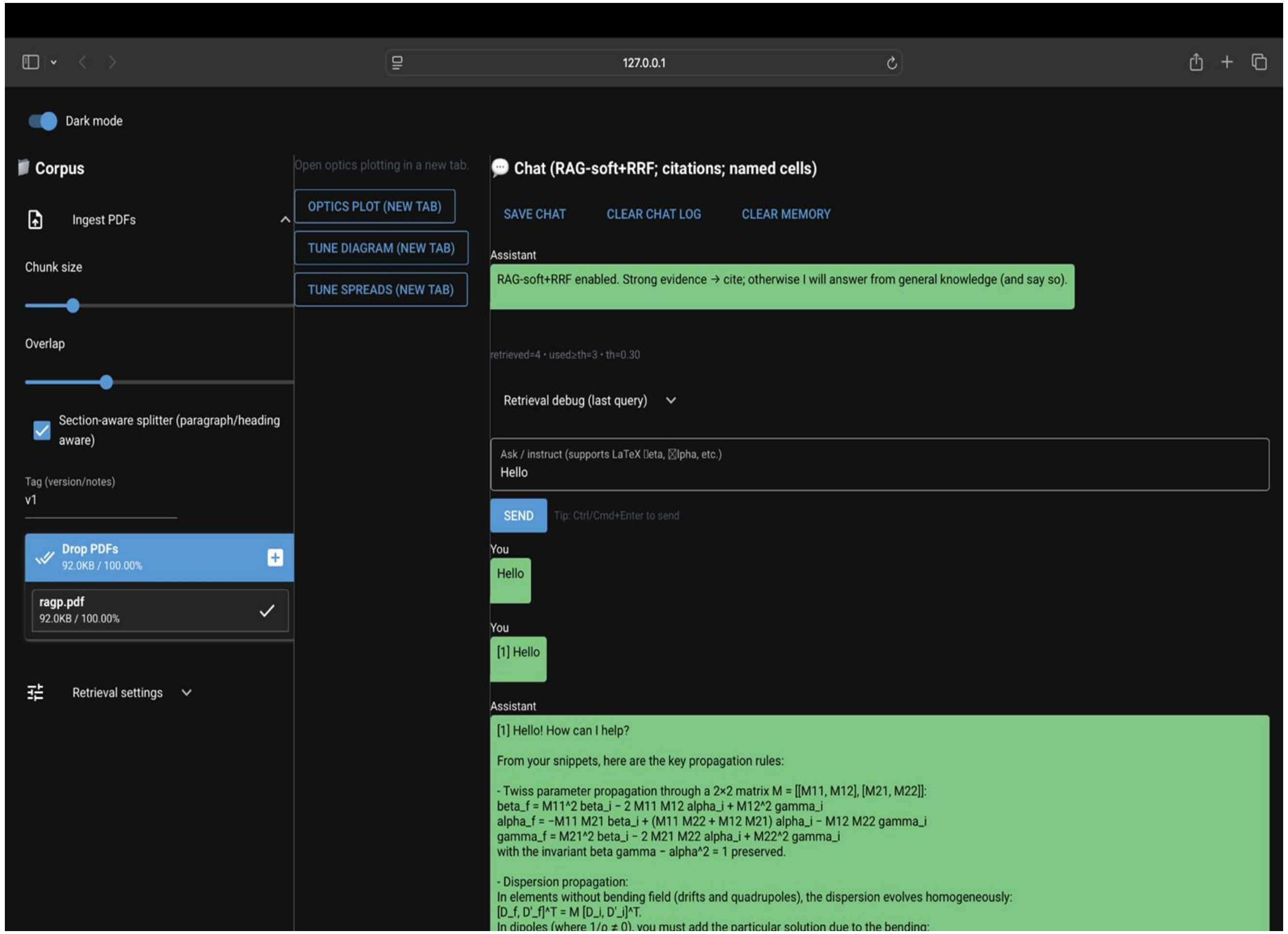
4th AI4EIC: Foundation Models and Generative AI

Talks

- Use of Generative AI and LLMs for Accelerator Design – Onur Gilanliogullari

Main Points

- LLMs begin assisting accelerator design workflows
- Natural-language interfaces to simulation and accelerator software
- Knowledge extraction from technical documentation
- AI agents emerging as workflow orchestrators rather than standalone predictors



Evolution of AI for Accelerators (2021–2025)

Workshop	Main Focus	Representative Technologies
2021	AI for accelerator design & control	Surrogate models, BO, GP, virtual diagnostics
2022	AI deployment & community roadmap	LHC applications, digital twins, modeling ecosystem
2023	AI-assisted accelerator operations	Online optimization, digital twins, forecasting, anomaly detection
2025	AI-native accelerators	Differentiable physics, trustworthy digital twins, agentic AI

***Overall trend:** AI evolved from individual algorithms toward integrated AI-native accelerator ecosystems.*