TRIUMF

Model Coupled Accelerator Tuning at TRIUMF

TRIUMF Science Week ’25
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Discovery, accelerated

TRIUMF ISAC Facility

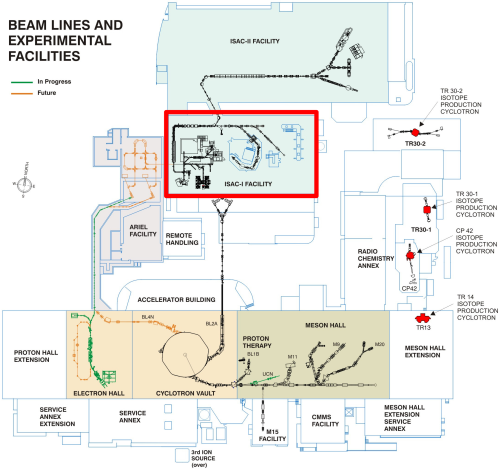

Figure: TRIUMF site layout, the ISAC facility is outlined in red.

- ISOL facility driven by TRIUMF 500 MeV H^- cyclotron
- Post-acceleration RIB linac for experimental delivery at low relativistic energies: 0.1–1.8 MeV/u, or to ISAC-II
- Experimental facility including: nuclear astrophysics, structure investigations, and measurements of nuclear properties

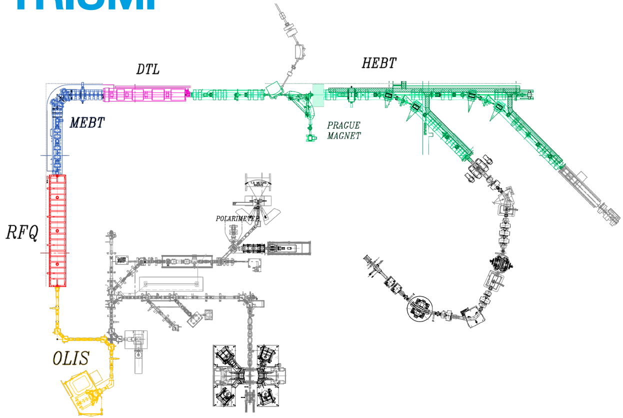

Figure: ISAC facility layout. The mass-selected RIB from the targets emerges from the basement next to OLIS. The post-acceleration linac is in the top left corner.

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TRIUMF ISAC Facility

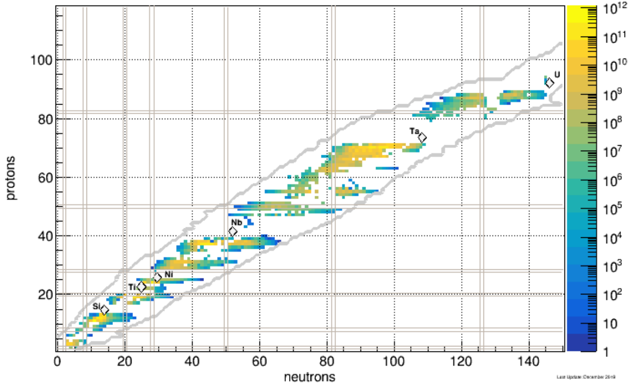

Figure: ISAC RIB measured yields as of 2020, colour indicates measured particles per second. Courtesy P. Kunz, TRIUMF.

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Motivation

ARIEL facility will significantly expand the possibilities for delivering RIB to experiments in ISAC.

- Additional RIB targets: cyclotron and elinac photo-fission target
- ARIEL switch-yard of beamlines: vast configuration options
- Designed for simultaneous delivery of multiple RIBs

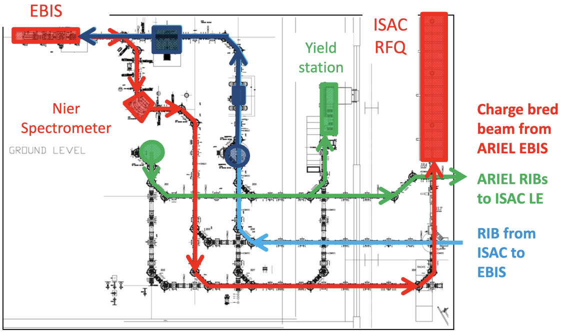
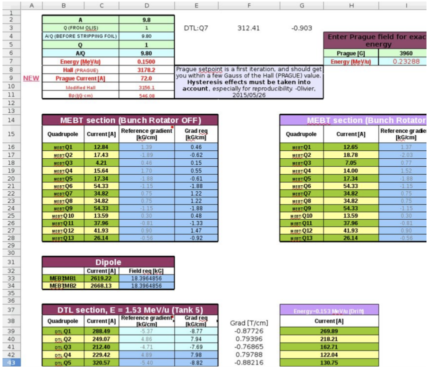


Figure: Layout and operational beam paths on the ground-level of the new ARIEL rare isotope beamline network.

- Maintaining current level of operational resources: need major efficiency improvements
- ISAC linac has always been an involved part of tuning
- Low intensity (nA range) beamlines are ideal for testing new ideas
- We needed a more efficient means to tune system



A	9.8
Q (FROM OLIS)	1
A/Q (BEFORE STRIPPING FOIL)	9.80
Q	1
A/Q	9.80
Energy (MeV/u)	0.1500
Hall (PRAGUE)	3178.2
Prague Current [A]	72.0
Modified Hall	3156.1
Bρ (kG·cm)	546.08

NEW

DTL:Q7 312.41 -0.903

Prague setpoint is a first iteration, and should get you within a few Gauss of the Hall (PRAGUE) value. **Hysteresis effects must be taken into account**, especially for reproducibility. -Olivier, 2015/05/26

Enter Prague field for exac energy	
Prague [G]	3960
Energy (MeV/u)	0.23288

MEBT section (Bunch Rotator OFF)			
Quadrupole	Current [A]	Reference gradient [kG/cm]	Grad req [kG/cm]
MEBT:Q1	12.84	1.39	0.46
MEBT:Q2	17.43	-1.89	-0.62
MEBT:Q3	4.21	0.46	0.15
MEBT:Q4	15.64	1.70	0.55
MEBT:Q5	17.34	-1.88	-0.61
MEBT:Q6	54.33	-1.15	-1.88
MEBT:Q7	34.82	0.75	1.22
MEBT:Q8	34.82	0.75	1.22
MEBT:Q9	54.33	-1.15	-1.88
MEBT:Q10	13.59	0.30	0.48
MEBT:Q11	37.96	-0.81	-1.33
MEBT:Q12	41.93	0.90	1.47
MEBT:Q13	26.14	-0.56	-0.92

MEBT section (Bunch Rotator		
Quadrupole	Current [A]	Reference gradie [kG/cm]
MEBT:Q1	12.65	1.37
MEBT:Q2	18.78	-2.03
MEBT:Q3	7.05	0.77
MEBT:Q4	14.00	1.52
MEBT:Q5	17.34	-1.88
MEBT:Q6	54.33	-1.15
MEBT:Q7	34.82	0.75
MEBT:Q8	34.82	0.75
MEBT:Q9	54.33	-1.15
MEBT:Q10	13.59	0.30
MEBT:Q11	37.96	-0.81
MEBT:Q12	41.93	0.90
MEBT:Q13	26.14	-0.56

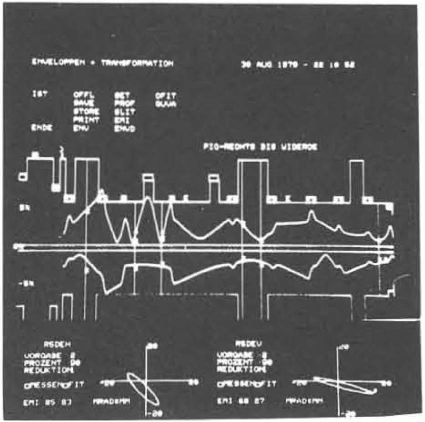
Dipole		
	Current [A]	Field req [kG]
MEBT:MB1	2619.22	18.3964856
MEBT:MB2	2668.13	18.3964856

DTL section, E = 1.53 MeV/u (Tank 5)				
Quadrupole	Current [A]	Reference gradient [kG/cm]	Grad req [kG/cm]	Grad [T/cm]
DTL:Q1	288.49	-5.37	-8.77	-0.87726
DTL:Q2	249.07	4.86	7.94	0.79396
DTL:Q3	212.40	-4.71	-7.69	-0.76865
DTL:Q4	229.42	4.89	7.98	0.79788
DTL:Q5	320.57	-5.40	-8.82	-0.88216

Energy=0.153 MeV/u (Drift)
Current [A]
269.89
218.21
162.71
122.04
130.75

Figure: Spreadsheet used to scale quadrupole optics for ISAC-I linac.

Motivation for MCAT



Beamline simulation software at GSI-UNILAC (1979).

- Tuning is a high-dimensional optimization problem
- Historically done manually by a few experts
- Parallel modeling and optimization are now essential for ARIEL delivery

Model Coupled Accelerator Tuning

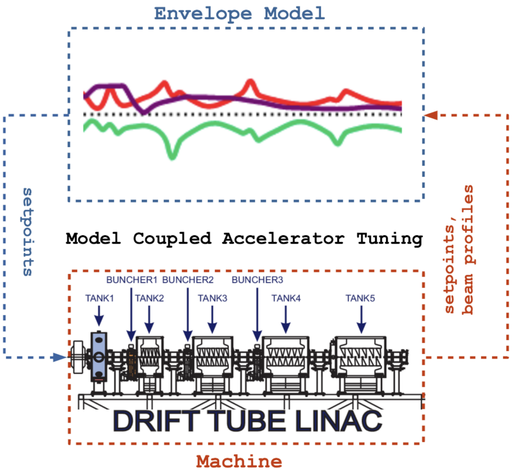


Figure: `MCAT` interface for tuning the ISAC RFQ.

- A parallel simulation of the beam runs in real time
- The simulation uses a detailed model that replicates the accelerator
- Optimizations performed on the model are predictive and directly transferable to the real machine

`TRANSOPTR`:

- Linear optics code with a fast matrix mode and a continuous space-charge mode: `RK45` adaptive step-size integration
- Optics routines for anything with a Hamiltonian: linac, rfq, dtl, dwa
- Designed for optimization: least-squares fit anything
- Flexible: the optics description is a Fortran subroutine
- Supports simulated annealing and downhill simplex methods
- Open source GPL-3 license, available at:

`https://gitlab.triumf.ca/beamphys/transoptr`

End to End Model

- An end-to-end model has been developed these past years
- Full coverage of the ISAC-I facility
- `MCAT` model has predictive power over the system

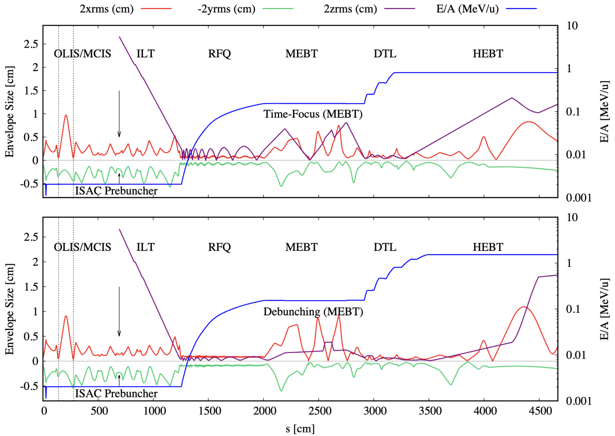


Figure: Start-to-end simulation of the ISAC-I RIB linac.

A Centralized Repository

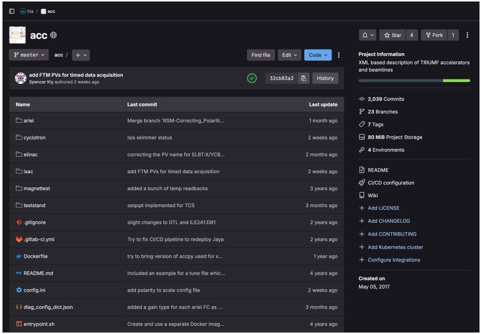


Figure: TRIUMF Gitlab page for the `acc` project.

Consolidated the scattered wisdom: technical drawings, design simulations, and oral history into one place: `acc`.

- XML files in a Git repository: features syntax validation, peer review, detailed history
- Design of the XML describes the optics as it's first priority
- Convenient Python interface for unit conversions, common lookup operations

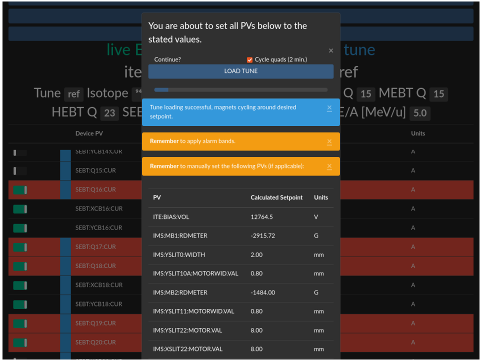


Figure: Tune loading and scaling app `tuneX`.

Why:

- Accessibility, in usage and development
- Version management and deployment

How:

- EPICS access through a gateway API server
- Provide templates with a common UI library for a uniform look and feel
- Common functionality provided by Python libraries

Sequential Optimization

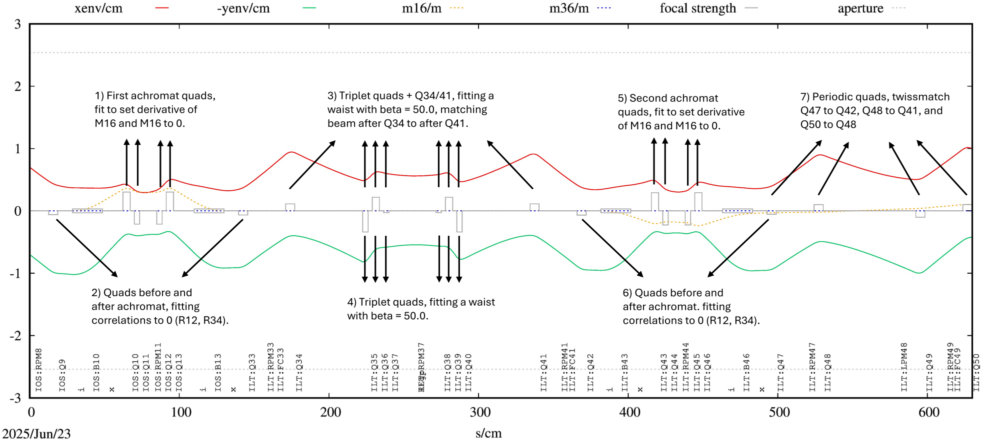


Figure: `MCAT` model of the low energy beamline to the RFQ. The autofocus optimization is split into 7 sequences, the varied parameters and objectives are indicated for each.

MCAT app arose from directly improving operations for the ISAC linac.

- TRANSOPTR model now spans all of ISAC-I
- MCAT has enabled a gain in efficiency for tuning; no more manual quadrupole tuning
- Operators can lean to recognize patterns in envelopes; helps diagnose tune issues

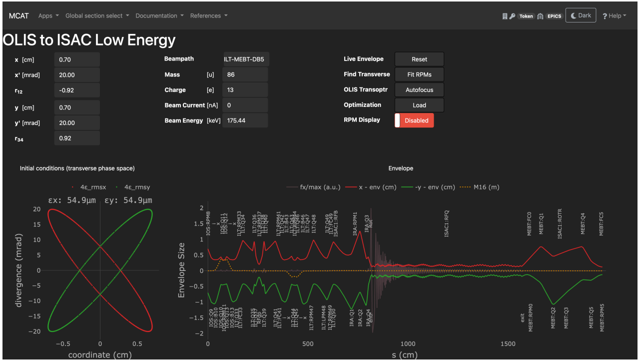


Figure: MCAT interface for tuning the ISAC DTL.

- MCAT has improved ISAC-I tuning.
- Now expanding to the cyclotron injection line.
- Recent success: model-based injection tuning for faster, more reliable setup.

Figure: MCAT used for cyclotron injection matching.

BOIS algorithm automatically steers the beam through the machine for maximum transmission. Now, in the process of adding this capability to MCAT.

- Goal is to provide one-button orbit correction
- Optimizes transmission, measured by a Faraday Cup, using correction benders
- Uses sequential optimization to improve the performance of Bayesian optimization: 4-17 parameters at a time

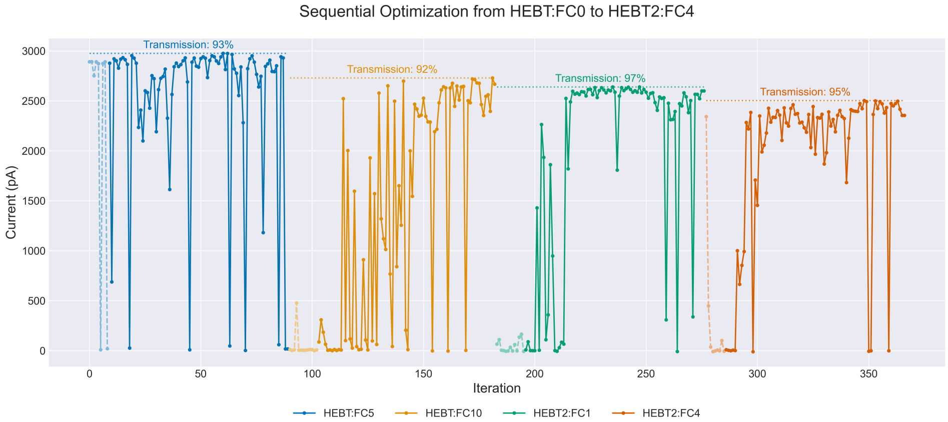


Figure: `BOIS` algorithm applied to sequentially correct steering through the DTL and HEBT sections at ISAC, maximizing beam transmission.

Case Study: MEBT

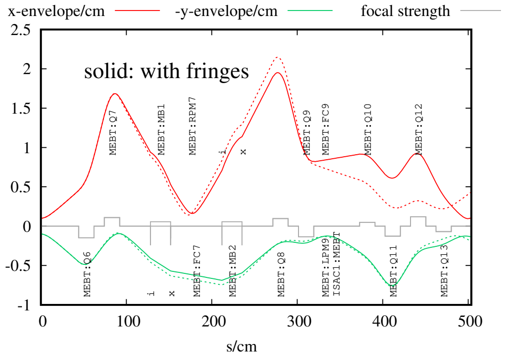


Figure: MEBT model with operational tune, the solid line shows the model with the quadrupole fringe fields included. The dashed lines show the same operational tune with hard-edged optics.

- Empirical data from operations was collected and studied over the past two years
- Adding the correct fringe fields to the MEBT quads made sense of the operational experience
- `MCAT` can now fully load the ISAC optics

Case Study: MEBT

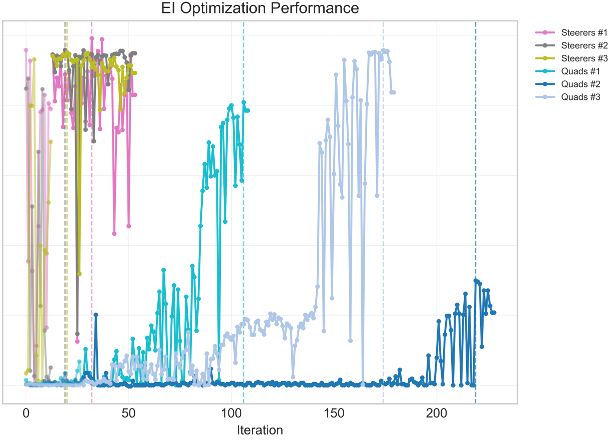


Figure: `BOIS` algorithm applied to optimize transmission through MEBT. Runs labelled ‘Quads’ are also optimizing the quadrupoles.

- The centroid correction performance is severely limited by tuning quads
- By improving the optics model, the black-box optimizer can perform much better
- Decoupling tune computation from beam centering improves performance vastly...

Near Future

- BOIS deployment imminent
- MCAT has been crucial for the commissioning of the new 500 MeV Cyclotron injection line
- Sequential optimization is now built directly into TRANSOPTR, incoming performance improvements: sub-second tunes
- Extending our tools to the new ARIEL beamlines, and to the drivers
- MCAT feature: fit initial beam parameters from diagnostics data

Conclusions

- Manual or black-box tuning does not scale
- It is beneficial to bring your simulations as close to the machine as possible
- Parallel modelling with `MCAT` reduces problem size, making orbit correction more efficient
- The constraint-oriented approach to tuning allows for tailored beam delivery to end-users

The lesson to be learned from this is that it is often undesirable to go for the right thing first. It is better to get half of the right thing available so that it spreads like a virus. Once people are hooked on it, take the time to improve it to 90% of the right thing.

–Richard P. Gabriel, *Lisp: Good News, Bad News, How to Win Big*

Thank you
Merci

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Discovery,
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