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Title: Beam-dynamics codes used at DARHT

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Beam-dynamics codes used at DARHT

Carl Ekdahl

We use several beam simulation codes to help us better understand beam dynamics in the DARHT LIAs. I'll discuss the most notable of these.

- **Beam Production**
  - Tricomp Trak orbit tracking code
  - LSP Particle in cell (PIC) code
- **Beam Transport and Acceleration**
  - XTR static envelope and centroid code
  - LAMDA time-resolved envelope and centroid code
  - LSP-Slice PIC code
- **Coasting-Beam Transport to Target**
  - LAMDA time-resolved envelope code
  - LSP-Slice PIC code

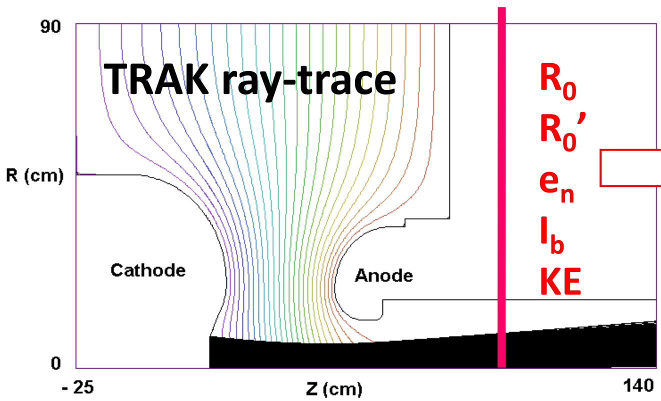
We are also using these to inform the design of Scorpius.

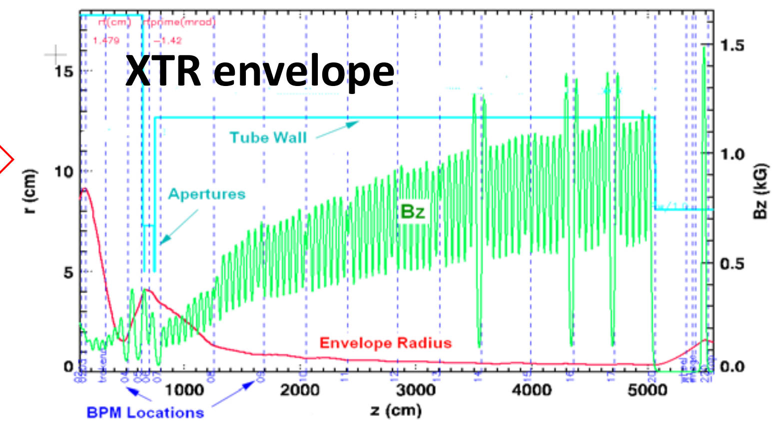
Trak is a self-consistent particle orbit tracking code using external electromagnetic fields generated by Tricomp finite element electromagnetic codes.

- **Author: Stanley Humphries, Jr.**
- **Support: Field Precision, LLC**
- **Type: Orbit tracking**
- **Language: Fortran**
- **User Interface: Graphical**
  - **Input: ASCII text script plus solution files produced by Tricomp electromagnetic field solvers**
  - **Output: Text files and graphical post processing**
- **Uses: Injected beam parameters, diode design**
- **Pros: Excellent documentation and user interfaces**
- **Cons:**
- **Comments: Experimentally validated with data from DARHT, and results agree with LSP PIC results. 3-D version (OmniTrak) available.**

Trak is used to provide initial conditions for envelope code simulations of DARHT-II beam. It has also been used as a diode design tool.

We have no beam measurements at the exit of DARHT-II diode, so we rely on predictions of Trak and LSP to provide initial conditions for envelope codes.





Diode Design Exercise

V_{AK} = 3 MV

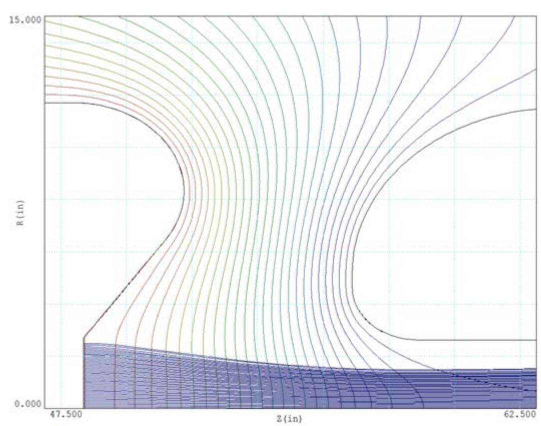
I_b = 2 kA

Calculated Beam Parameters

R_{env} = 4.2 cm

R'_{env} = 0.0 mr

ε_n = 693 π-mm-mr



Results showed that a beam produced by a 5-inch diameter hot cathode can be focused into a 6-inch diameter beam pipe.

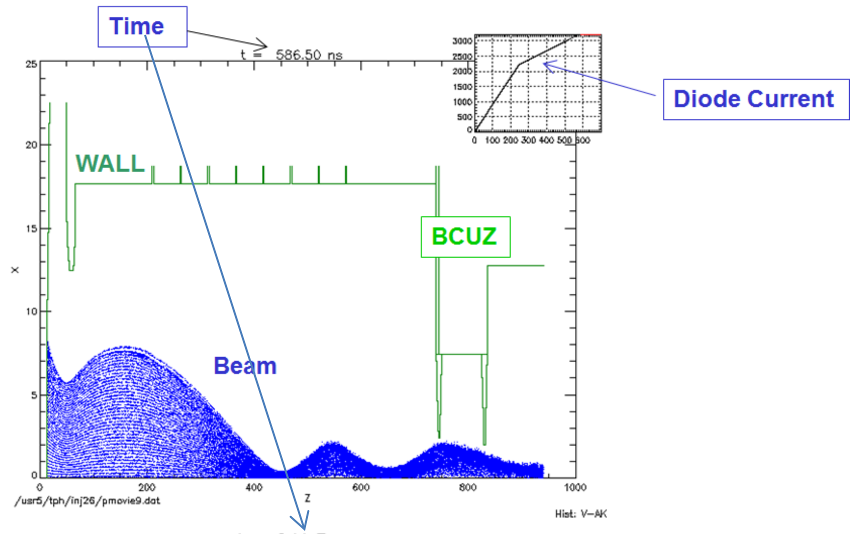
LSP (Large Scale Plasma) is a particle-in-cell (PIC) code.

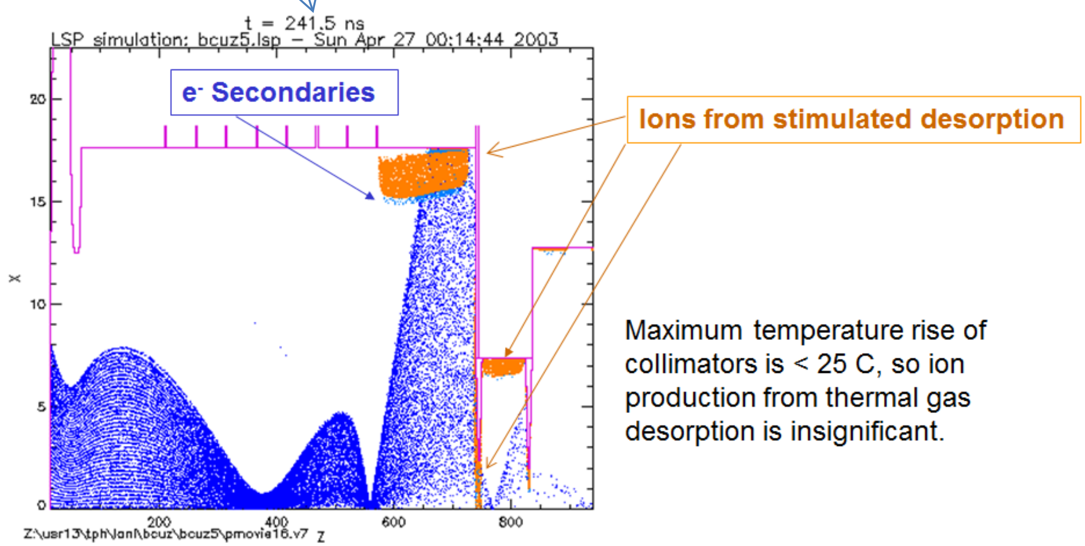
- Original Author: Tom Hughes
- Type: Particle in cell (PIC)
- User Interface: Graphical
  - Input: ASCII text script, text files defining external electromagnetic fields
  - Output: IDL-based file viewer for binary output
- Uses: Injected beam parameters, diode design, explosive cathode emission
- Pros: Good documentation of GUI, parallel processing
- Cons: Arcane settings of options, undocumented physics and algorithms
- Comments: Used to investigate ion evolution from DARHT-II beam dump in months-long run

The LSP PIC code was used extensively during the design of the DARHT-II injector.

DARHT-II Injector Design

- V_{diode} = 3.2 MV
- I_{scl} = 2.0 kA
- V_{cell} = 173 kV
- KE_{final} = 4.6 MeV





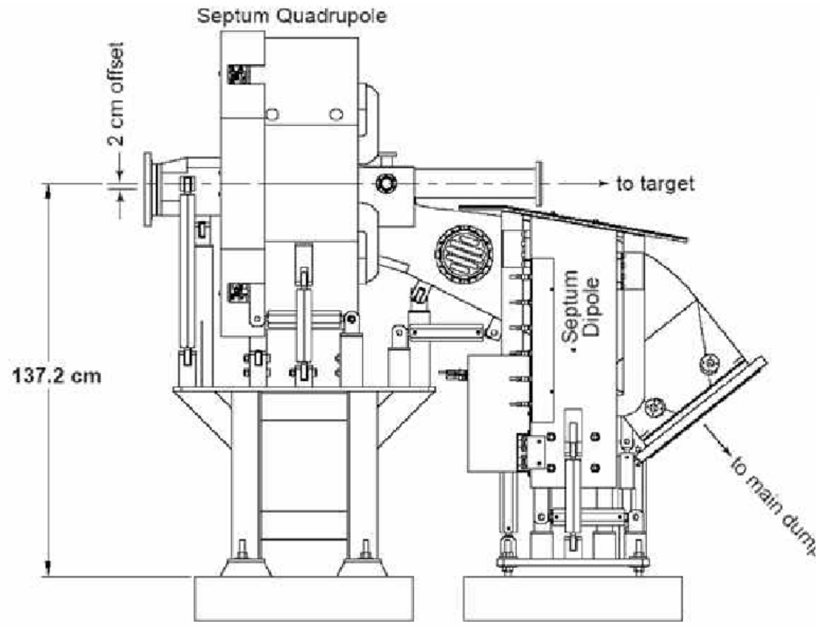
During the diode risetime, LSP simulations showed modest stimulated ion production from mismatched beam spill. However, temperature rise of components was to low for significant thermal desorption.

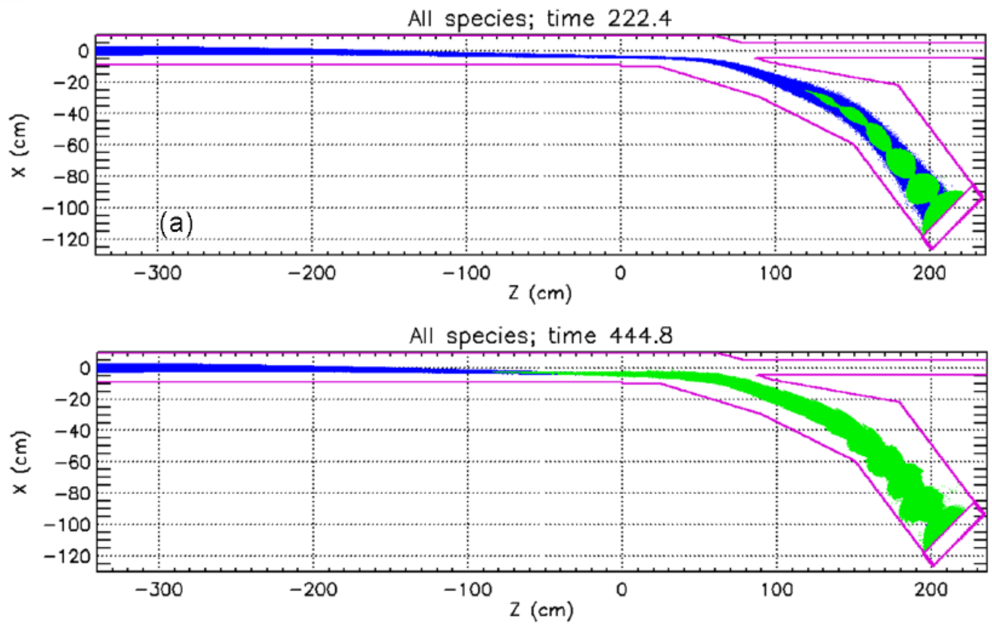
Maximum temperature rise of collimators is < 25 C, so ion production from thermal gas desorption is insignificant.

LSP simulations showed that it is possible for ions generated in the dump to be accelerated into the main beamline by the electron beam space charge.

LSP simulations of septum dump region for a 2-kA, 18.4-MeV electron beam.

There is enough time between pulses for ions to be accelerated into main beam pipe, where they can affect transport of the next beam-pulse.



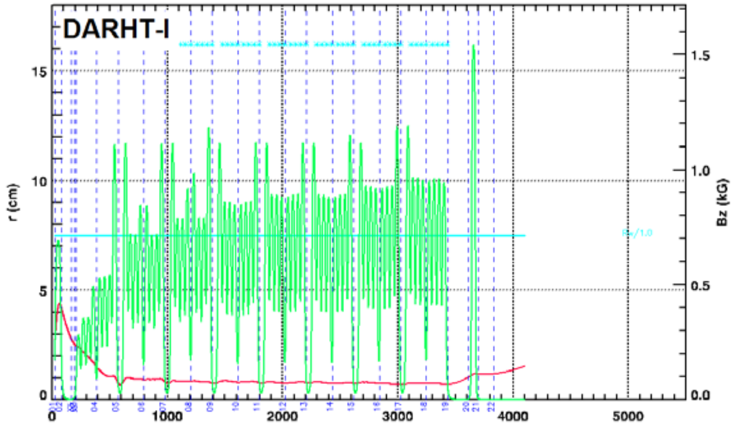


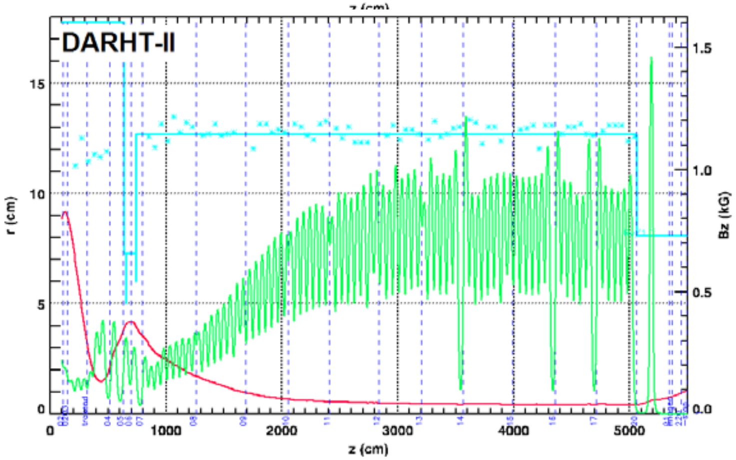
XTR is a static envelope equation solver. Also a static beam centroid solver.

- Author: Paul Allison
- Type: Solver for envelope and centroid differential equations
- Language: IDL
- User Interface: IDL development platform
  - Input: IDL command line, IDL subroutines, ASCII text files
  - Output: Envelope and centroid plots
- Uses: Tuning DARHT accelerators, studying mismatch concerns
- Pros: Easily customizable
- Cons: Easily corrupted
- Comments: Leading code for tuning DARHT LIAs

The XTR envelope code is our primary tool for tuning the DARHT LIAs. It is also used to explore tunes for new LIA designs.

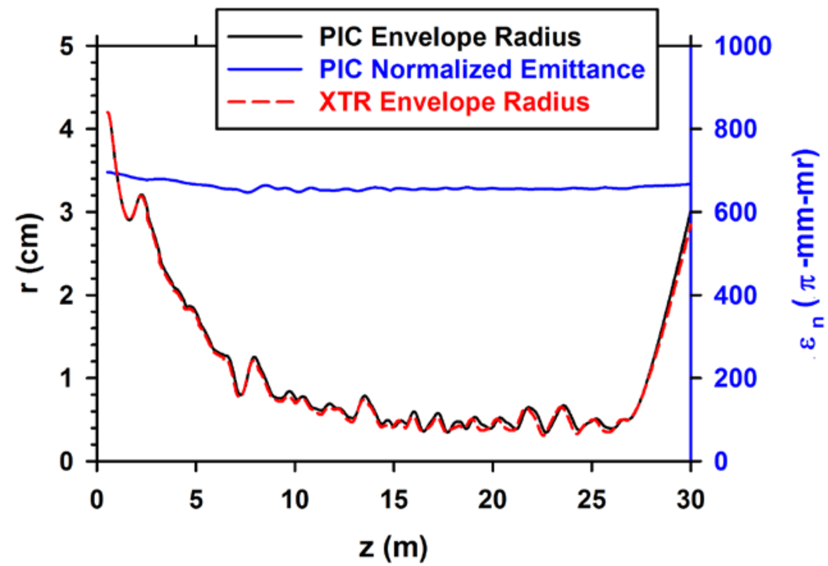
DARHT-I LIA is much shorter than DARHT-II, because fewer Volt-seconds are needed.





XTR and LSP-Slice PIC code were used to explore tunes for a proposed 12-MeV multi-pulse LIA.

- **The agreement between calculated results lends credibility to the envelope-code method.**

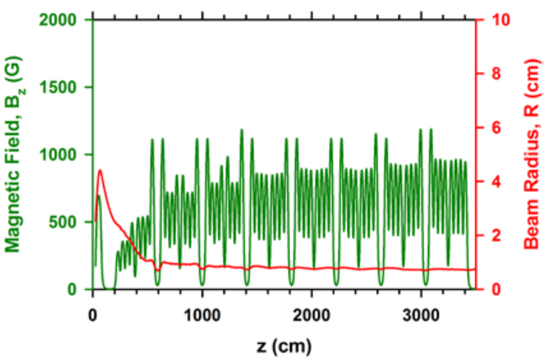


LAMDA (Linear Accelerator Model for DARHT) is a time-resolved envelope and centroid solver. It also has many algorithms for beam instabilities.

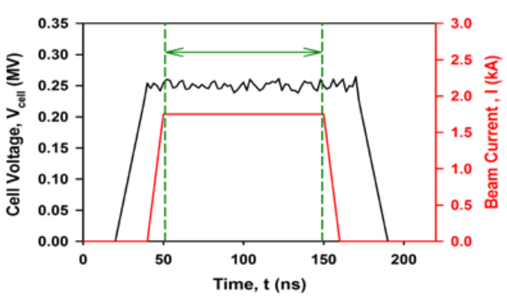
- **Authors: Tom Hughes, Tom Genoni , et al.**
- **Support: Voss Scientific, LLC**
- **Type: Envelope and centroid differential equations solver**
- **Language: C++**
- **User Interface: MS Excel Spreadsheet**
  - **Input: Spreadsheet entries, ASCII text files**
  - **Output: Binary file, IDL-based File Reader**
- **Uses: Beam Acceleration, Transport, and Stability; Tuning DARHT-II downstream transport system**
- **Pros: Time resolved; algorithms for major instabilities; excellent documentation of physics models**
- **Cons: Tricky input interface and setup for new problems**
- **Comments: LAMDA is a “Swiss Army Knife” beam dynamics code.**

LAMDA simulations have shown that the corkscrew growth formula derived from idealized theory is also valid for realistic LIA architectures, such as DARHT.

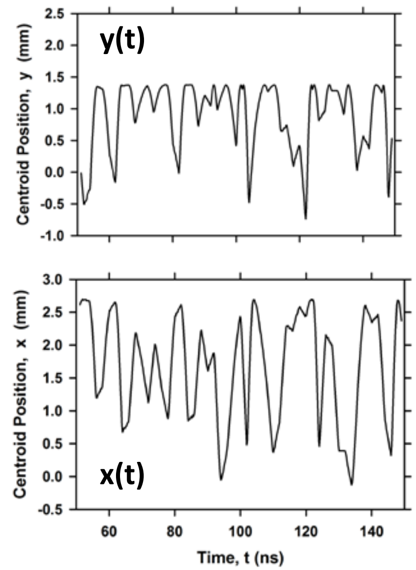
DARHT-I Tune and Beam Size

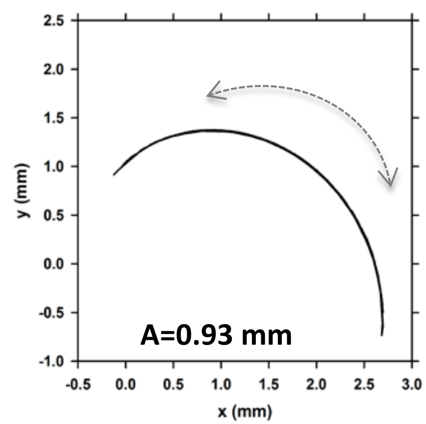


Voltage Fluctuations were applied to every cell

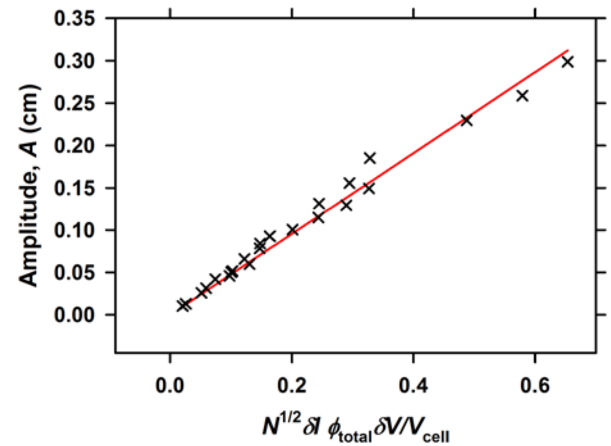


Centroid Motion at LIA Exit





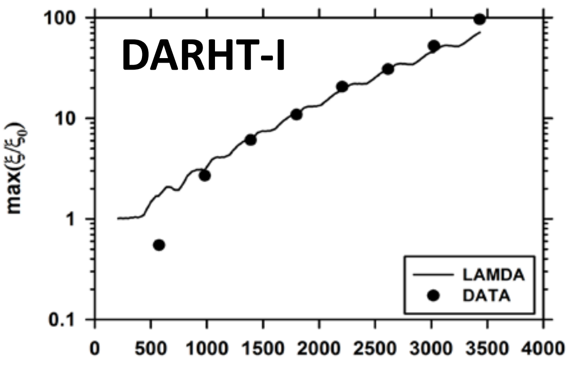
Results of many simulations with varied parameters have validated the theoretical formula for growth.

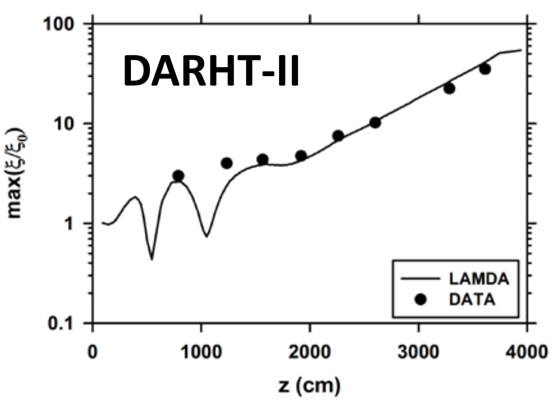


$$A = 0.49\sqrt{N}\,\delta\ell\,\frac{\delta V}{V_{cell}}\phi_{total}$$

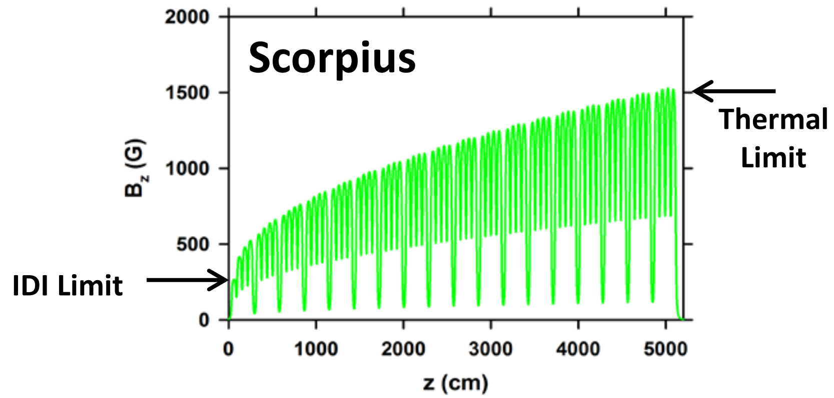
LAMDA simulations of BBU instability have been validated with experimental data, and then used to predict BBU growth in advanced LIAs, such as Scorpius.

BBU growth measured on DARHT LIAs agrees with LAMDA simulations.

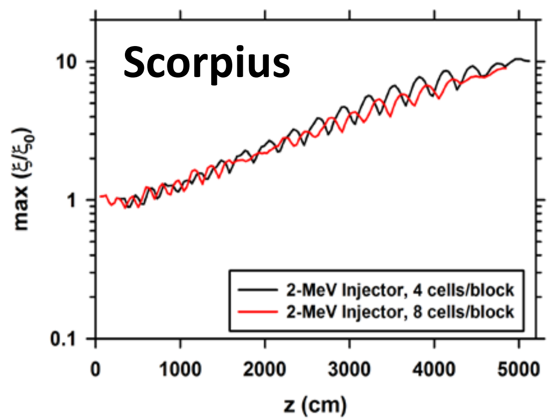




Field-constrained optimum tune



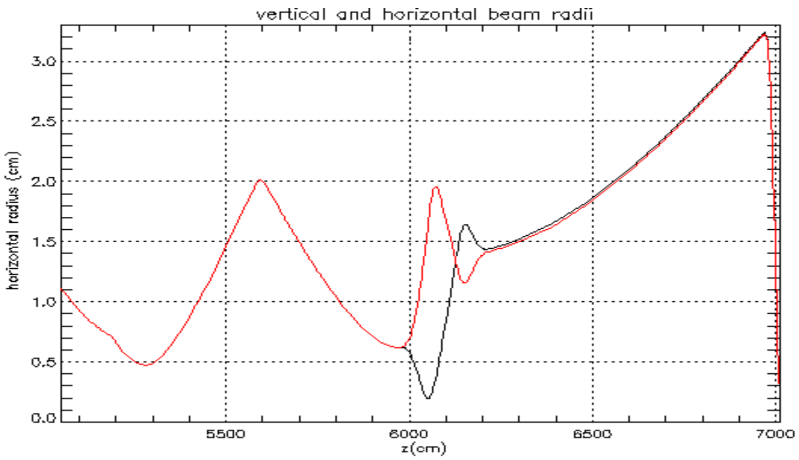
Cells/block comparison using field-constrained optimum tune



LAMDA elliptical-envelope simulations agree with LSP (PIC) through quadrupole transport system.

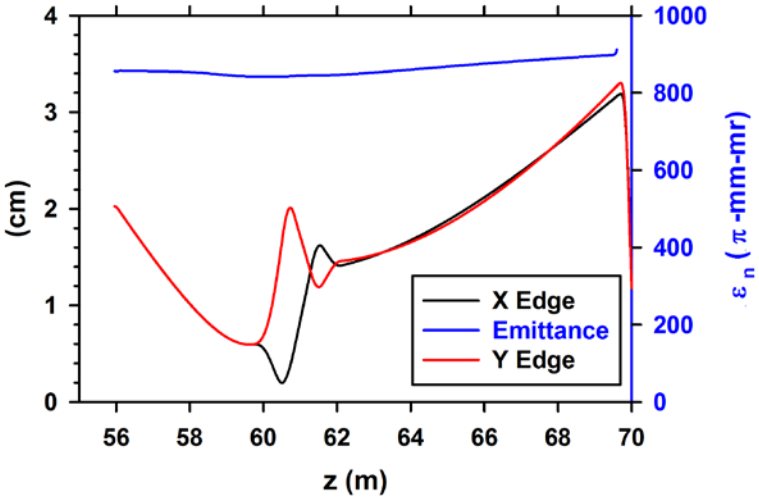
Simulations of Quadrupole Transport
(Four active quadrupole magnets)

- **Top: LAMDA (envelope code)**
  - Uniformly filled ellipse beam
  - Red: Vertical edge
  - Black: Horizontal edge

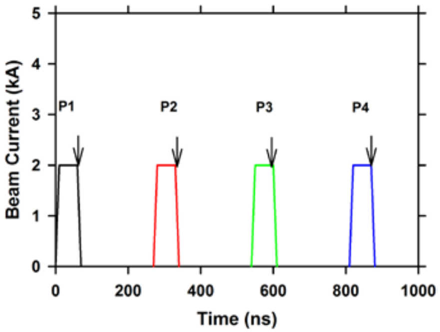


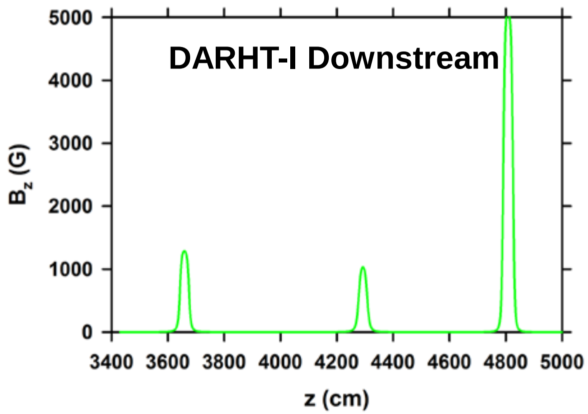
- **Bottom: LSP-Slice (PIC code)**
  - Initially uniformly filled ellipse
  - Red: Vertical edge
  - Black: Horizontal edge

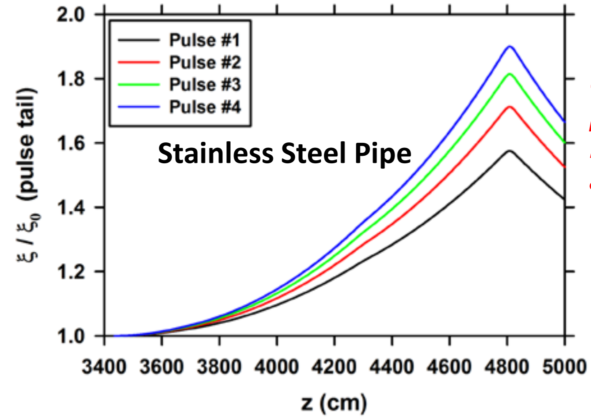
  - Note only ~5% growth of beam emittance through system



LAMDA simulations have confirmed the possibility of pulse-to-pulse coupling of the resistive-wall instability in multi-pulse LIA downstream drift regions.







Coupling produces spot blur and spread at focus !

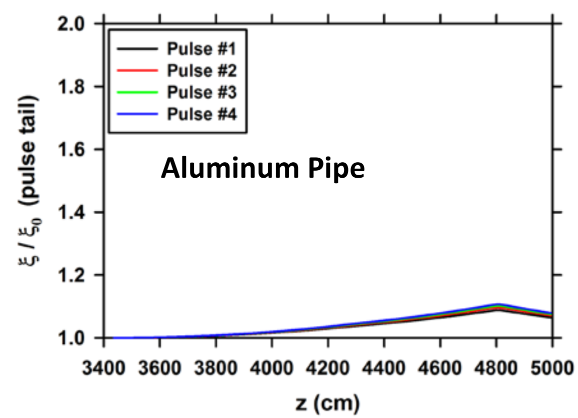
- Input parameters:
- (Scorpius-like)

- 4 pulses
- 2-kA
- 10-ns rise and fall
- 50-ns flattop
- 200-ns separation

- 2-Mev injected to LIA
- 0.25-MeV / cell for 72

- 20-Mev injected to DST

Switching to Aluminum Pipe mitigates instability .

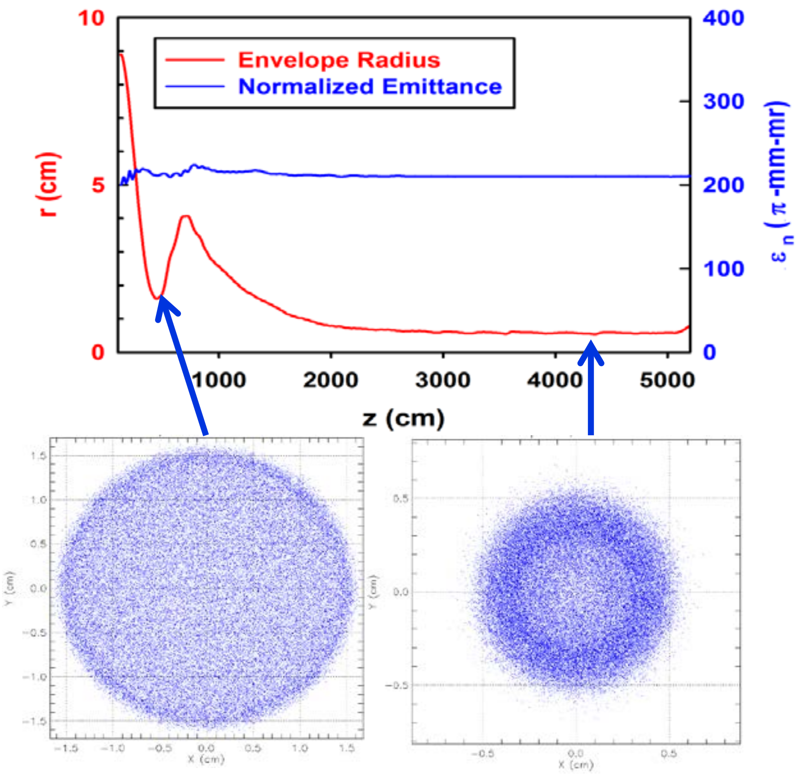


LSP-Slice is a PIC code that follows a single thin slice of the beam through the LIA.

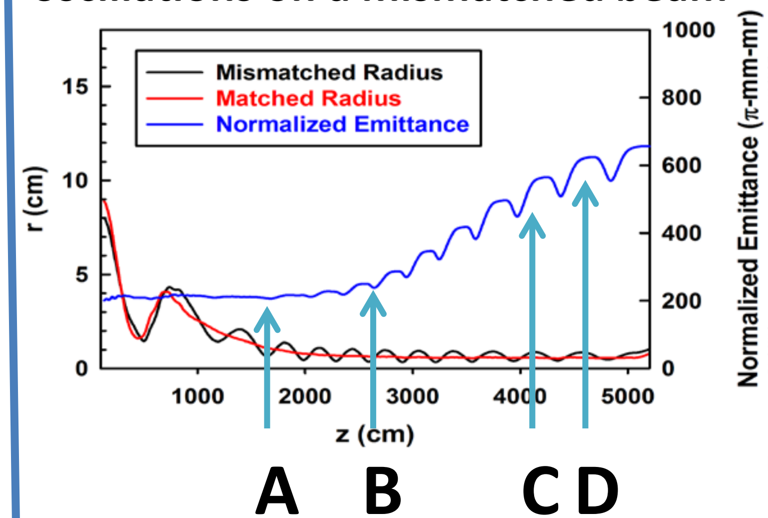
- **Author: Carsten Thoma**
- **Support: Voss Scientific**
- **Type: Particle in cell (based on LSP)**
- **Language: C++**
- **User Interfaces:**
  - **Input: ASCII text script plus text files describing external electromagnetic fields**
  - **Output: Binary files, IDL-based file reader**
- **Uses: Beam transport through LIA and downstream, with emphasis on emittance growth concerns.**
- **Pros: Fast running on multiple-processor workstations**
- **Cons: Arcane problem setup and post-processing.**
- **Comments: Emittance growth investigation showed that the culprit is likely halo generation pumped by envelope oscillations on a mismatched beam.**

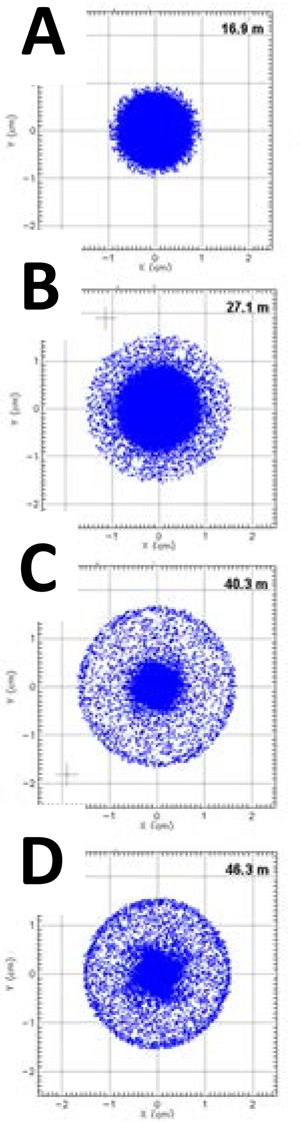
LSP-Slice has been useful for exploring possible causes of emittance growth.

PIC results showed that mild edge-focusing by spherical aberrations has little effect on beam emittance in DARHT-II.



The most likely cause of emittance growth was shown to be beam halo parametrically pumped by envelope oscillations on a mismatched beam





These PIC results emphasize the value of having well-known initial conditions for envelope codes when tuning.

Occasionally, we have used other codes for unique beam-dynamics problems. Examples:

- **TRANSPORT**
  - Matrix Based beam optics code
  - CERN version has been used
  - Crosscheck of LSP-Slice simulations
  - Investigation of beam quadrupole moment evolution through downstream transport evolution
- **Custom IDL programs written to explore theory**
  - Parametric envelope instability
  - Halo growth
  - Image Displacement Instability (IDI)

Thank You for your attention !

Questions ?

Bibliography

All of the articles in this brief collection are available online.

More examples of Trak results can be found in the following publications:

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2. **C. Ekdahl, "DARHT Axis-I diode simulations II: Geometrical scaling," *Los Alamos National Laboratory* Report LA-UR-12-22199, 2012. Online: arXiv: 1701.03820**
3. **C. Ekdahl, "Tuning the DARHT long-pulse linear induction accelerator," *IEEE Trans. Plasma Sci.*, vol. 41, pp. 2774 - 2780, 2013.**
4. **J. E. Coleman, C. A. Ekdahl, D. C. Moir, *et al*., "Correcting the beam centroid motion in an induction accelerator and reducing the beam breakup instability," *Phys. Rev. STAB,* vol. 17, pp. 092802, 2014.**
5. **J. E. Coleman, D. R. Welch, and C. L. Miller, "Scattered hard X-ray and γ-ray generation from a chromatic electron beam," *J. Appl. Phys.*, vol. 118, pp. 184505, 2015**

More examples of LSP results can be found in the following publications:

1. T. P. Hughes, *et al.*, "Design of beam cleanup zone for DARHT-2," in *19th Part. Accel. Conf.*, Chicago, IL, USA, 2001.
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6. **J. Coleman, *et al.*, "Increasing the intensity of an induction accelerator and reduction of the beam breakup instability," *Phys. Rev. ST Accel. Beams*, vol. 17, pp. 030101, 1 -11, 2014.**
7. **C. Ekdahl, *et al*., "Emittance growth in linear induction accelerators," in *20th Int. Conf. High Power Part. Beams*, Washington, DC, USA, 2014.**
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9. **C. Ekdahl, J. E. Coleman and B. T. McCuistian, "Beam Breakup in an advanced linear induction accelerator," *IEEE Tran. Plasma Sci.,* vol. 44, no. 7, pp. 1094 - 1102, 2016.**

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More examples of LSP-Slice results can be found in the following publications:

1. **C. Thoma and T. P. Hughes, "A beam-slice algorithm for transport of the DARHT-2 accelerator," in *22nd Part. Acc. Conf.*, Albuquerque, NM, 2007, pp. 3411- 3413.**
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