OAK RIDGE National Laboratory

Laser Assisted Charge Exchange (LACE) Injection at the Spallation Neutron Source (SNS)

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FRIB Seminar, April 10, 2026

U.S. DEPARTMENT OF ENERGY

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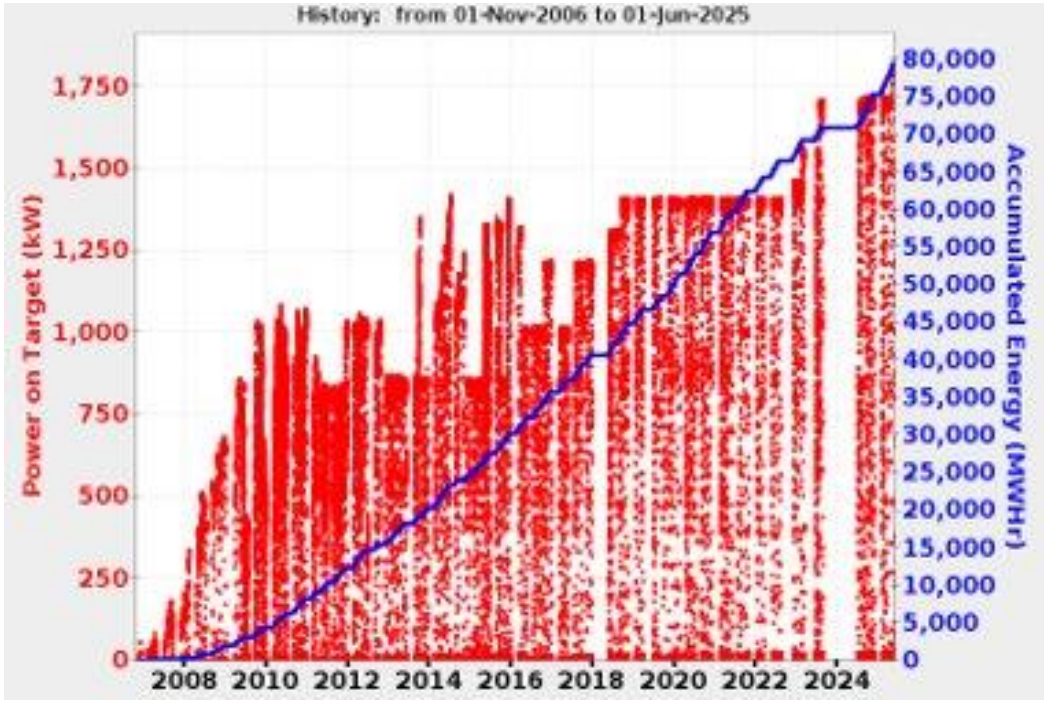
FOR THE US DEPARTMENT OF ENERGY

Outline

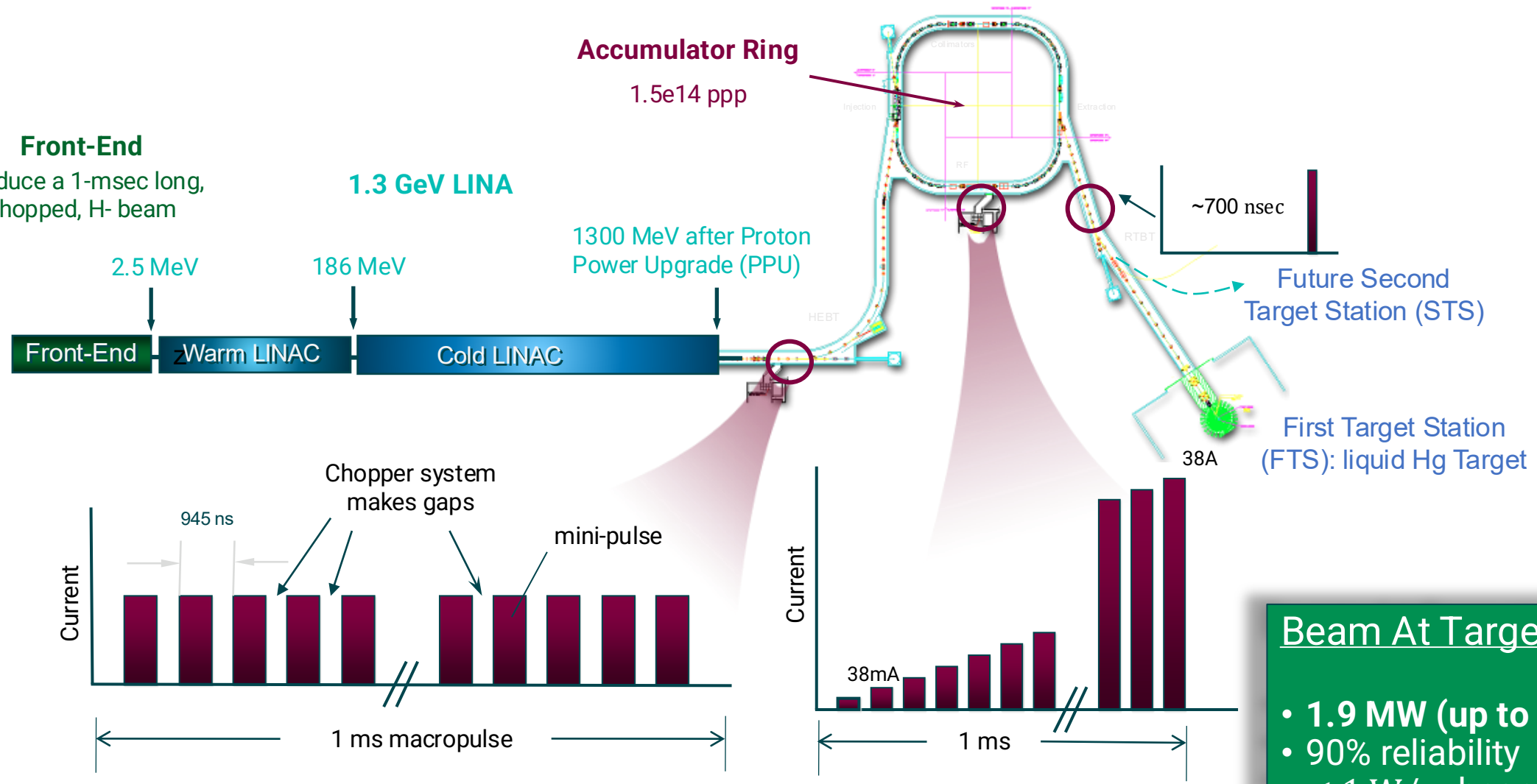
- Overview of SNS
- Laser Assisted Charge Exchange (LACE)
  - Concept
  - Current experiments
  - Injection demonstration
- Outlook

The Spallation Neutron Source (SNS)

World's highest power proton accelerator : 1.9 MW (currently)



The Spallation Neutron Source (SNS)



Beam At Target (now):

- **1.9 MW (up to 2.8 MW)**
- 90% reliability
- $< 1\ \mathrm{W/m}$ beam loss (~ 100 mrem/hr @ 30 cm)

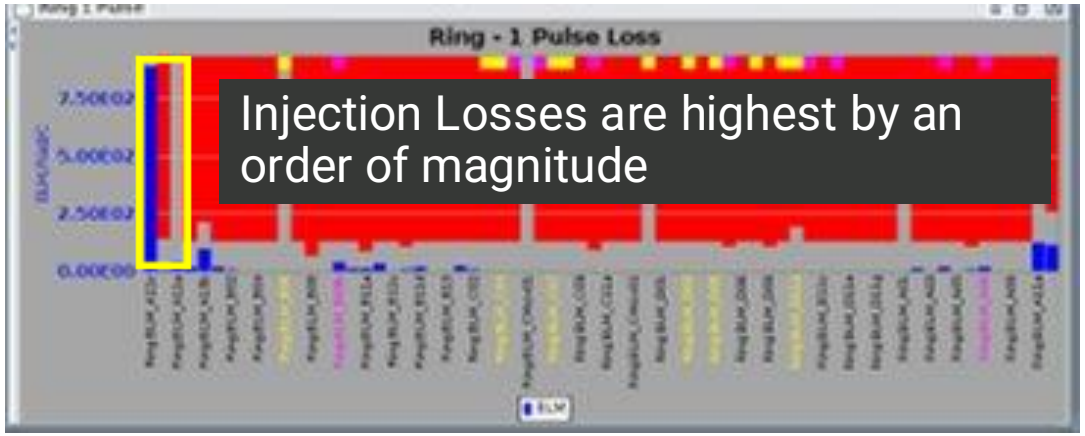
SNS, PPU and STS

- SNS is a 1.3 GeV H- linac, 1ms long, 24uC pulse compressed to ~700ns in Accumulator ring for average power of 1.4 MW
- After the Proton Power Upgrade (PPU), the accelerator will be capable of 2.8 MW
- Until the Second Target Station (STS) is online (~2030's), it is only possible to run at 2 MW
- Three 'eras' of operation – 1.4 MW, 2.0 MW, 2.8 MW

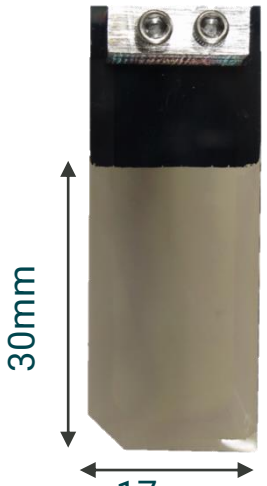
	SNS	PPU-FTS	FTS-STS
Charge/Pulse [uC]	24	26	35
Energy[GeV]	1.0	1.3	1.3
Power[MW]	**1.4**	**2.0**	**2.8**
Rep Rate [Hz]	60	60	60

Primary limitation with foil charge exchange is activation

- **Activation from beam losses**
- Unpredictable foil deformation
- Foil heating and eventual sublimation
- New foil conditioning ~40 hours

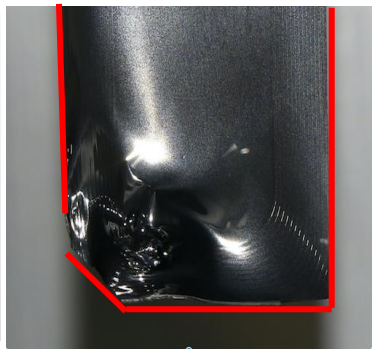


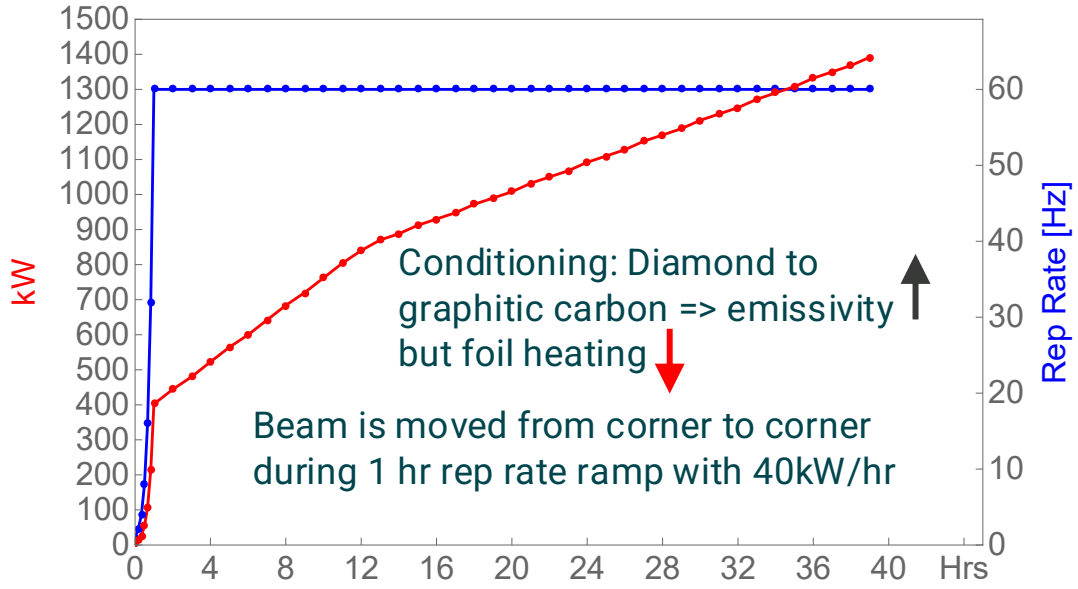
Nanocrystalline diamond foil



Foil 3162

Foil 3073





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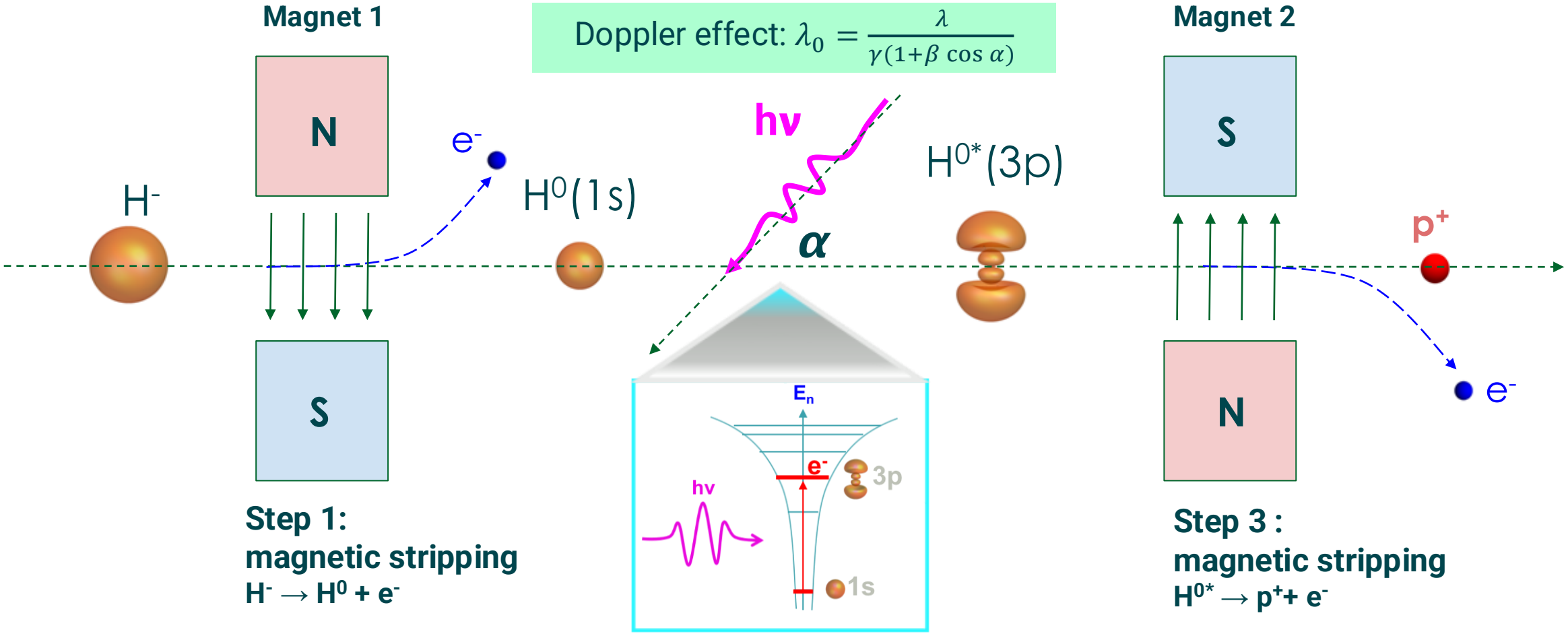
LACE Concept

Laser Assisted Charge Exchange (LACE) replaces foil with magnets and a laser

Doppler effect: $\lambda_0 = \frac{\lambda}{\gamma(1+\beta\cos\alpha)}$



Step 1:
magnetic stripping
$H^- \rightarrow H^0 + e^-$

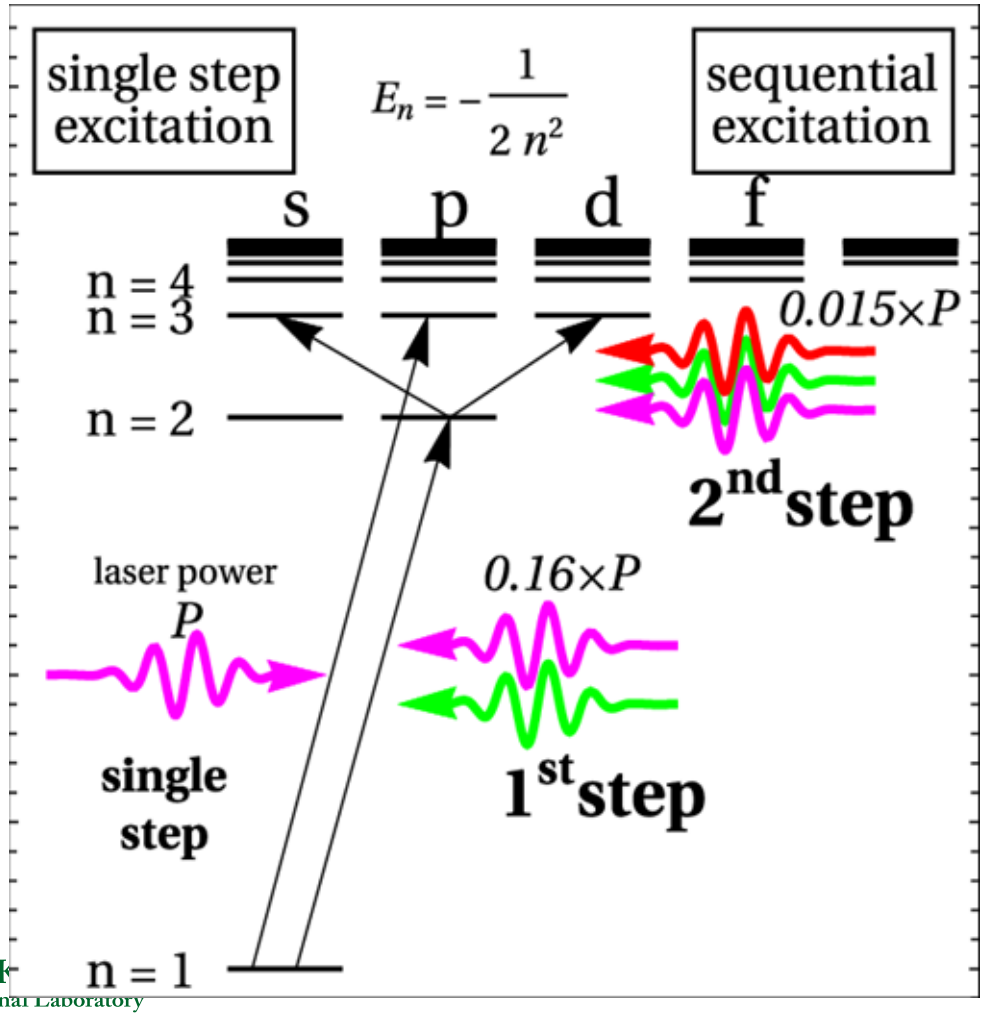
Step 2:
Resonant laser excitation
$H^0 + h\nu \rightarrow H^{0*}$

Step 3 :
magnetic stripping
$H^{0*} \rightarrow p^+ + e^-$

Lorentz transformation: $|E_\perp| = \beta\gamma c|B_\perp|$

More excitation options with higher beam energy of 1.3 GeV after PPU

Hydrogen H^0 atom structure

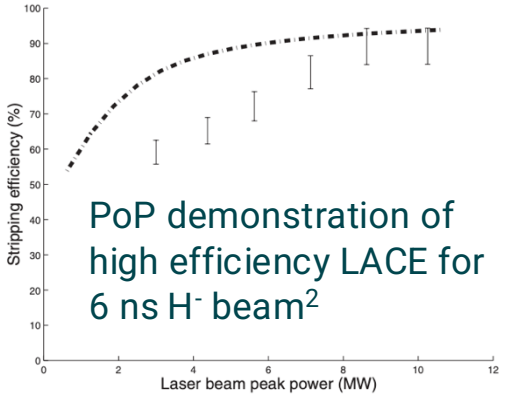


Doppler effect: $\lambda_0 = \frac{\lambda}{\gamma(1+\beta\cos\alpha)}$

	Single-Step	Two-step (Sequential)
Laser	UV	Green-Green or Green-IR
Configuration	Simple	Complex
Laser Power	Large*	Small

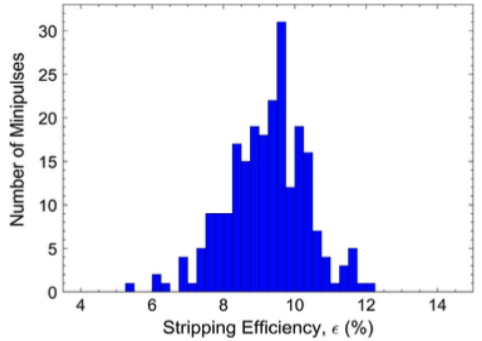
* P_{peak} ~ order of MW, corresponding to P_{ave} at the order of kW

LACE has been developed over the past Two Decades



PoP demonstration of high efficiency LACE for 6 ns H^- beam[2]

Experimental demonstration of sequential excitation for LACE with multiple beam pulses[4]

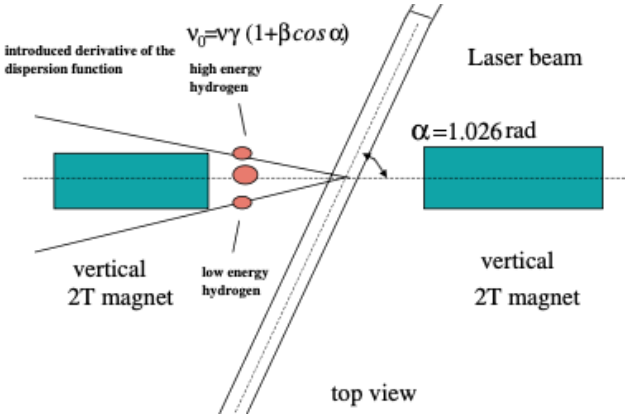


With the proton beam of 1.3GeV, LACE work focuses on:

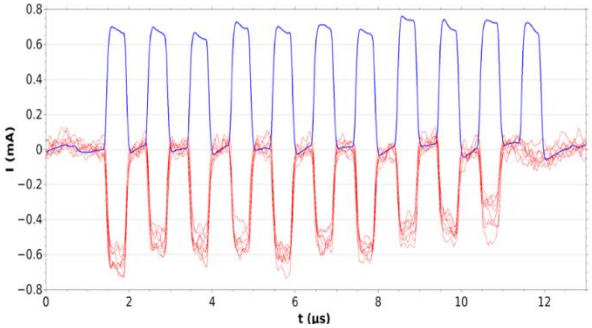
- Optimization of parameters and configuration based on experiments
- Design of the injection system
- Demonstrate LACE in experiments

2003 → 2007 → 2017 → 2019 → 2023 → 2025 -

Achieved nearly 100% excitation efficiency with a narrow-band laser for a 30 ps H^- beam[1]

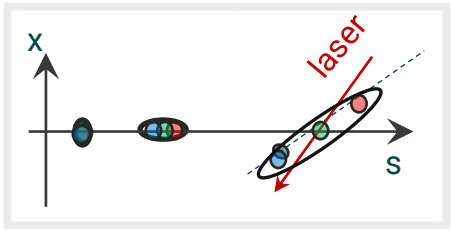


First demonstration of LACE for us H^- beam[3]



Unstripped H^- current
Stripped p current

Crab-crossing collision to increase the interaction of laser and H^- beam[5]

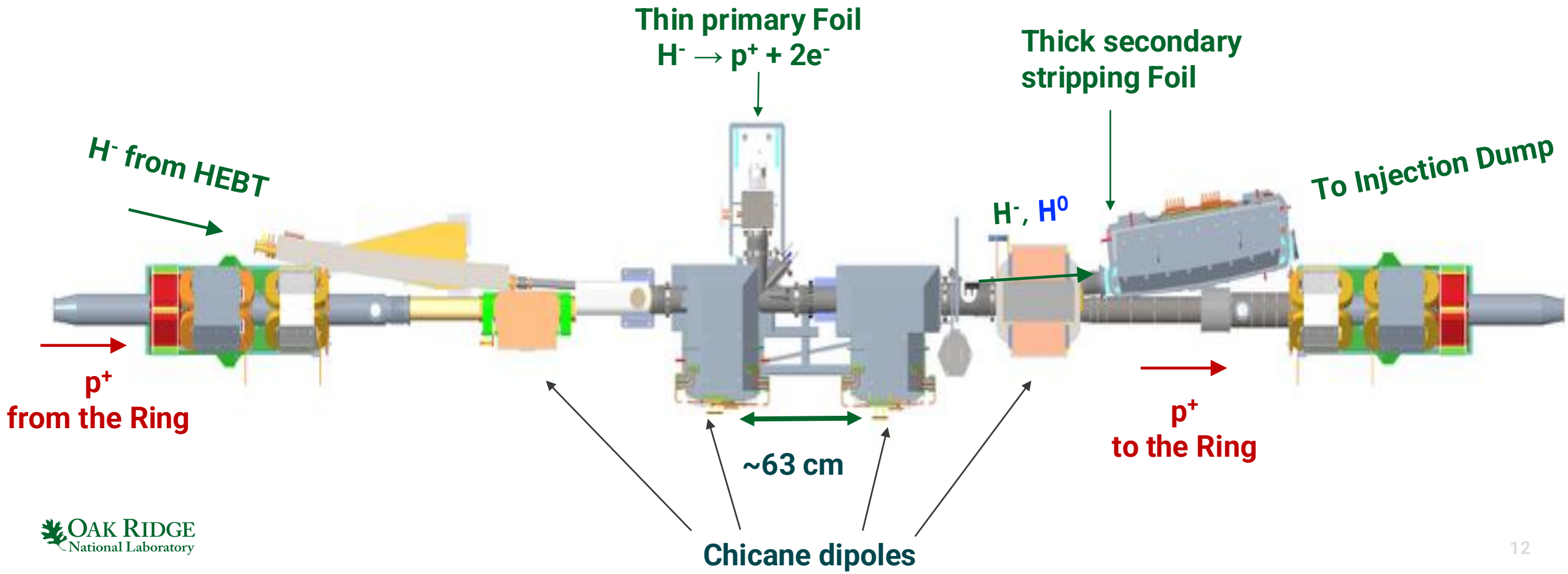


References 1, 2, 3, 4, 5 are listed on slide “References”

LACE-related Experiments

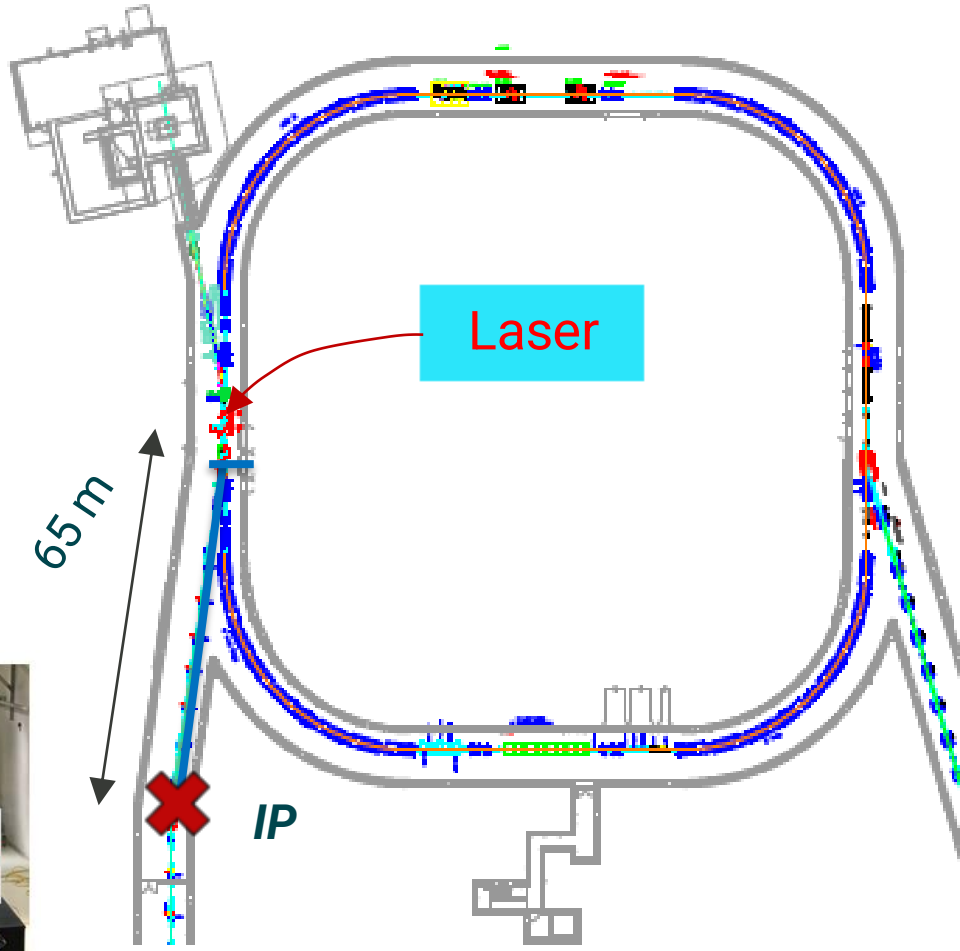
Limited Injection Region after PPU for LACE Experiments

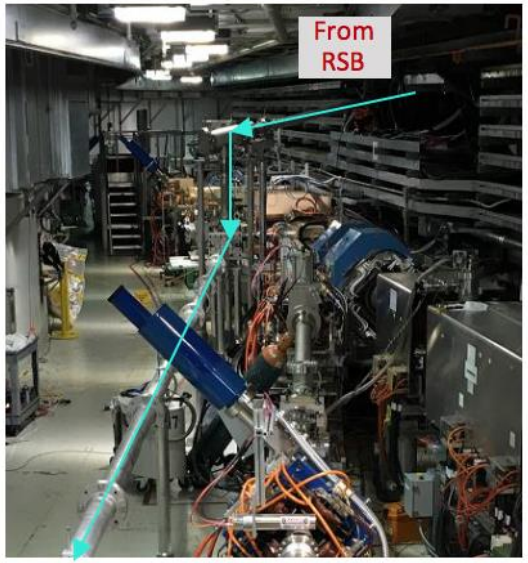
- Higher beam energy after the PPU offers us more excitation options.
- Purpose of LACE experiments: select scheme configurations, one- or two-step, and optimize laser and beam parameters.

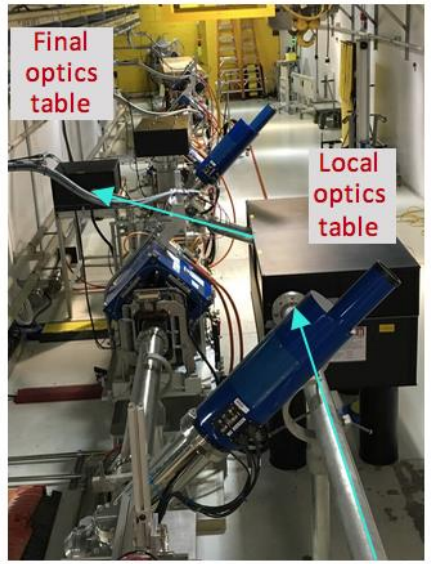


All LACE experiments were/are in transport line

- 65-meter away from the current ring injection, located in the High Energy Beam Transport (HEBT)
  - avoid high radiation
  - utilize the available space and diagnostic systems
  - sufficient tuning knobs to obtain the desired beam
- Laser Transport Line (LTL) has been established for LACE experiments

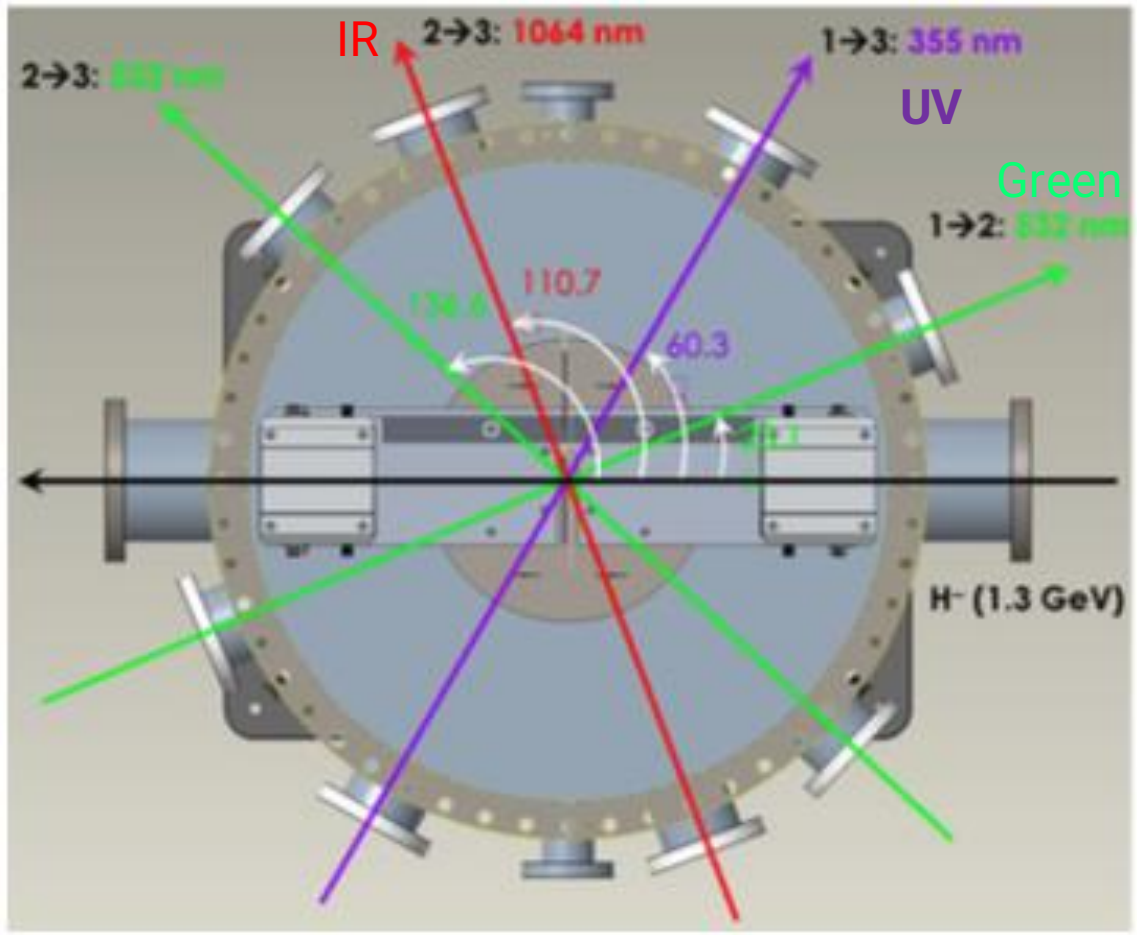


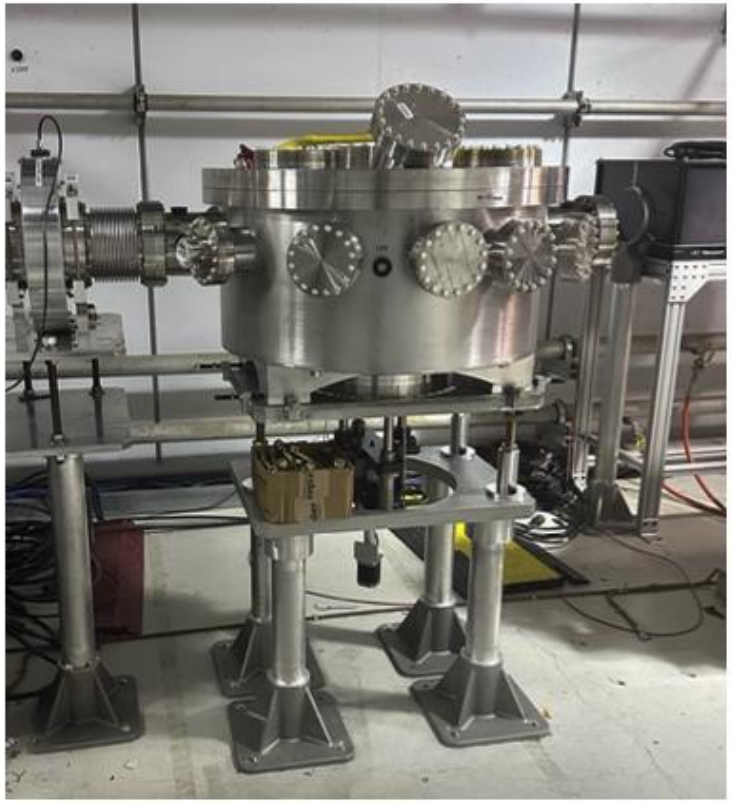




New Vessel is Ready for LACE Experiments

1.3 GeV beam energy after PPU provides more options on laser and beam interaction angles

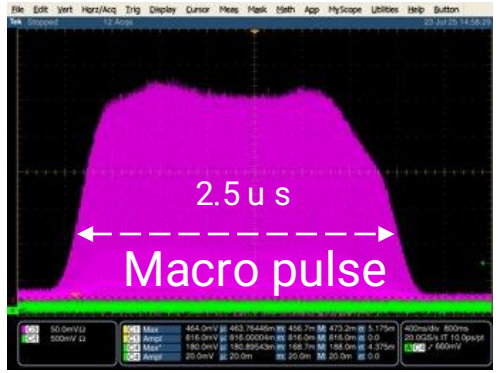


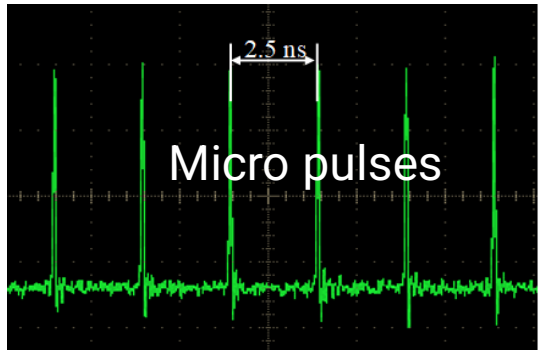


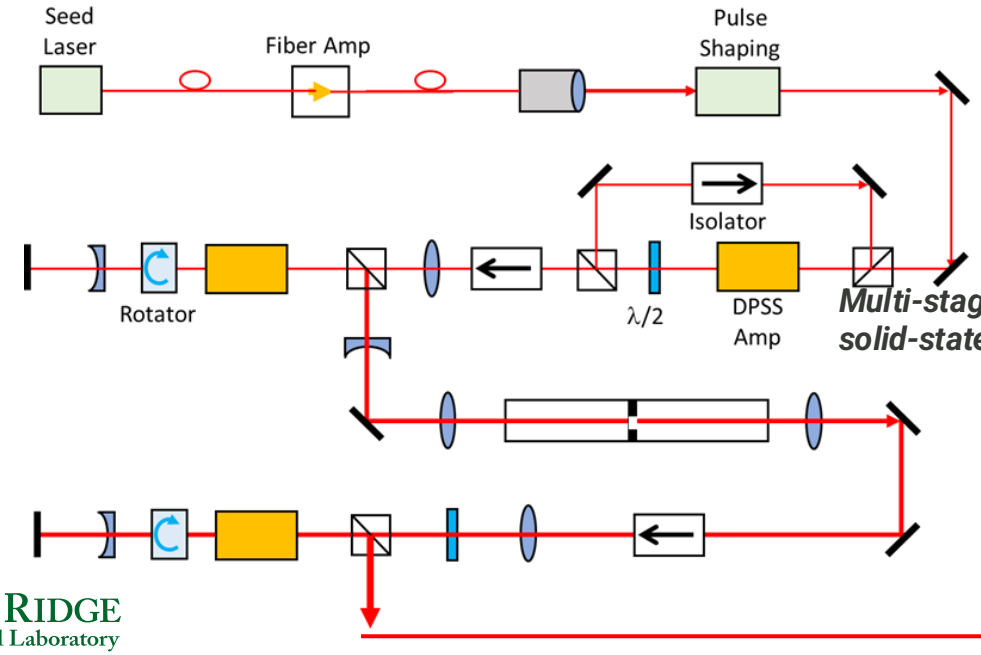
- Demonstrate configurations of UV, IR and green lasers for optimum laser and beam parameters
  - Singel-step: UV
  - Two-step: green-green and green-IR

Commercial laser for experiment; a custom laser is under development

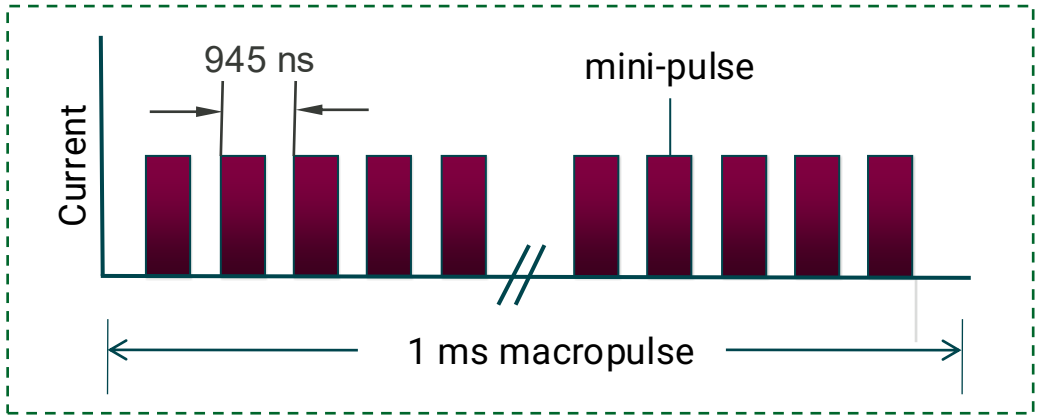
- A commercial Laser is used in the current LACE experiments
- A new custom laser system is under development with a goal of providing **1-2 MW** peak laser power for **1 millisecond** duration at 60 Hz for LACE







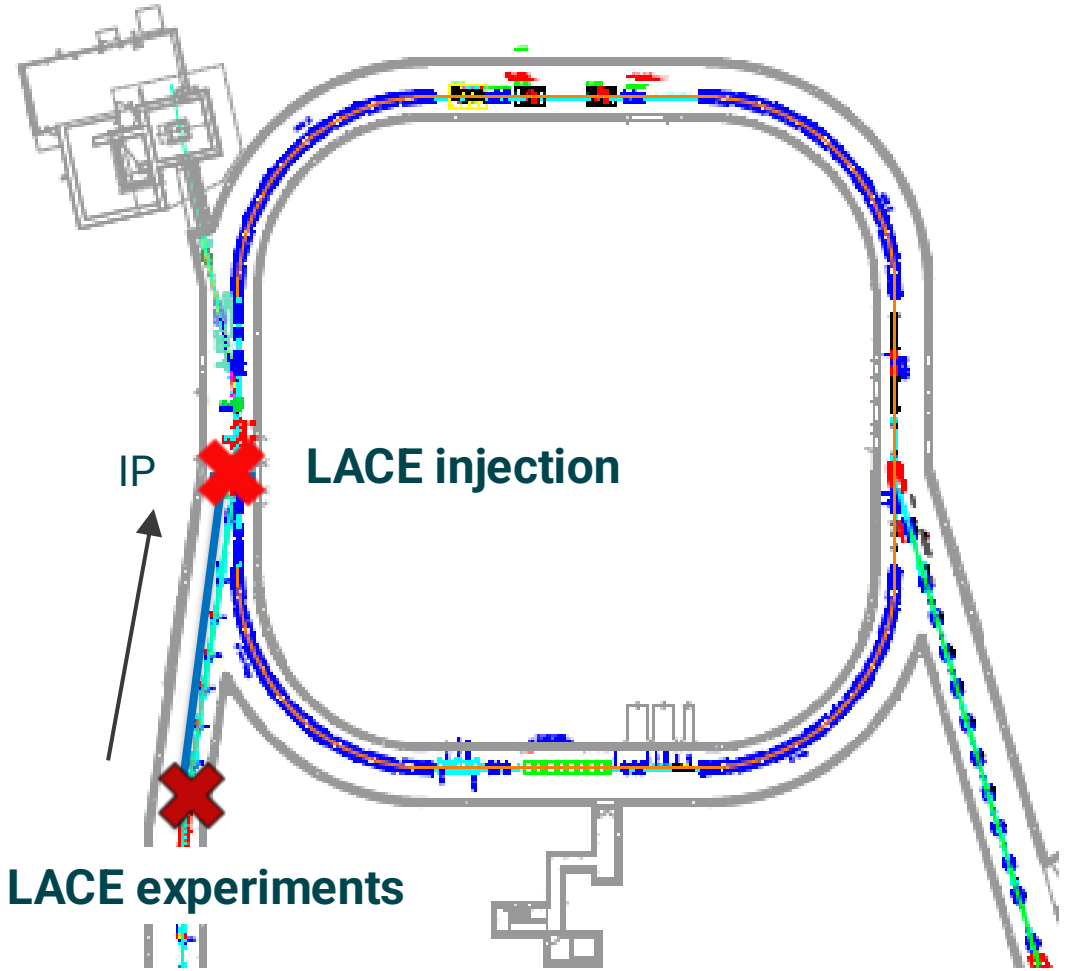
Multi-stage diode-pumped solid-state amplifier (DPSS)



LACE Injection Demonstration

LACE injection design is for the ring injection

- Experiments demonstrate laser assisted charge exchanging only, but not injection
- The design and simulation aim to create an **injection demonstration** in the ring
- Focus on the following challenges:
  - Explore the HEBT capability with existing hardware limitations
  - Mechanical design of the injection region that coexists with the current foil system
  - Design of the required magnetic fields
  - Study of beam dynamics for injection, accumulation and circulation of beams in the ring

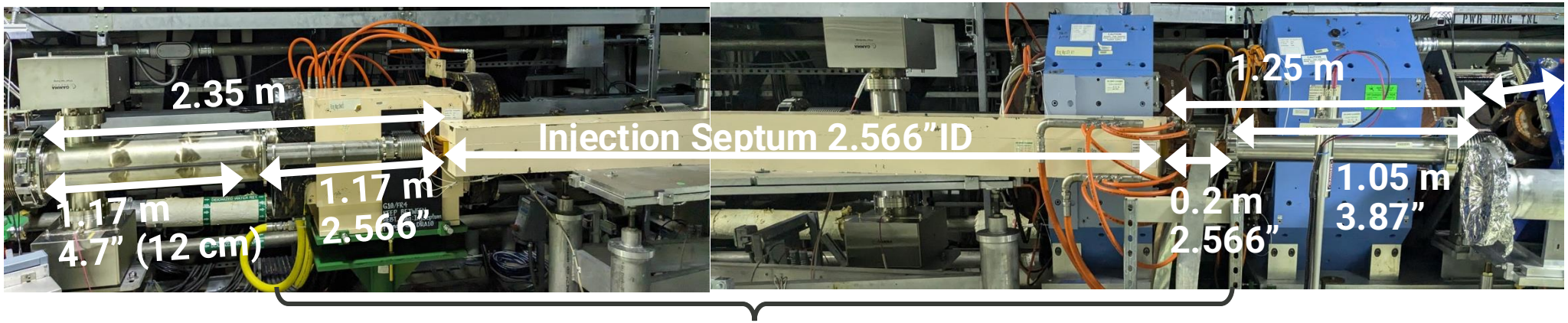


Injection region design has several challenges

- Optics Tune-up for required beam parameters at the IP
  - Small σ_y and δ to increase the laser power density
  - Finite D_x to create a crab-crossing collision of laser and beam
  - Finite D_x' to eliminate the Doppler broadening of linewidth

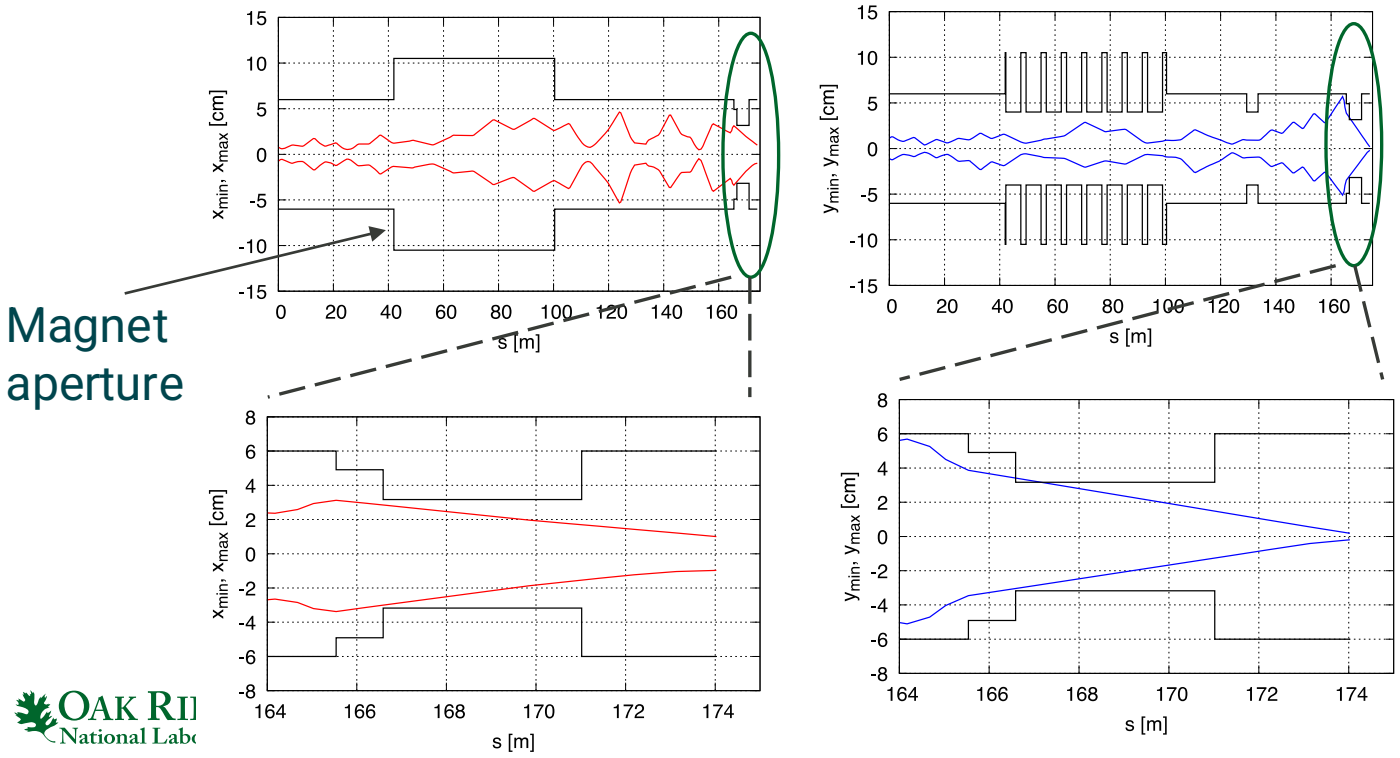
  } ⇒ Increase the laser and beam interaction
  ⇒ Save the laser power
- Hardware limitations:
  - Magnet pole tip field < ~0.2 T to avoid any possible stripping of electrons in the HEBT
  - Small aperture at the injection septum ID~2.6”

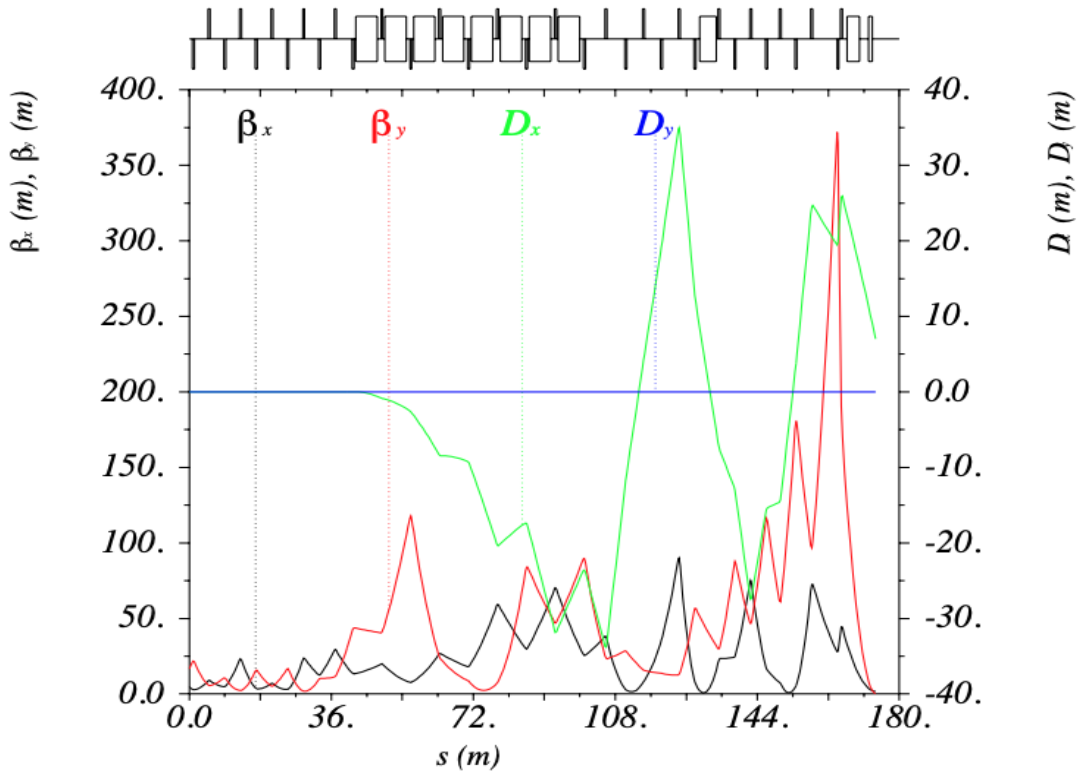
σ_y (mm)	**0.4**
$\sigma_{x\beta}$ (mm)	1.0
σ_x (mm)	3.35
$\epsilon_{x,y}$ (um)	0.6, 0.4
ϵ_z (um)	1.5
δ (10^{-4})	**5**
σ_z (mm)	3
D_x (m)	**7.03**
D_x'	**-2.34**
$\beta_{x,y}$ (m)	1.67, 0.42



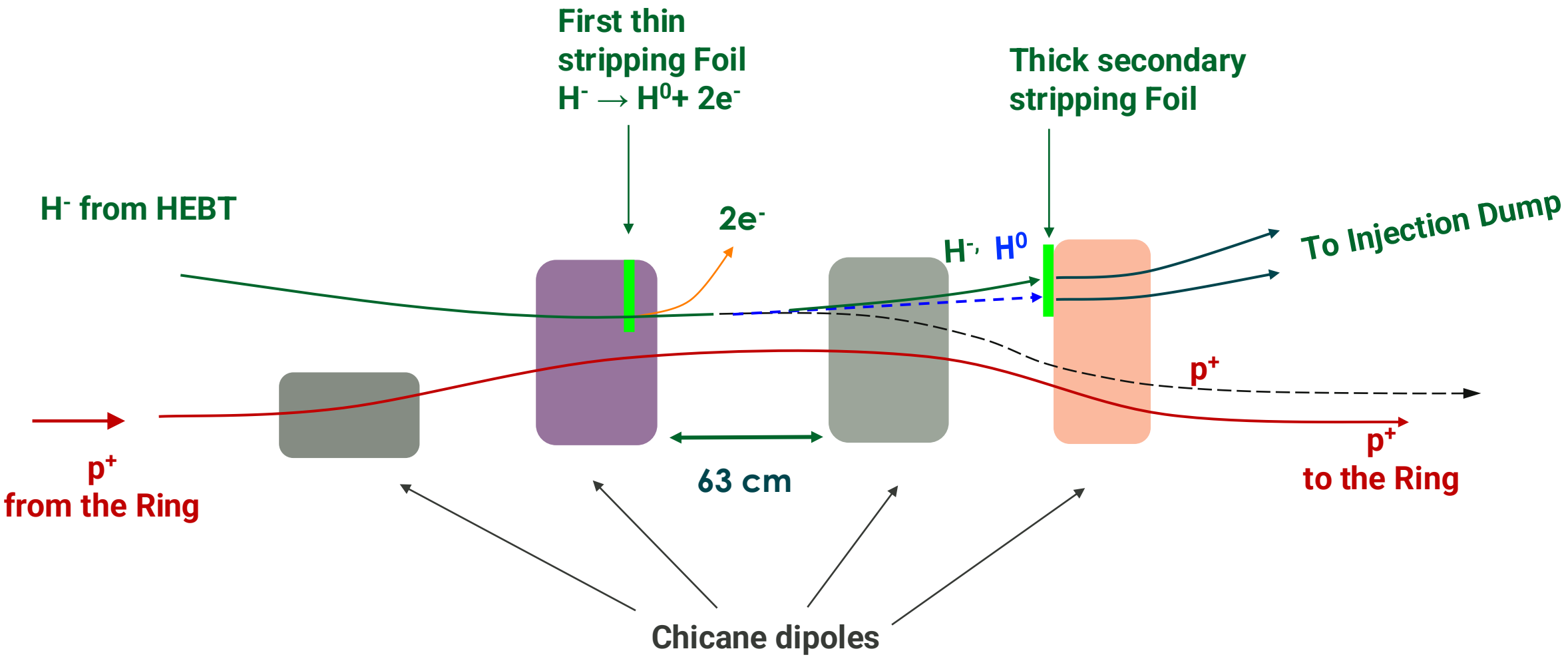
HEBT optics can support required H^- beam for LACE

- All magnet strengths are within the limits
- Two solutions near the injection septum
  - mild scrapping of beam
  - enlarge the aperture if needed

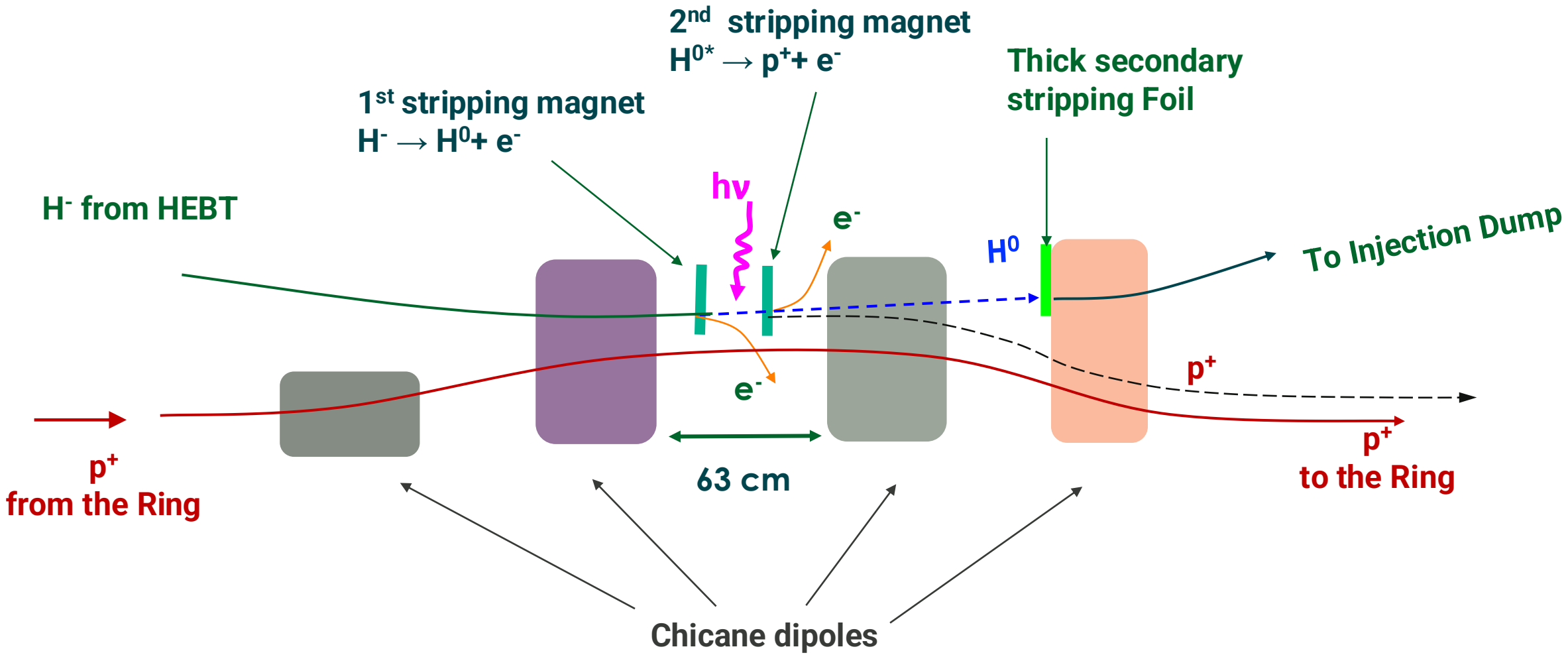




Injection Region after PPU

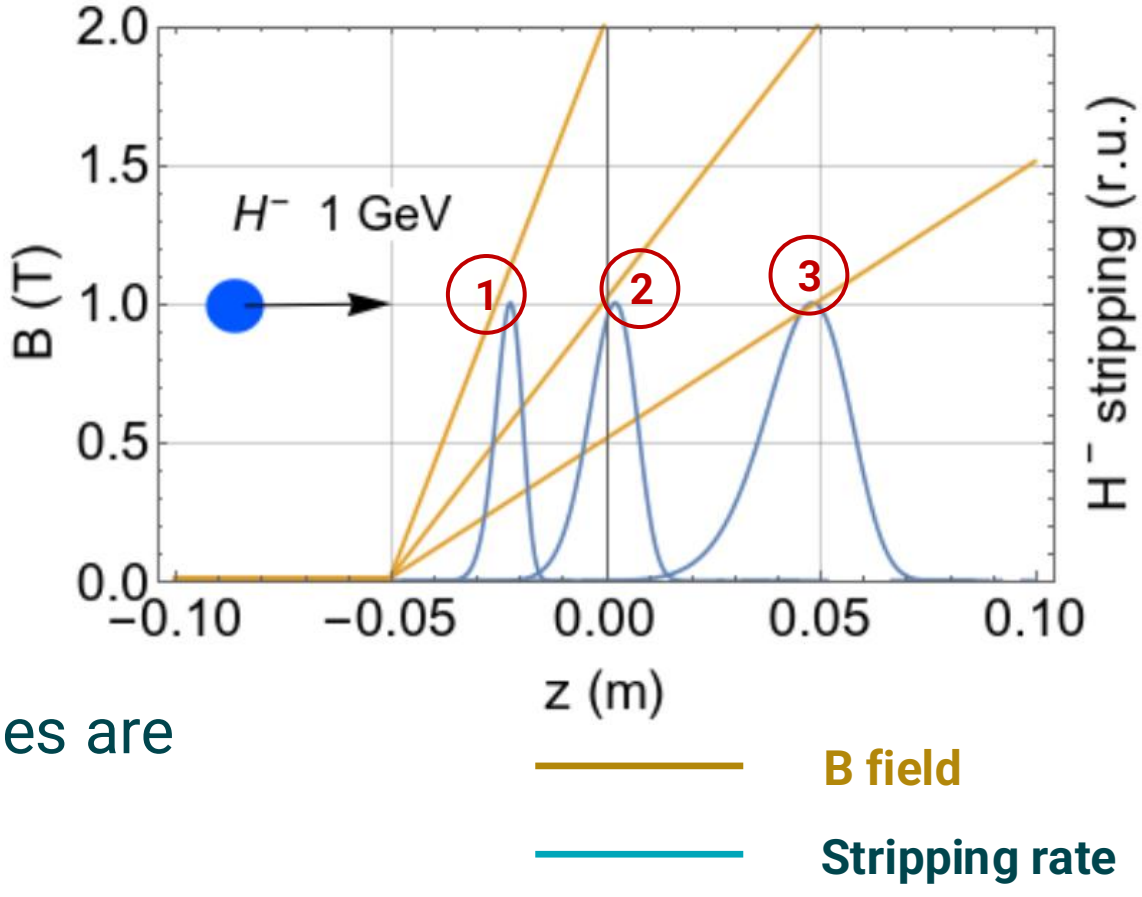


Injection Region after PPU for LACE

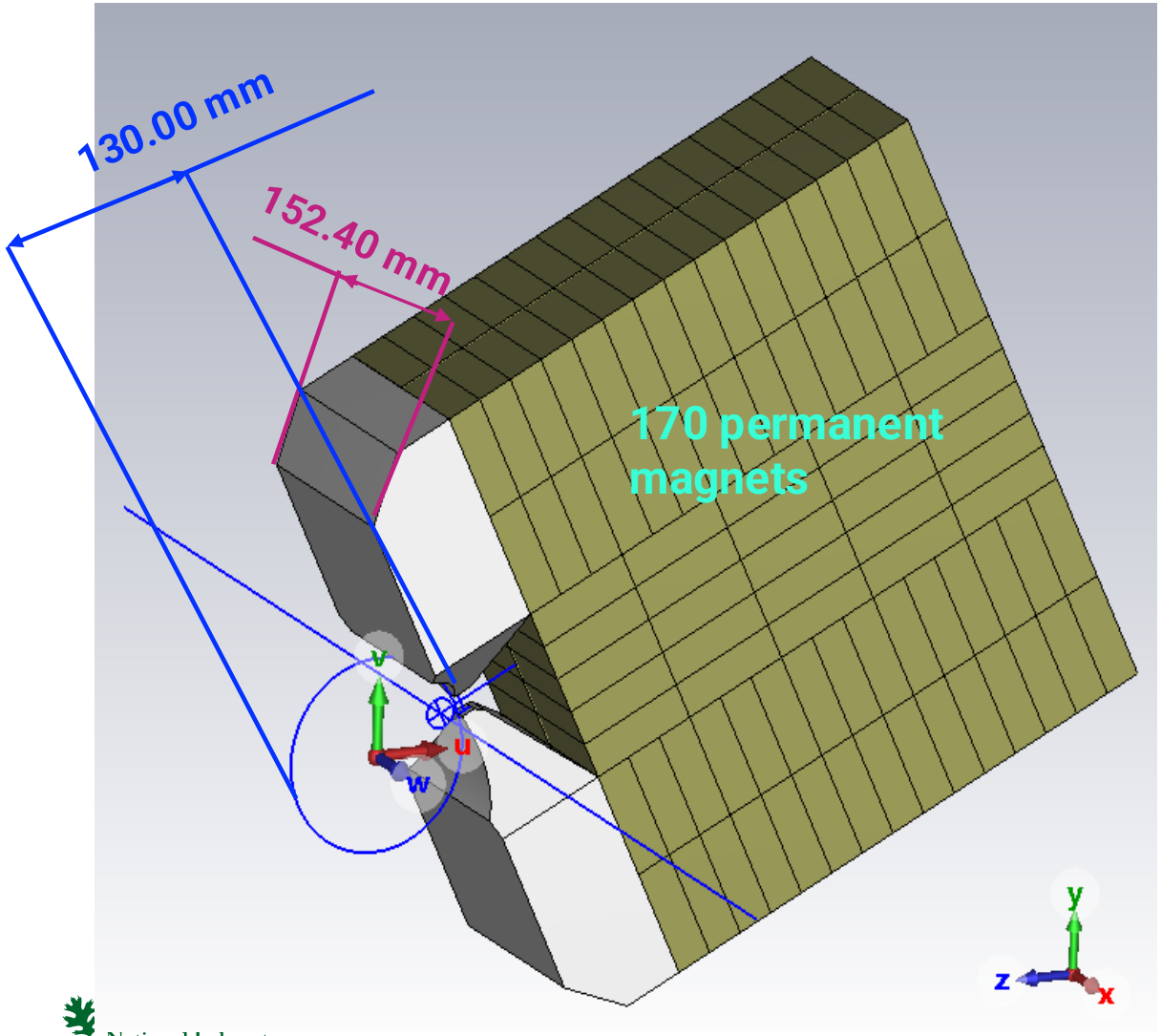


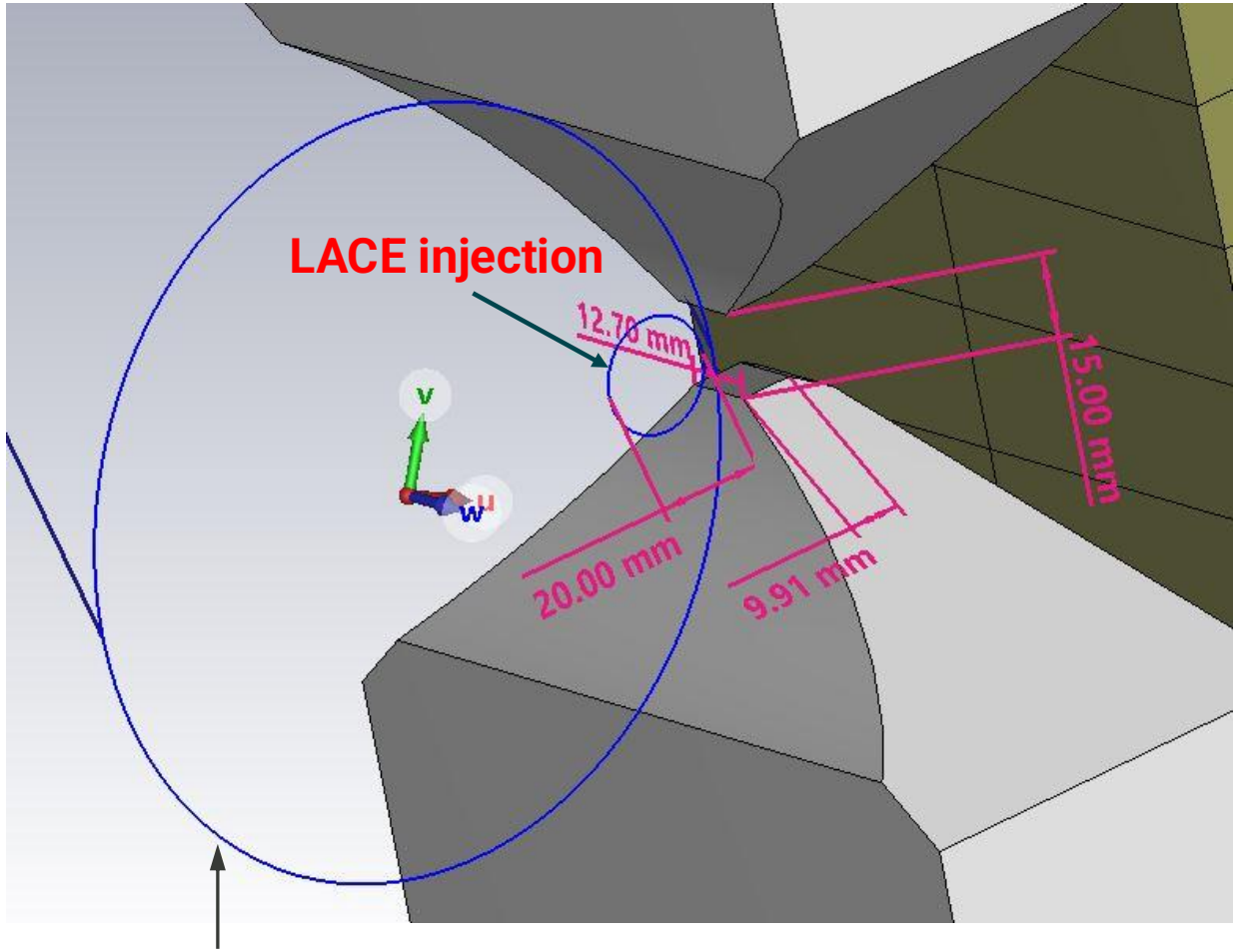
Stripping magnet requires a rapid linear growth of transverse field

- Maximum stripping rate occurs when B =1 for H^- beam at 1 GeV.
- **A rapid growth of field, option (1), is preferred to**
  - minimize the energy spread for subsequent resonant excitation
  - minimize the emittance growth
  - Limit the extent of fringe fields
- Two such magnets but with opposite polarities are required to
  - Ensure zero field at the interaction point
  - Strip two electrons of H^-, one at a time
  - Reduce nonlinear effects to circulating proton beams in the ring



Explored permanent magnet (PM) design with field concentration: requiring large PM volume



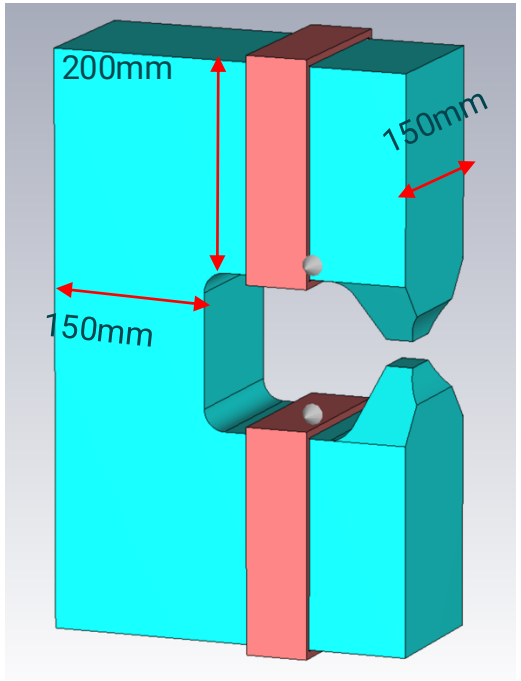


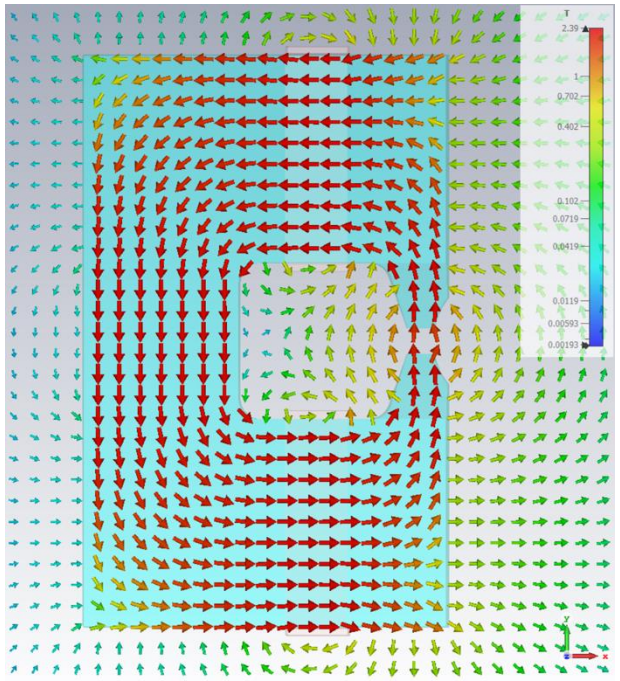
2nd chicane magnet aperture

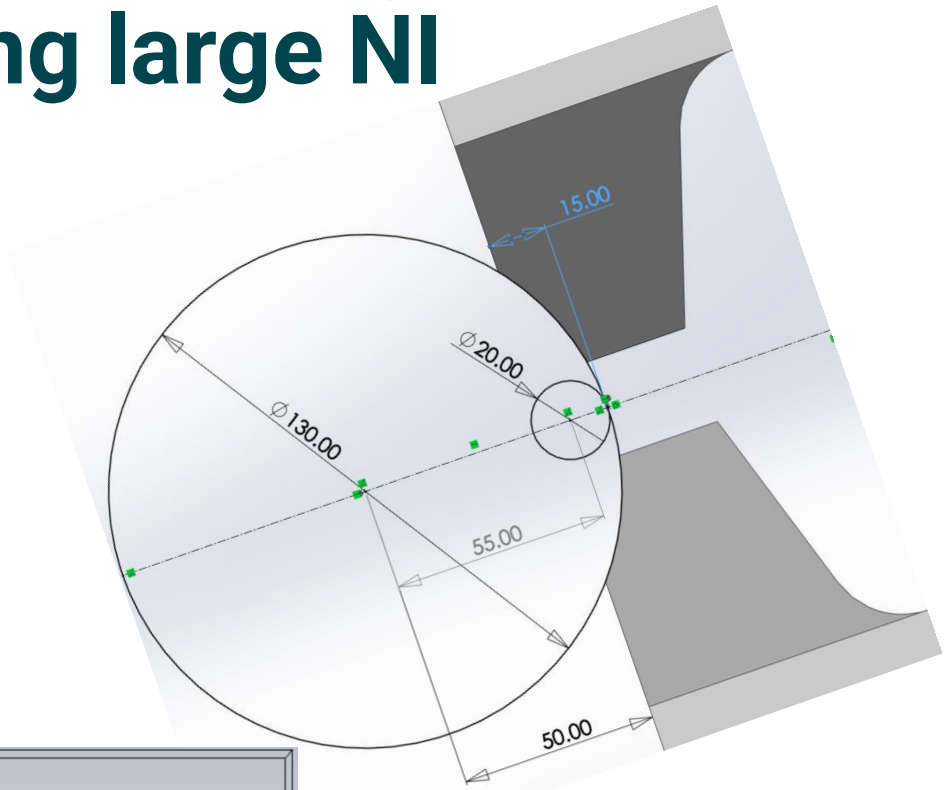
Sasha Menshov

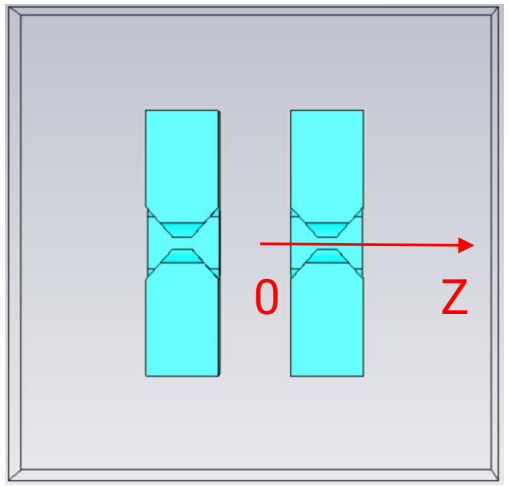
Explored electric magnet (EM) design with a yoke material of SUPERMENDUR: requiring large NI

Hiperco 50A, a type of SUPERMENDUR alloy, with a high relative magnetic permeability $\mu/\mu_0 = 16{,}000$, NI = 50,000 per coil

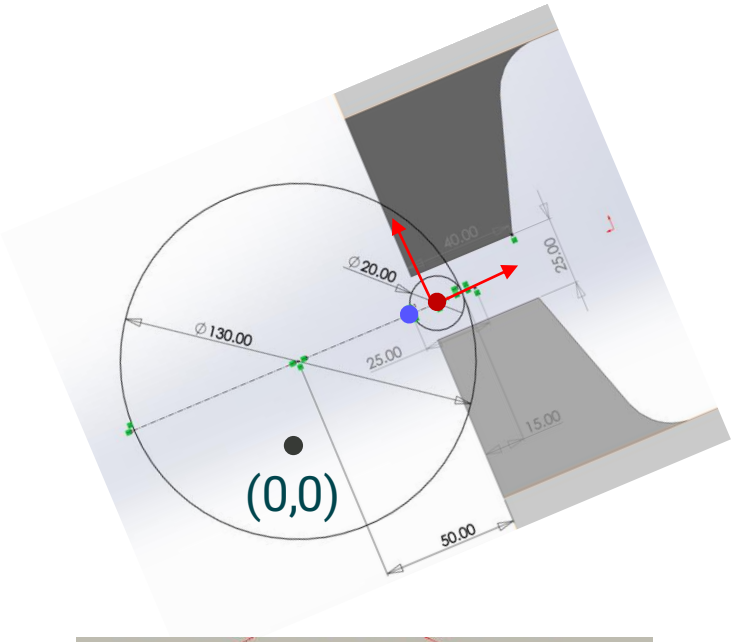


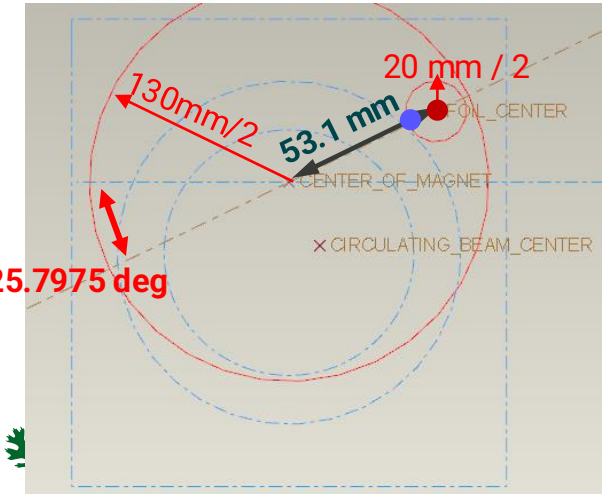


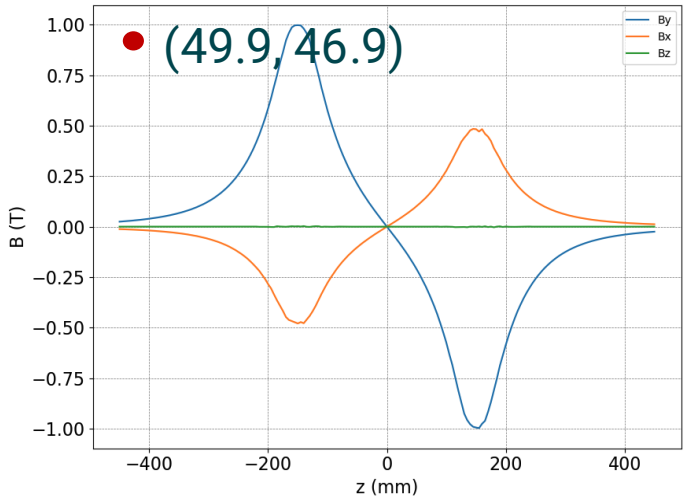


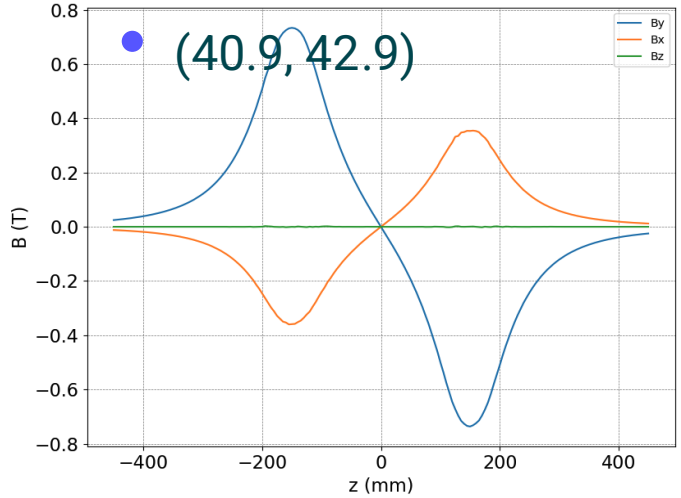


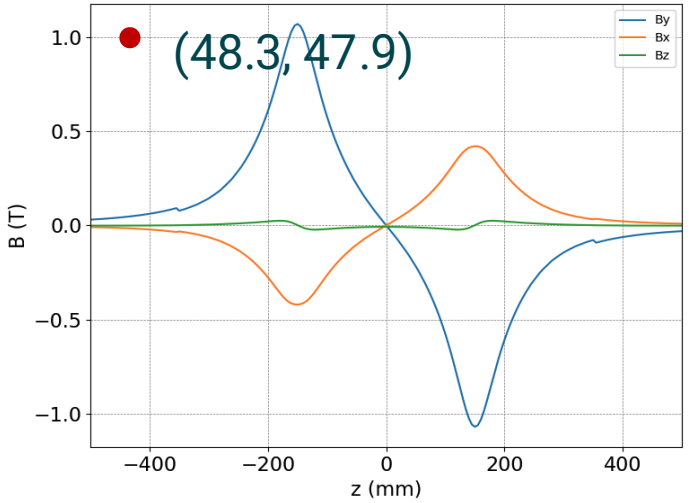
Both PM and EM designs meet 1T requirement at the injection point, with very non-uniform field distribution

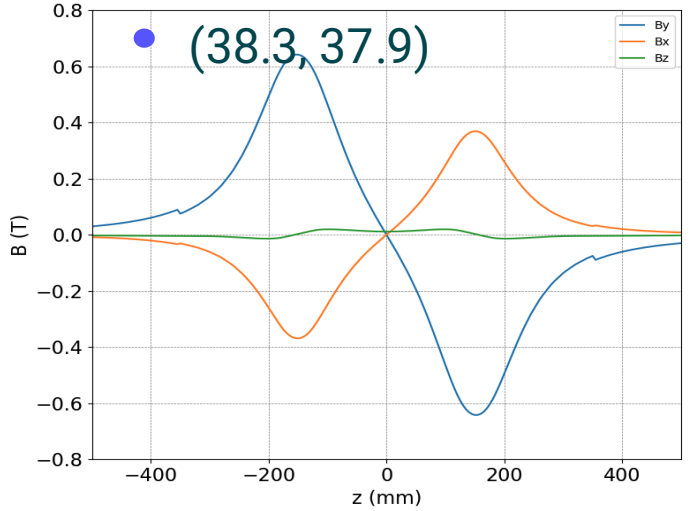




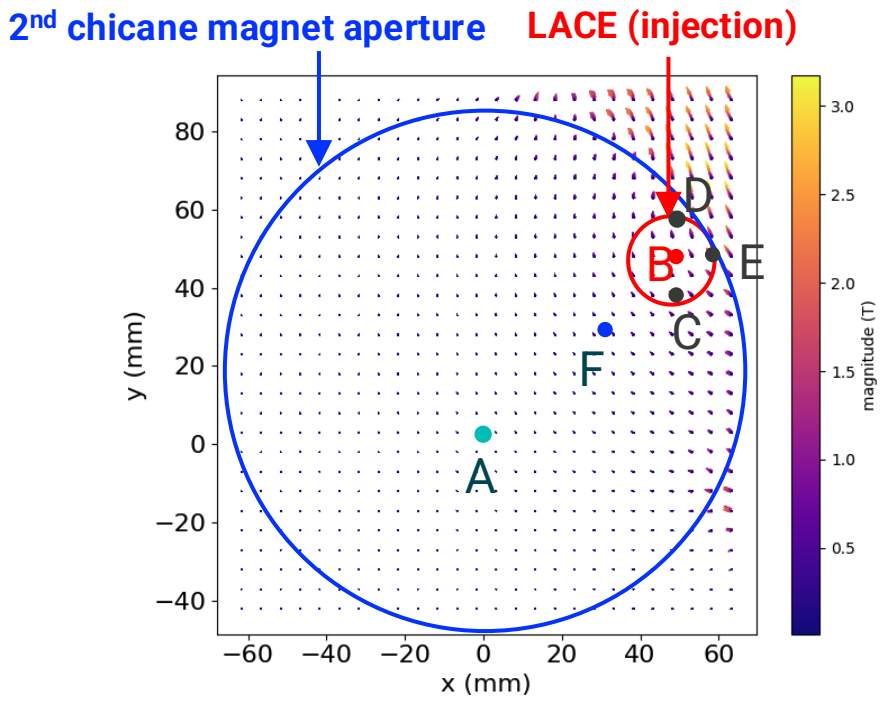








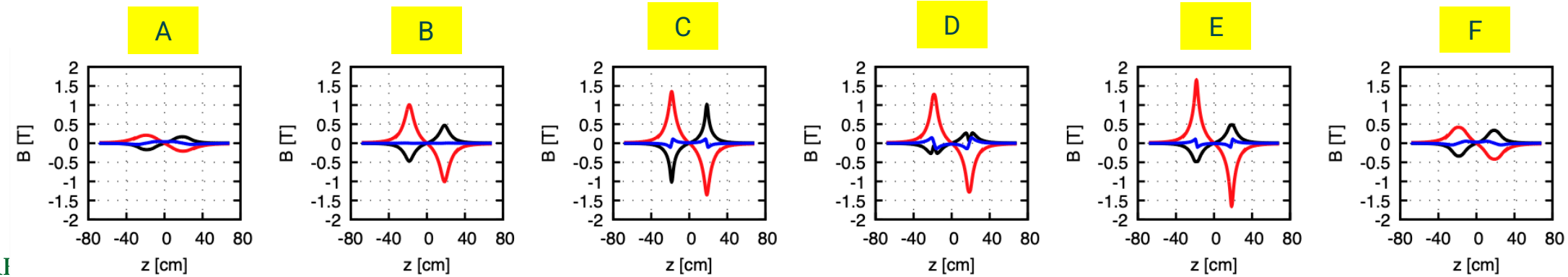
LACE non-uniform magnetic field distribution



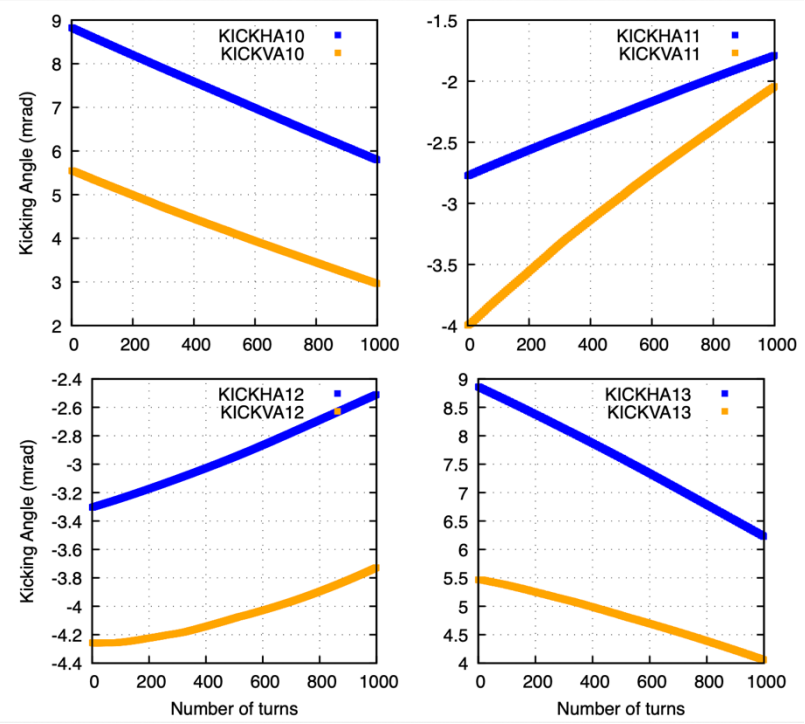
A: ring designed orbit

B: LACE injection point (current foil location)

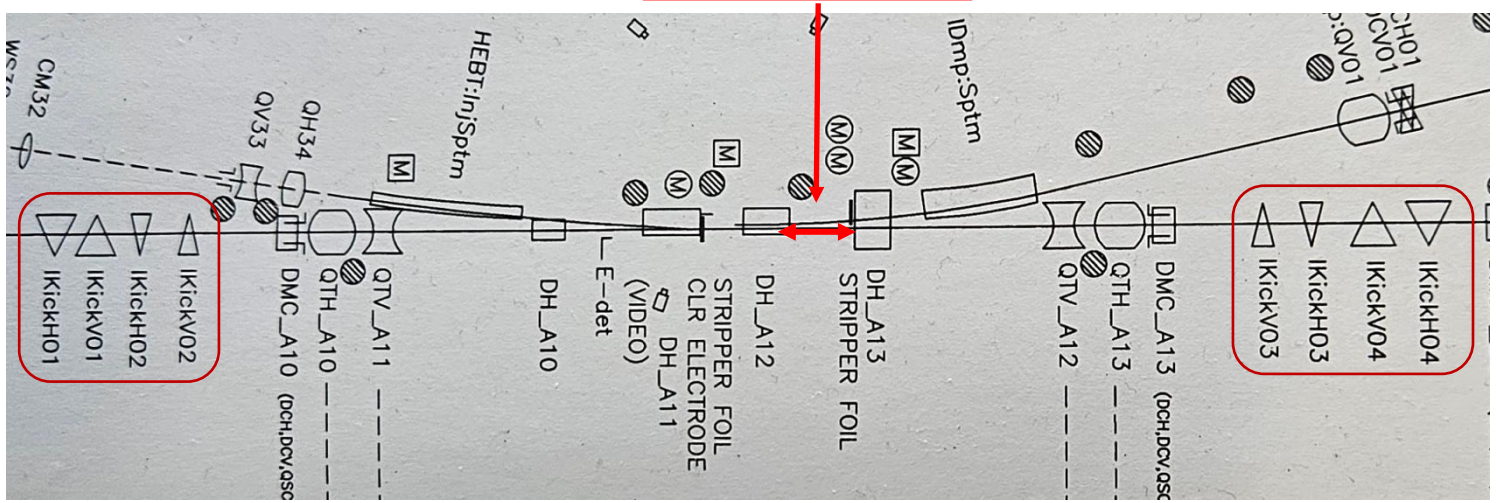
F: ring closed orbit with kickers at the 1st turn

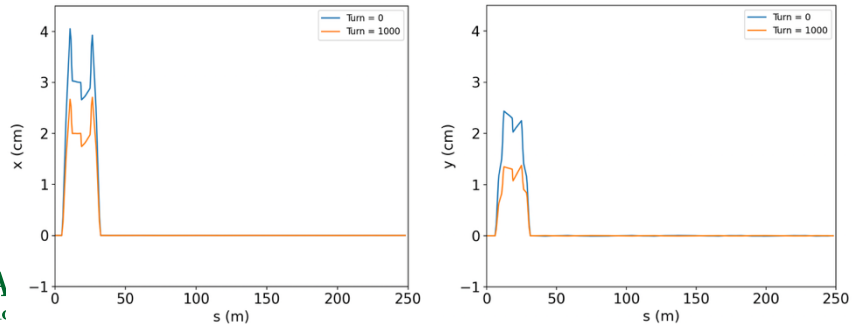


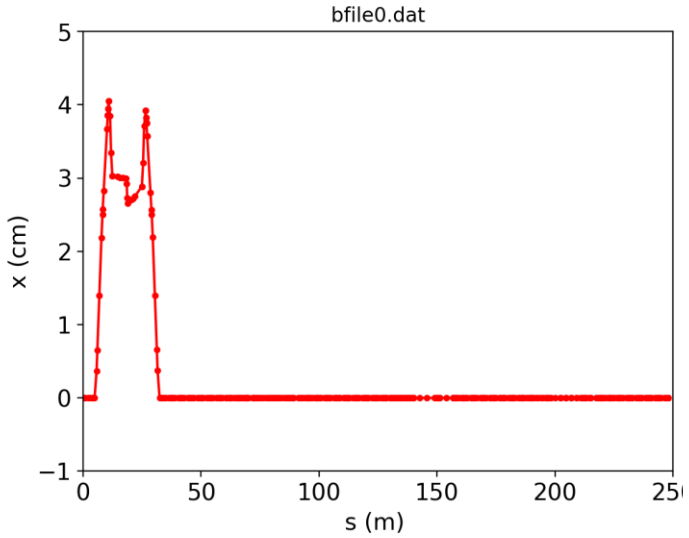
Orbit is corrected with horizonal and vertical 4 bump kickers

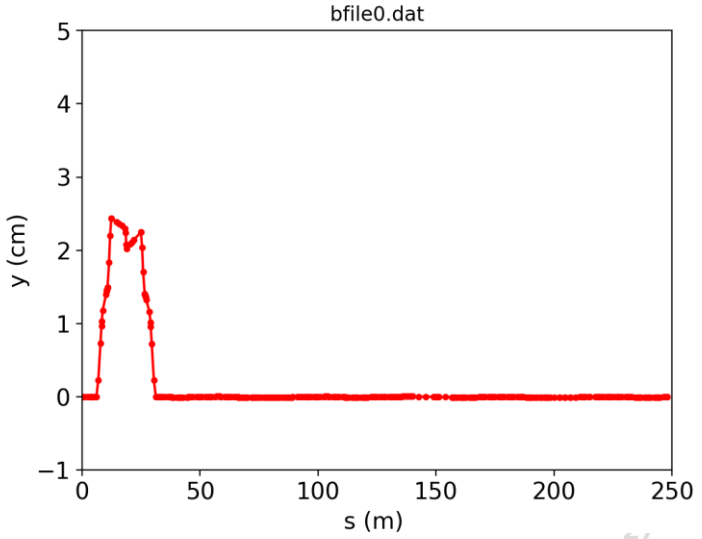


LACE space



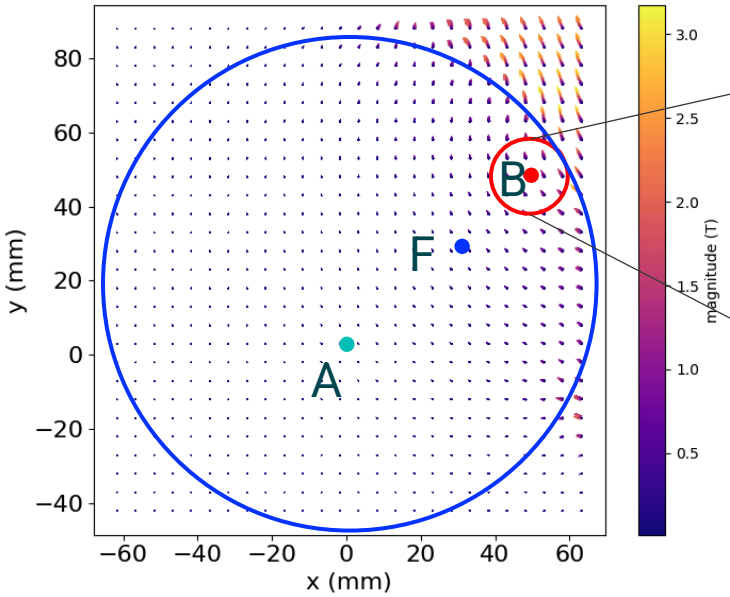


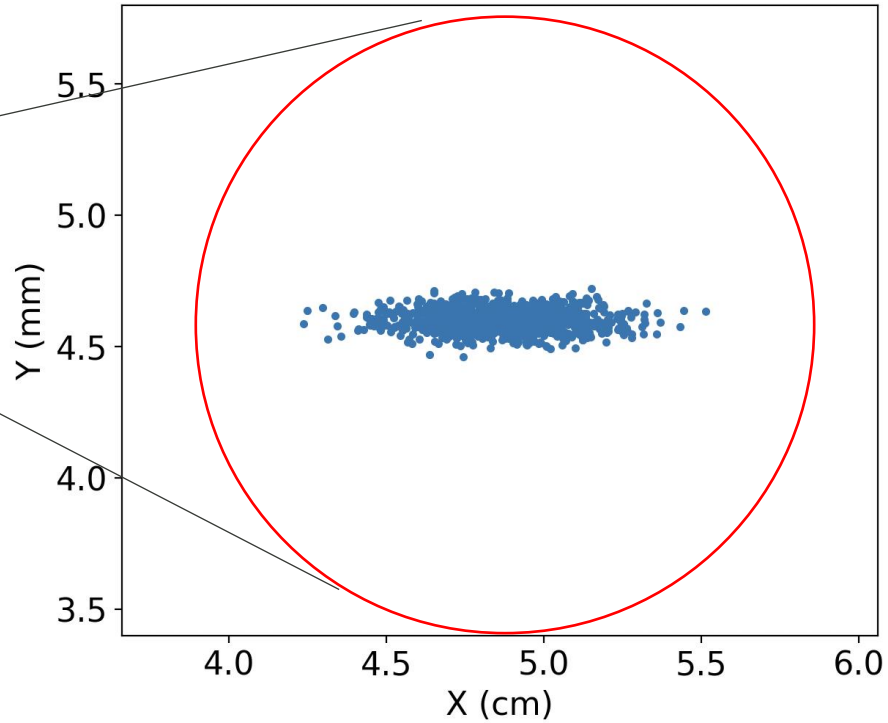


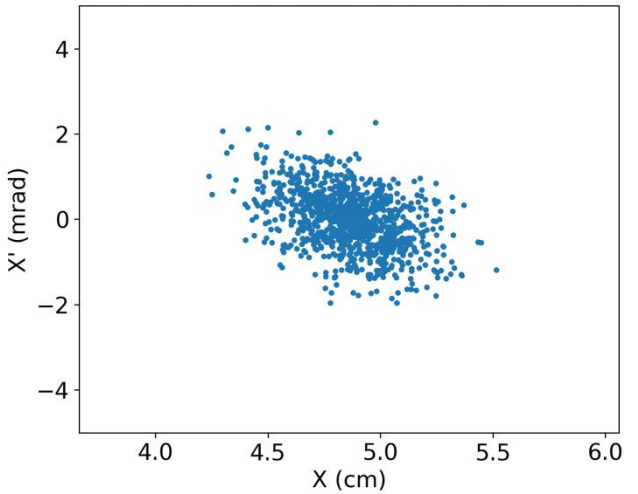


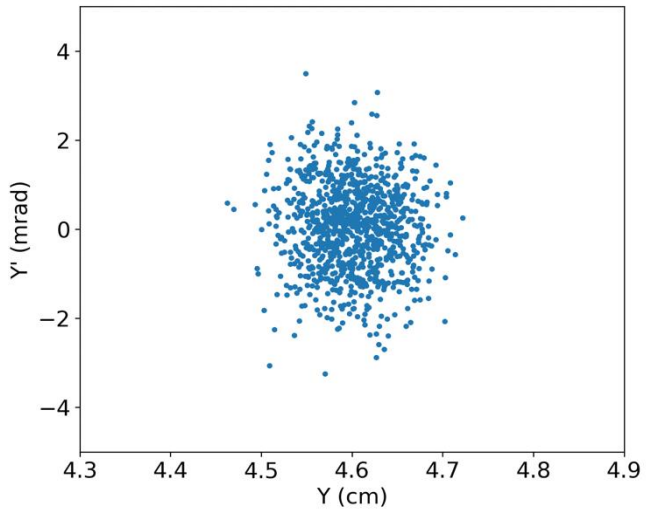
Particles experience significant different high non-linear fields of 1-2 T at the ring injection area

- Beam distributions are from the optimized HEBT optics for LACE and used for Ring Injection Simulations

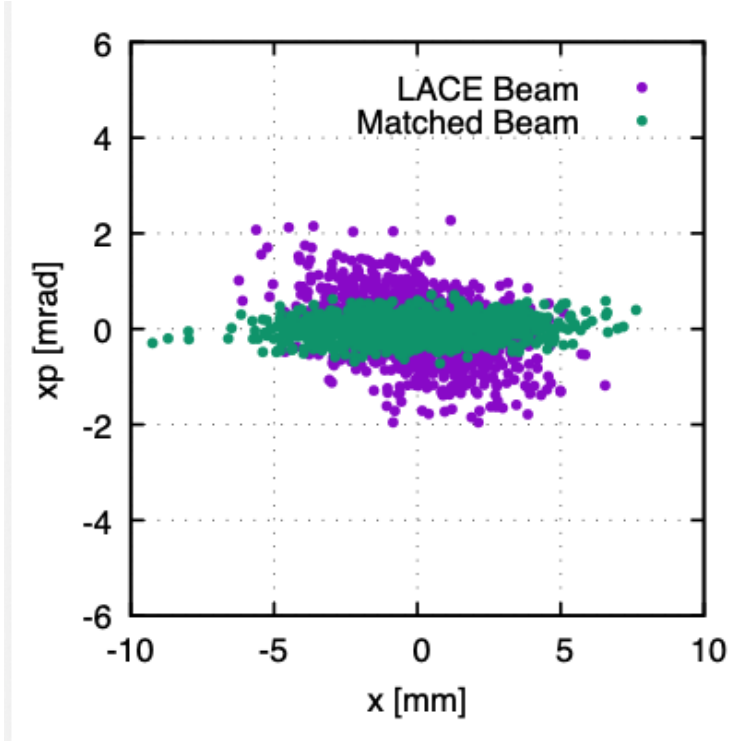


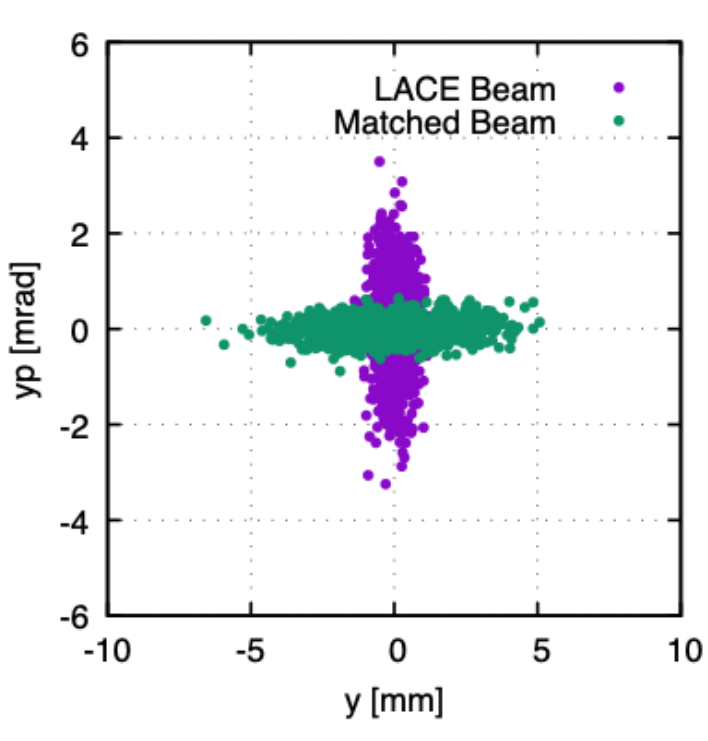


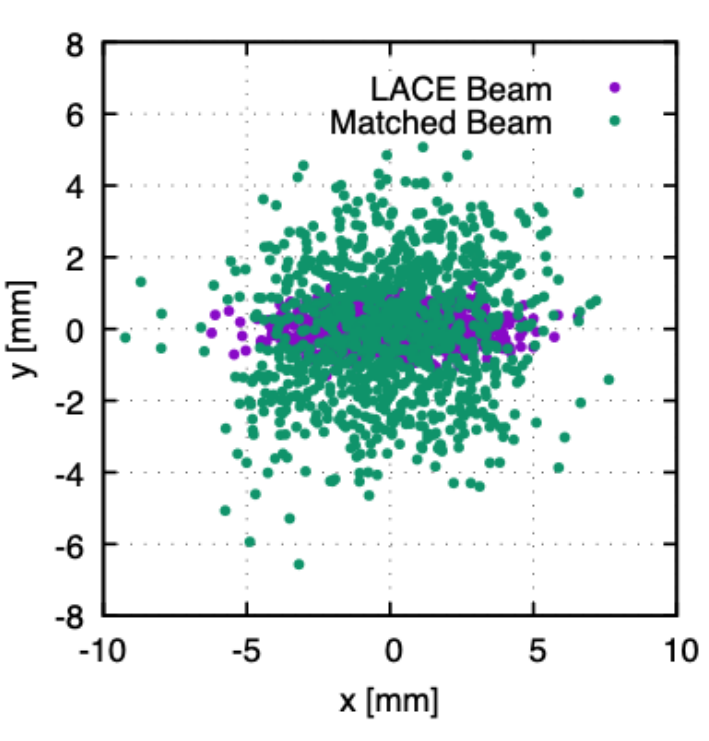




LACE beam vs. Match beam

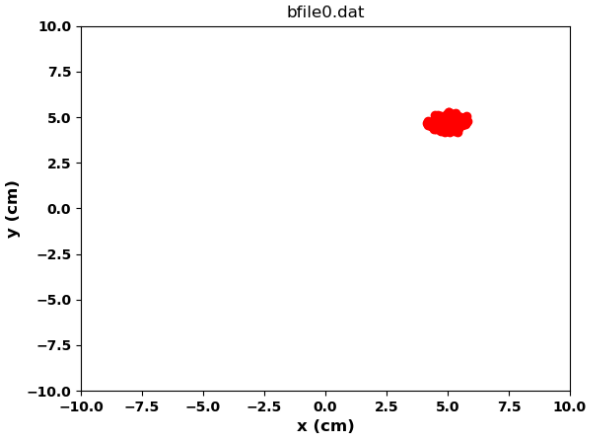


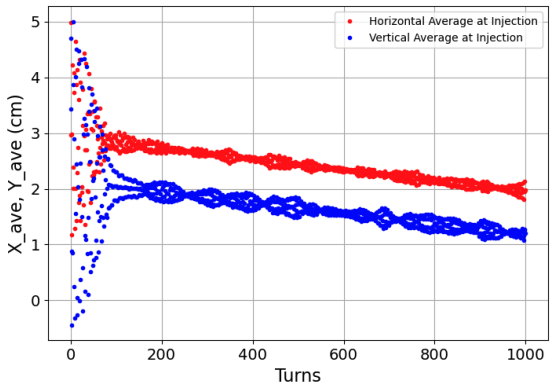




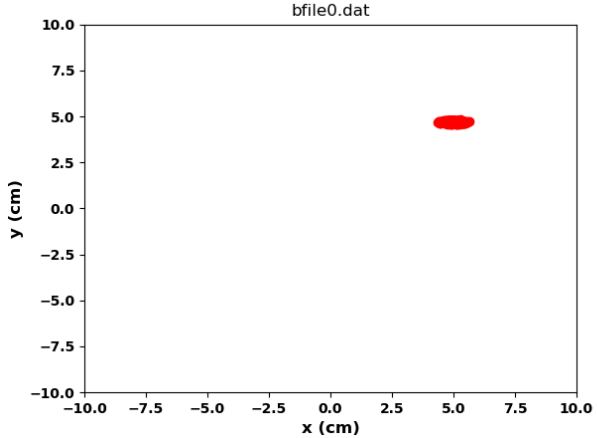
Painting of 1000 particles for 1000 turns w/ injection point at the beginning of LACE fields

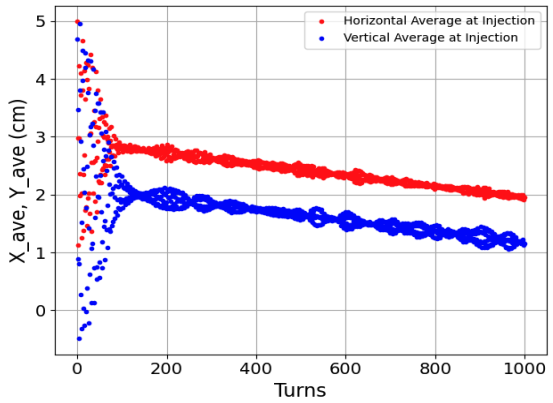
Matched Beam

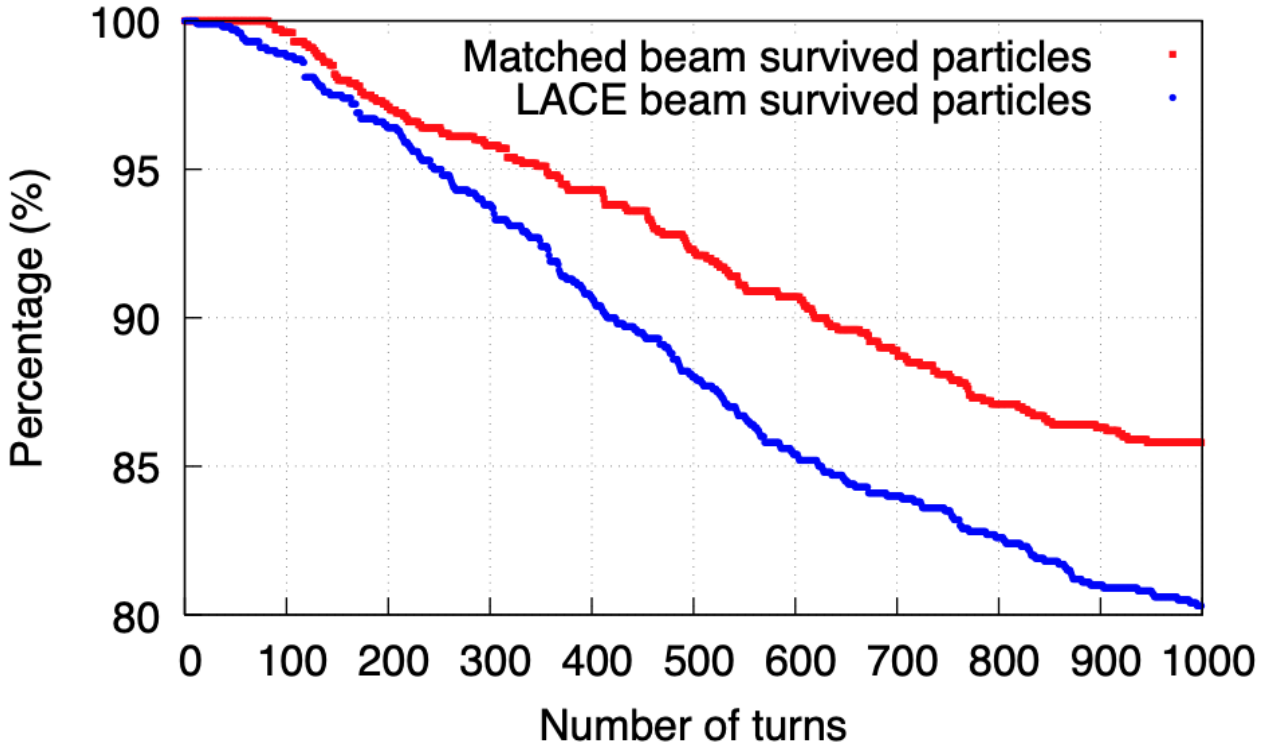




LACE Beam

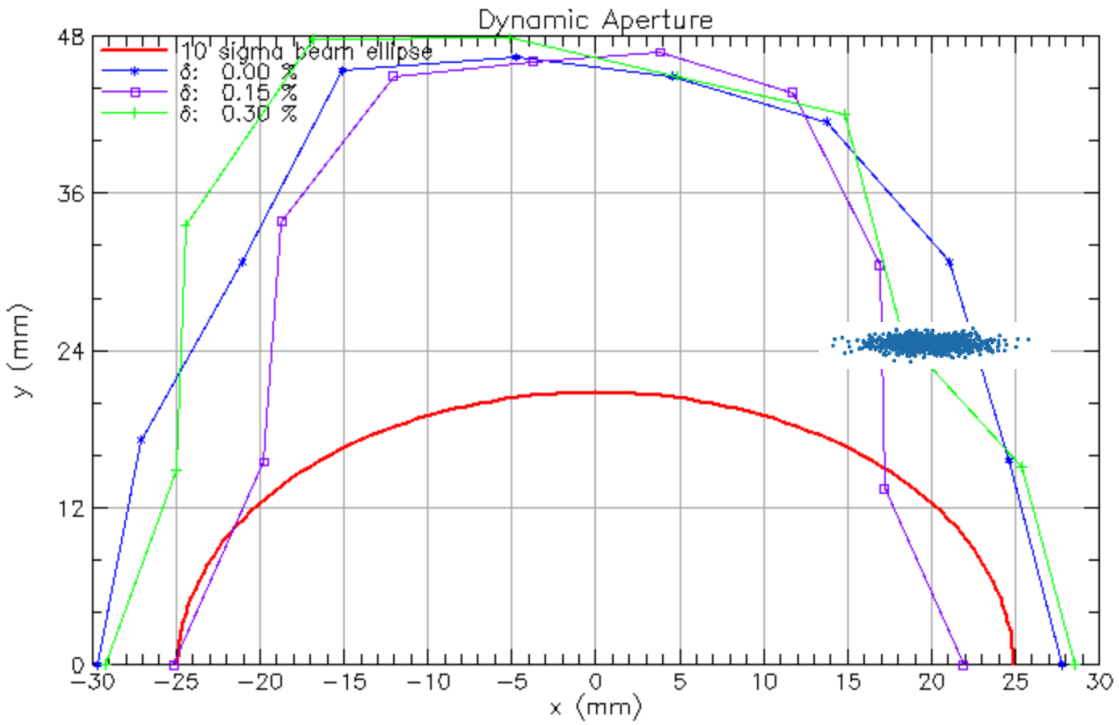


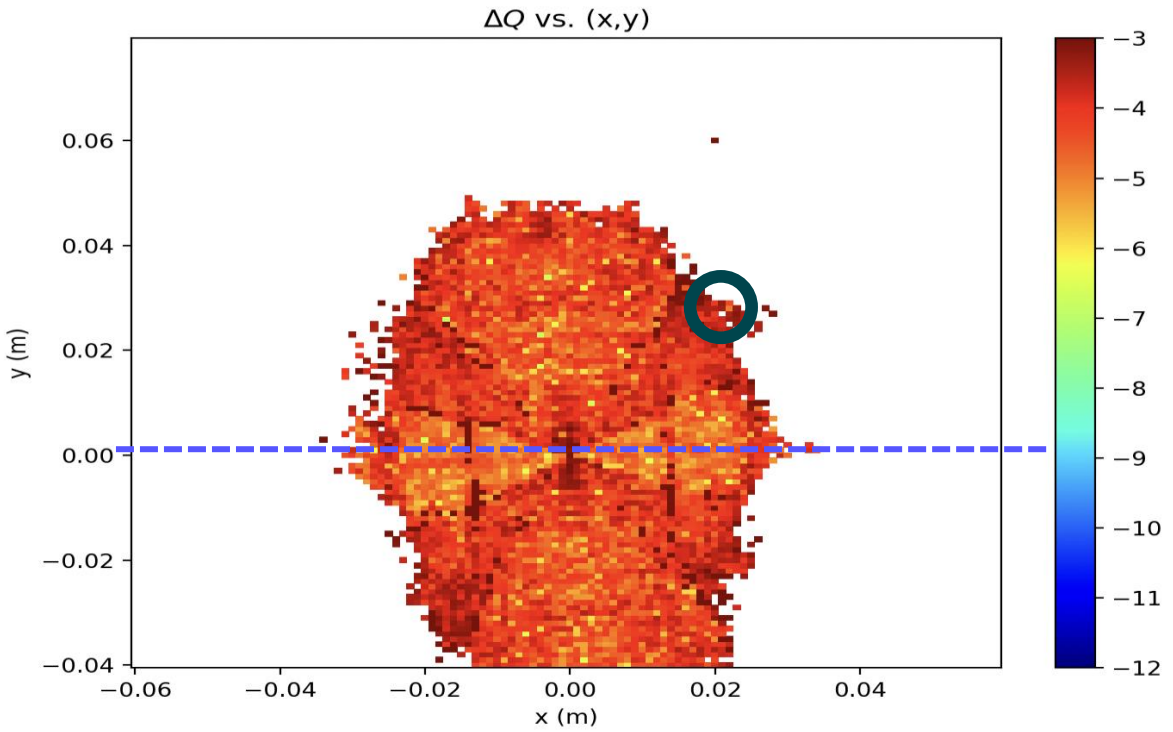




NO apertures applied, LACE and matched beams experience dynamic particle loss (with coordinates greater than ~30 cm set in PyOrbit)

Dynamic Aperture and Frequency Map are used to investigate the LACE magnet induced nonlinearity





Note that, this is the results from BMAD simulations. The kicker strengths were running for the 1st turn injection only.

Outlook

- Goal of this project is to design the LACE injection demonstration system
- Experimental tests of single vs. sequential excitation using the new vessel will provide input optimization of LACE parameters
- Balancing the magnetic field requirements for injection with beam stability in the ring is difficult
- Plan to build and install the LACE injection demonstration in the next 5 years

References

1. V. Danilov, etc., “Three-step H^- charge exchange injection with a narrow-band laser”, PRST-AB, 6, 053501, (2003)
2. V. Danilov, etc., “Proof-of-principle demonstration of high efficiency laser-assisted H^- beam conversion to protons”, PRST-AB, 10, 053501, (2007)
3. S. Cousineau, etc., “First Demonstration of Lase-Assisted Charge Exchange for Microsecond Duration H^- Beams”, PRL, 118, 074801, (2017)
4. A. Aleksandrov, etc., “Experimental demonstration of sequential excitation scheme for H^- laser assisted charge exchange”, PRAB, 26, 043501, (2023)
5. A. Aleksandrov, etc., “A crab-crossing scheme for laser-ion beam applications”, NAPAC2019, WEYBB5, (2019).

Thank you for your attention !