TRIUMF

Canada's national laboratory for particle and nuclear physics and accelerator-based science

RECENT IMPROVEMENTS IN BEAM DELIVERY WITH THE TRIUMF'S 500 MeV CYCLOTRON

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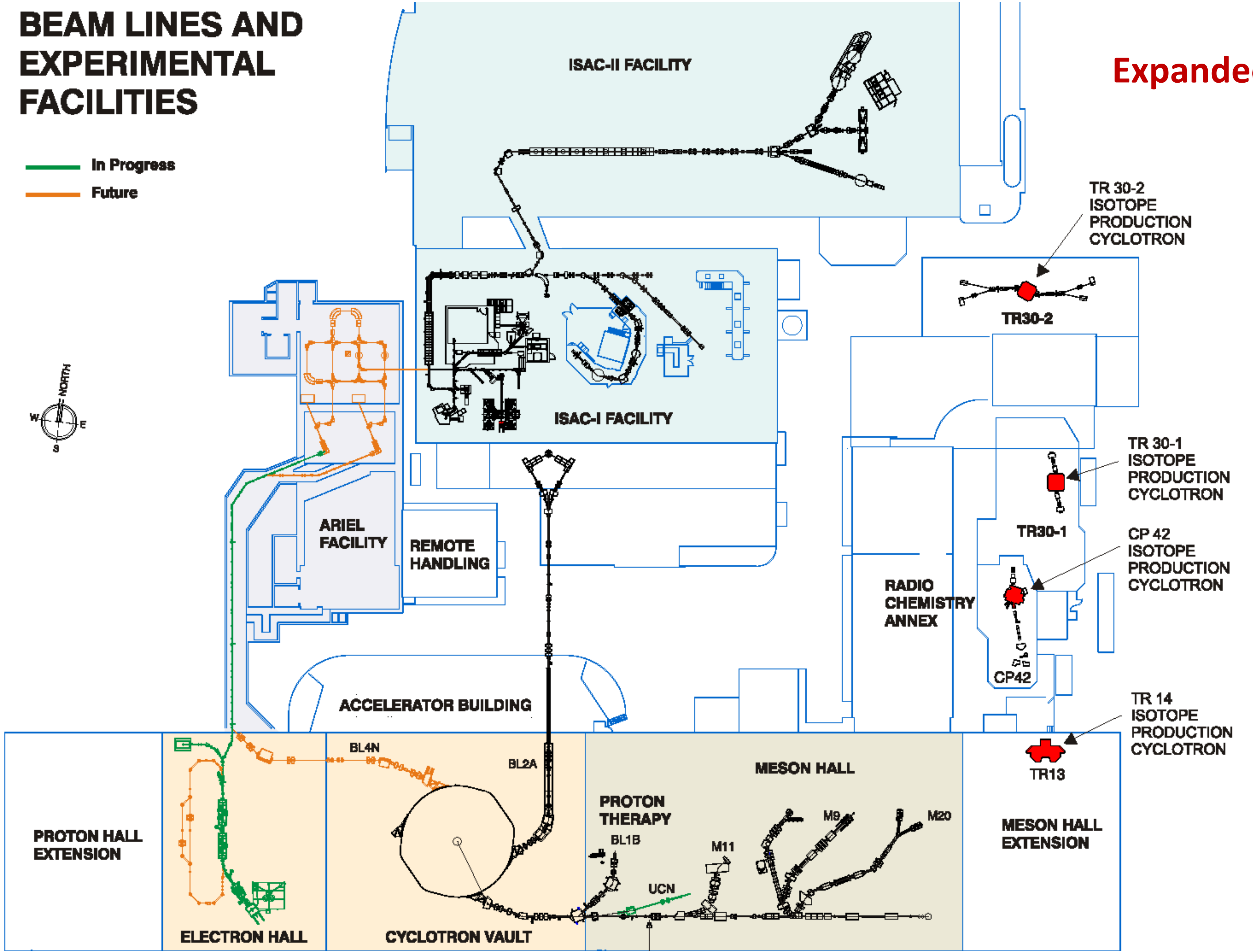
On behalf of the Cyclotron Development Team

Outline

- Introduction
- Ion Source & Injection
- Intensity Stabilization
- Sr-82 Isotopes Production
- Extraction Foils
- Beam Losses
- Beam Rastering
- Outlook

TRIUMF Facilities Layout



Expanded RIB – TRIUMF's flagship program

Three simultaneous beams

- increased number of hours delivered per year
- new beam species
- increased beam
- development capabilities

ARIEL-I (complete)

- Electron linac
- Buildings

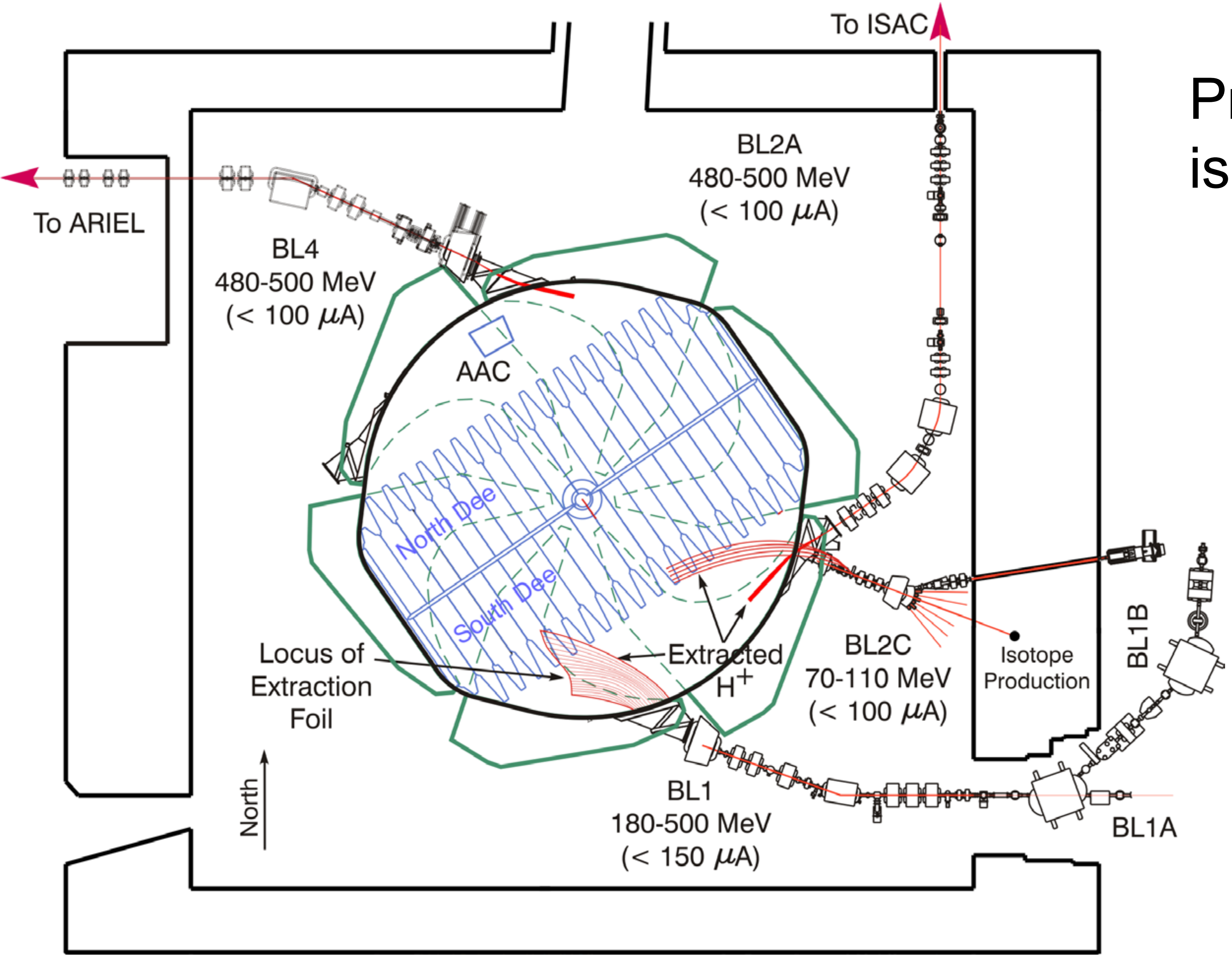
ARIEL-II (2016-2021)

- Beta-NMR
- Photo-fission
- CANREB
- BL4N
- High Power Photo-fission

3 Simultaneous Proton Beams:

BL1A: 120 µA @ 480 MeV or	Molecular & Materials Science, µSR
BL1B: few nA @ 200-480MeV	Proton & Neutron Irradiations
BL2A: 100 µA @ 480 MeV	ISAC (Nuclear & Astro-physics)
BL2C4: 100 µA @ 100 MeV or	Medical Isotopes (Sr-82)
BL2C1: few nA @ 116 MeV or	Proton & Neutron Irradiations
BL2C1: few pA @ 70 MeV	Proton Therapy (Ocular Melanoma)

Cyclotron High Intensity Capability



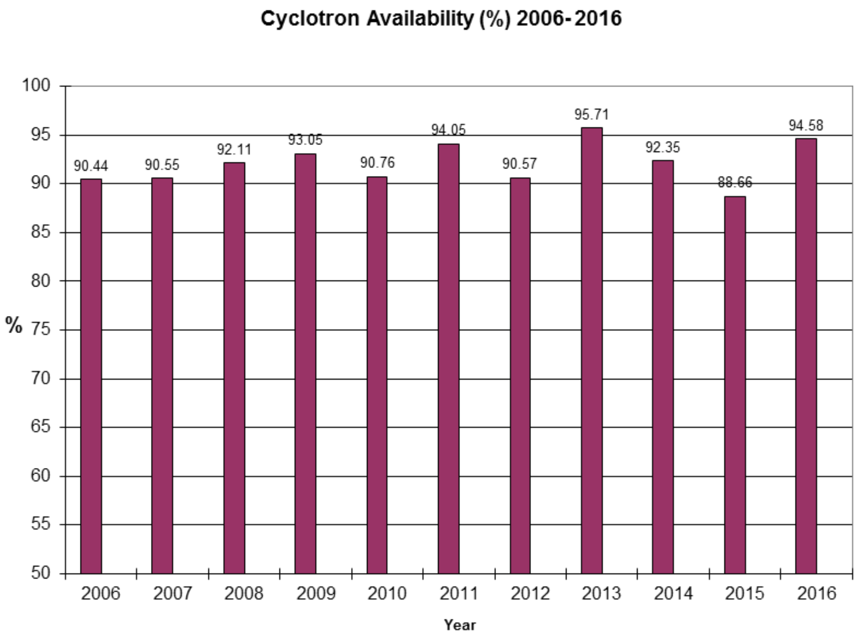
Present stable performance is limited to 300 μA

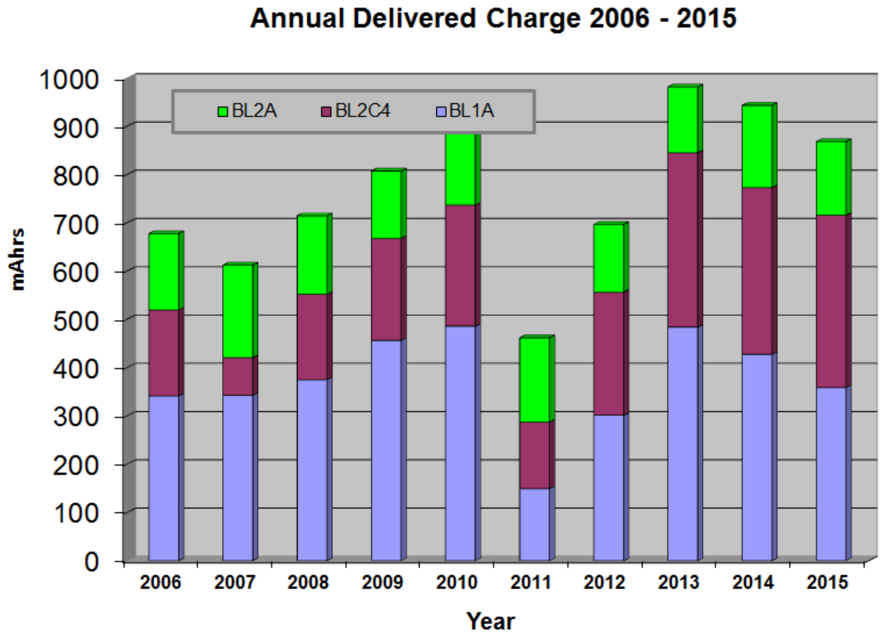
BL Capacity	Routine
• BL1A (150μA)	(120μA)
• BL2A (100μA)	(70μA)
• BL2C (100μA)	(95μA)

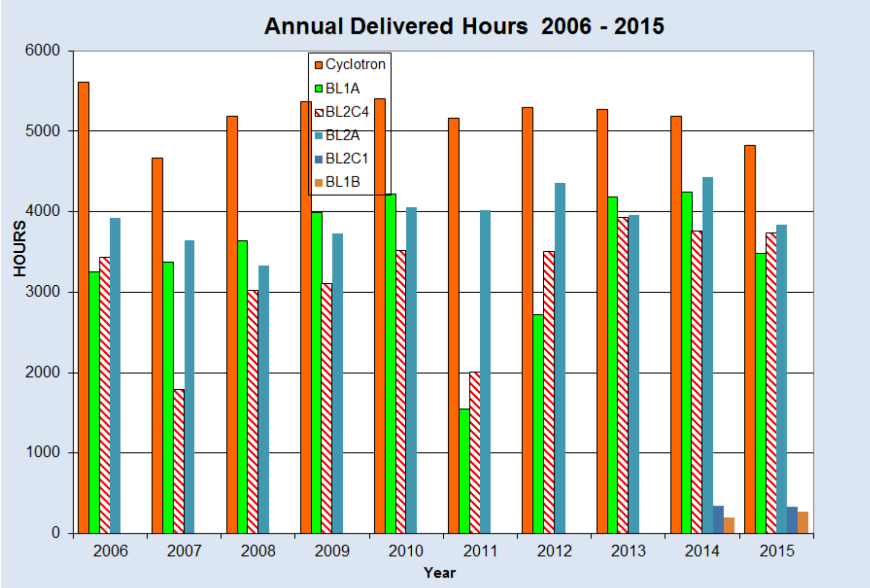
Future

BL4N (100μA)	TBD

Cyclotron Annual Performance: – 10 years





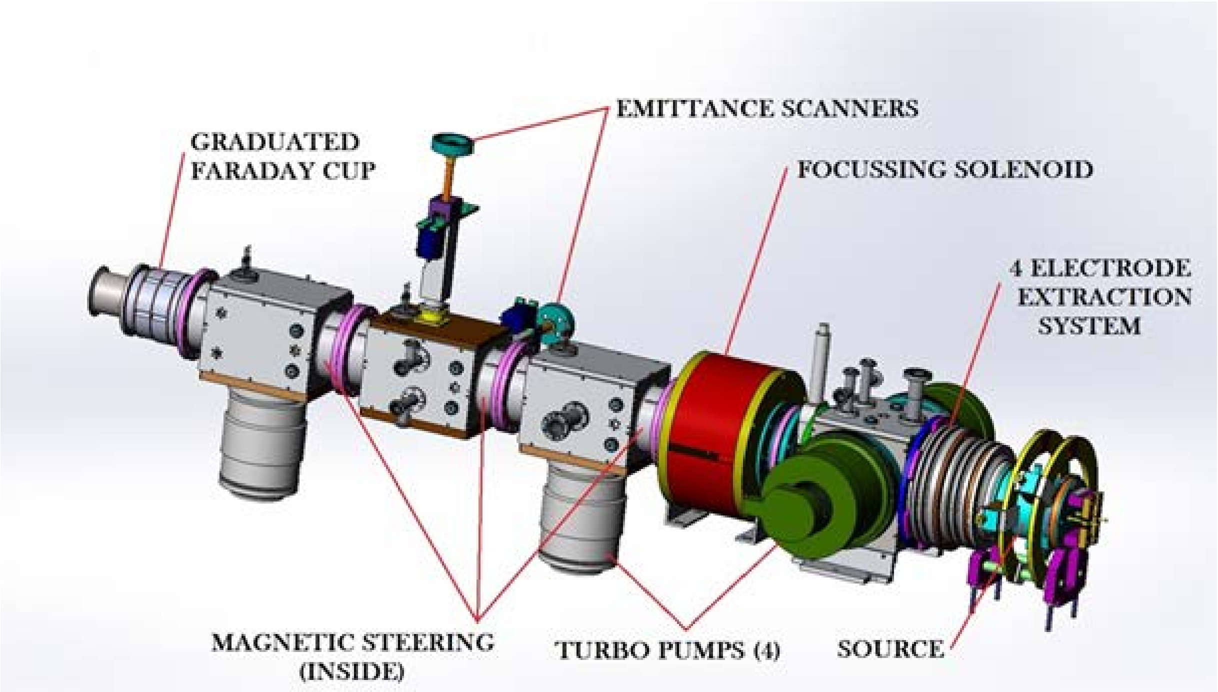


Availability – 5000+ hours
Reliability – 90%
Charge – 900 mA·hours

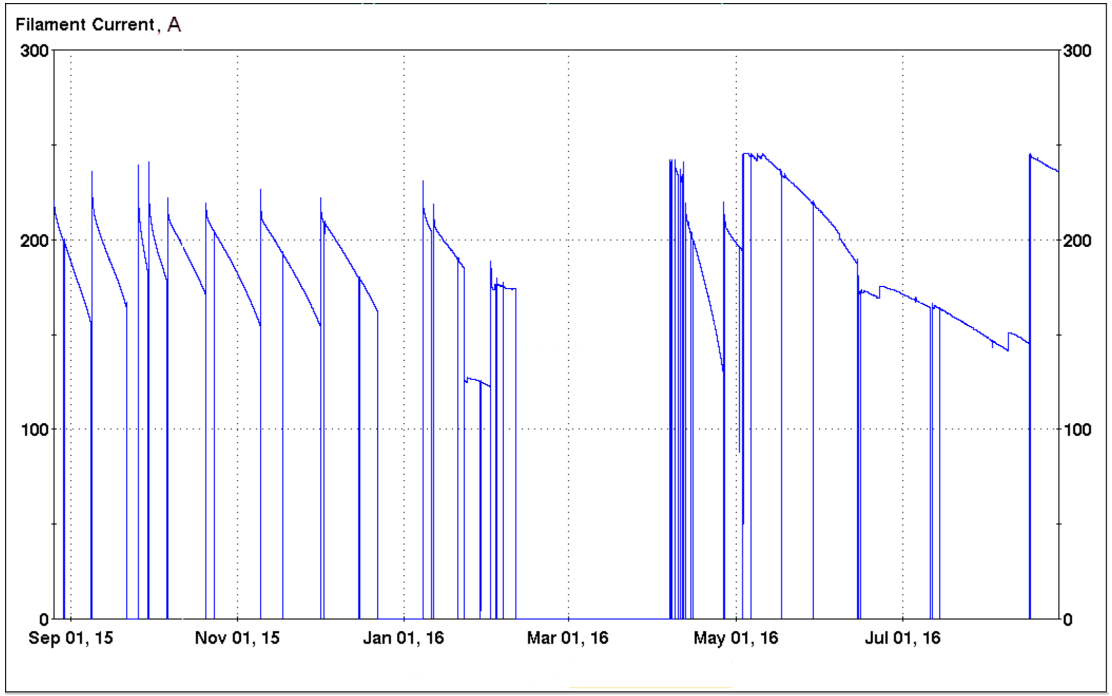
Motivation for Upgrades

- Increase reliability (>90%)
- Increase uptime (>5500 hours/year)
- Increase total intensity to 400 μA
- Increase beam stability
- Reduce beam interruptions (<50 per week)
- Reduce activation and contamination
- Reduce maintenance overhead

- Powerful and versatile H- source test stand established for hardware and beam studies:
  - Filament lifetime studies: 3 weeks => 4 months
  - High performance demonstration: 25 mA cw
  - New efficient source development for 500 MeV cyclotron (1 mA in 2 mrad·mm)
- Future: New operational source will be installed in the spare HV terminal

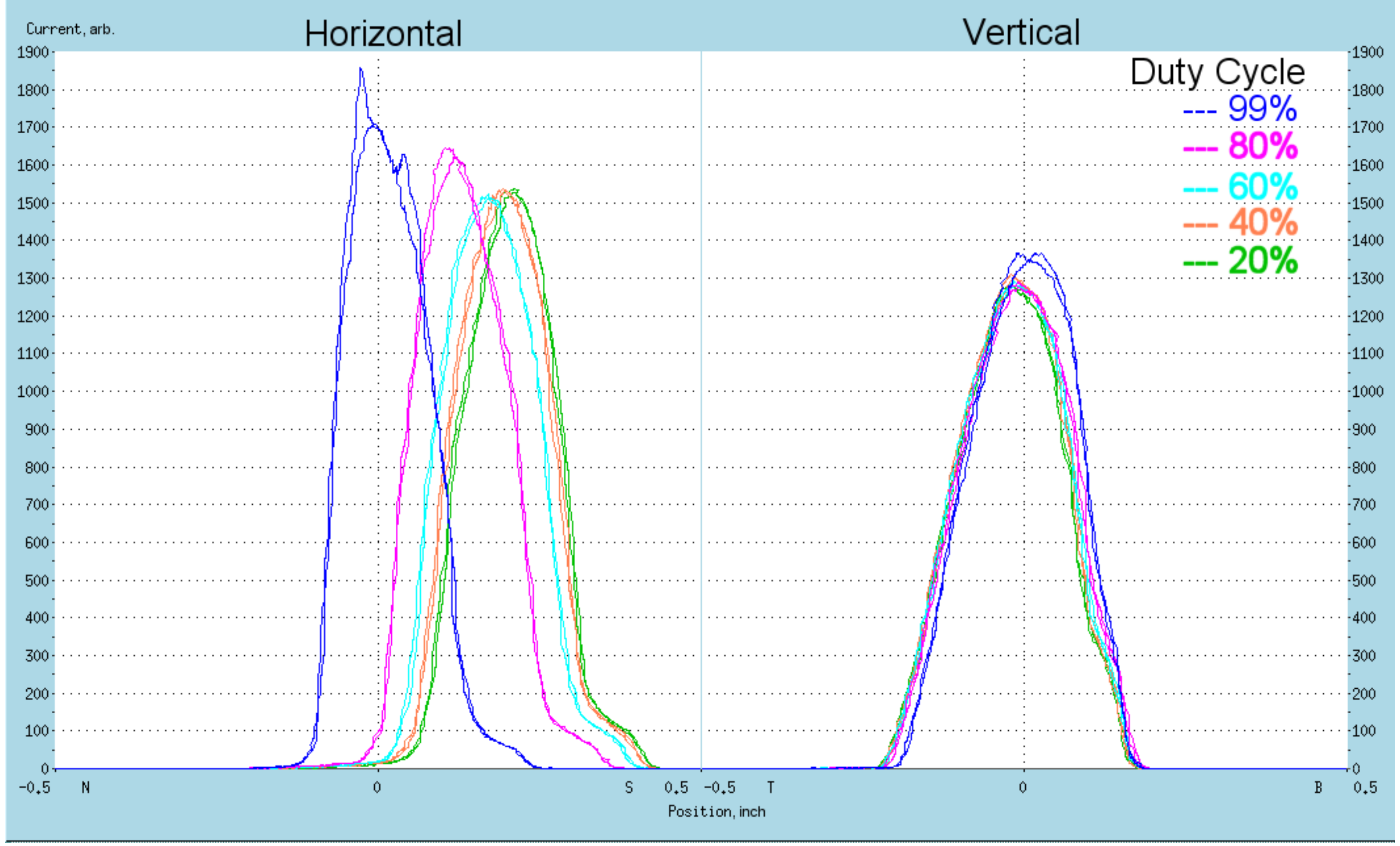


Source test stand components



Source filament current evolution

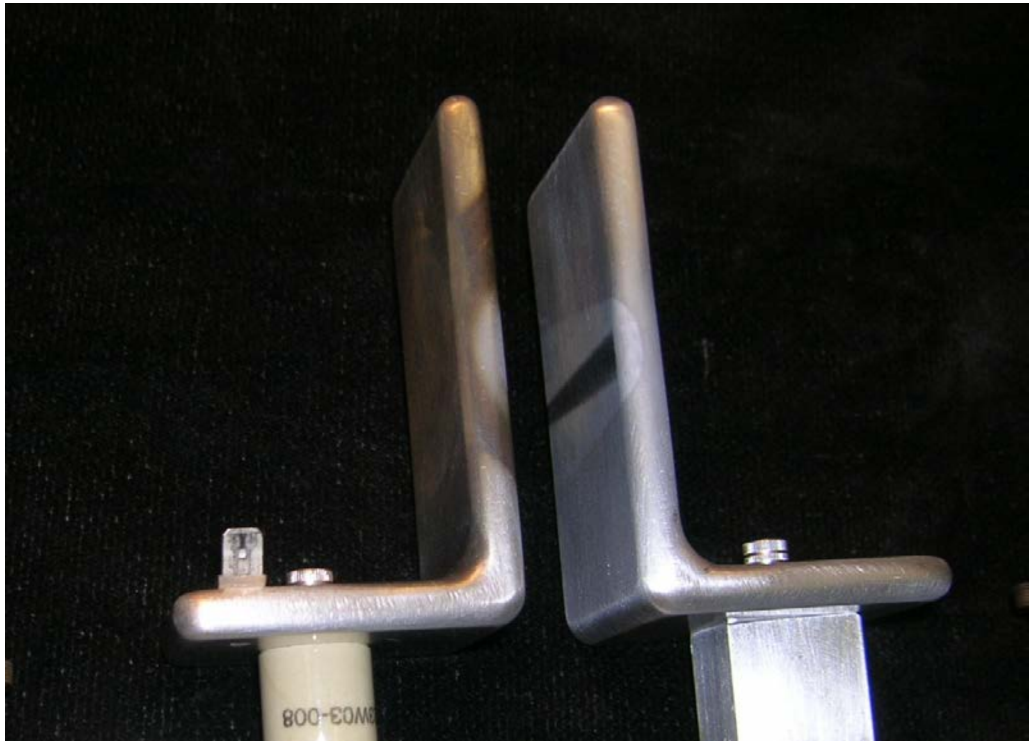
Source Instability



Issue: Strong dependence of beam steering at the output of the optics box on beam pulser setting (duty cycle)

Reason: Insulating coating layer on the electrostatic steering plate charged by beam provided deflecting field

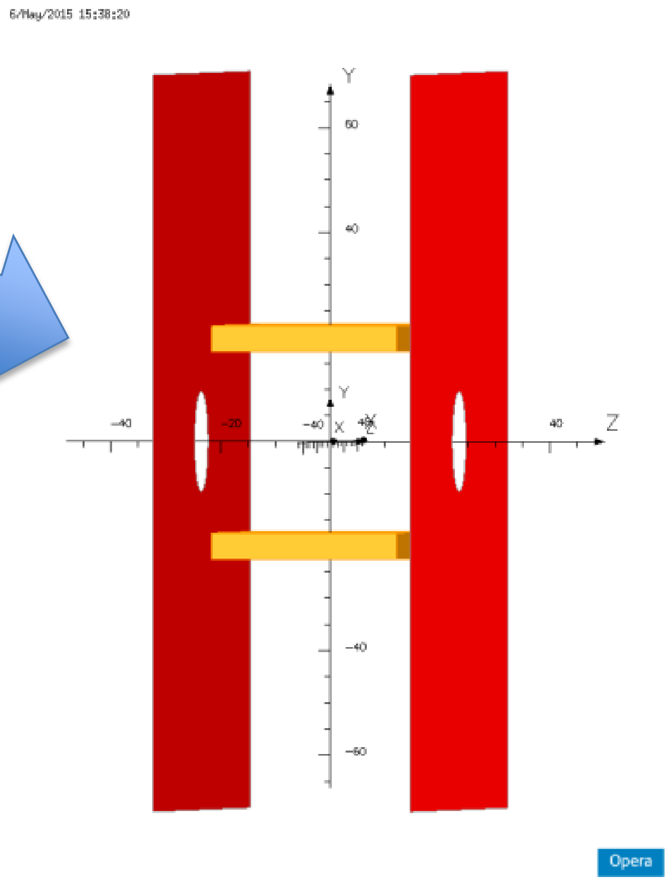
Resolution: Aluminium steering plates replaced with stainless steel plates



Beam Distortion in the Source Optics Box

Pulser dump Horizontal steerer Vertical steerer

Issue: Beam asymmetry out of acceleration column



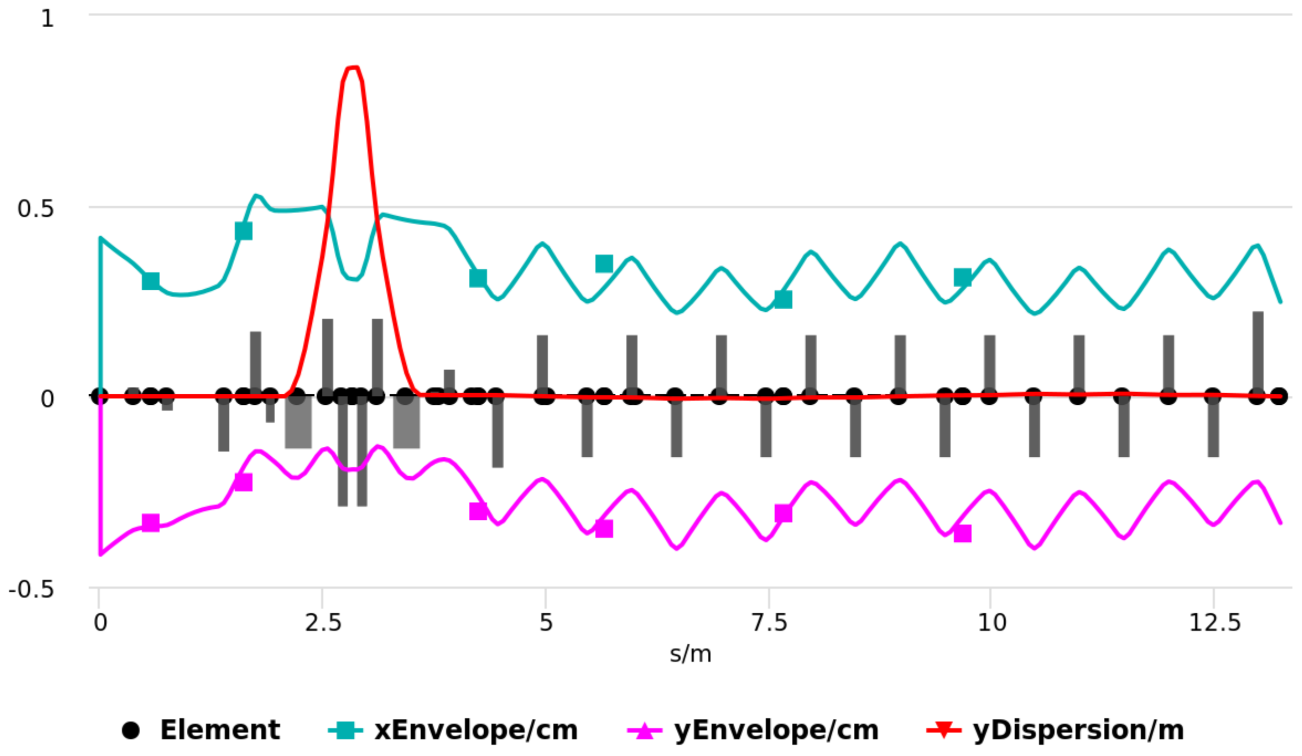
OPERA model of electrostatic steerer

Reason: Circular apertures with biased parallel plates act as a quadrupole

Resolution:

- Include field maps into simulations **or**
- balance opposite polarity bias on the plates **or**
- make rectangular slot apertures

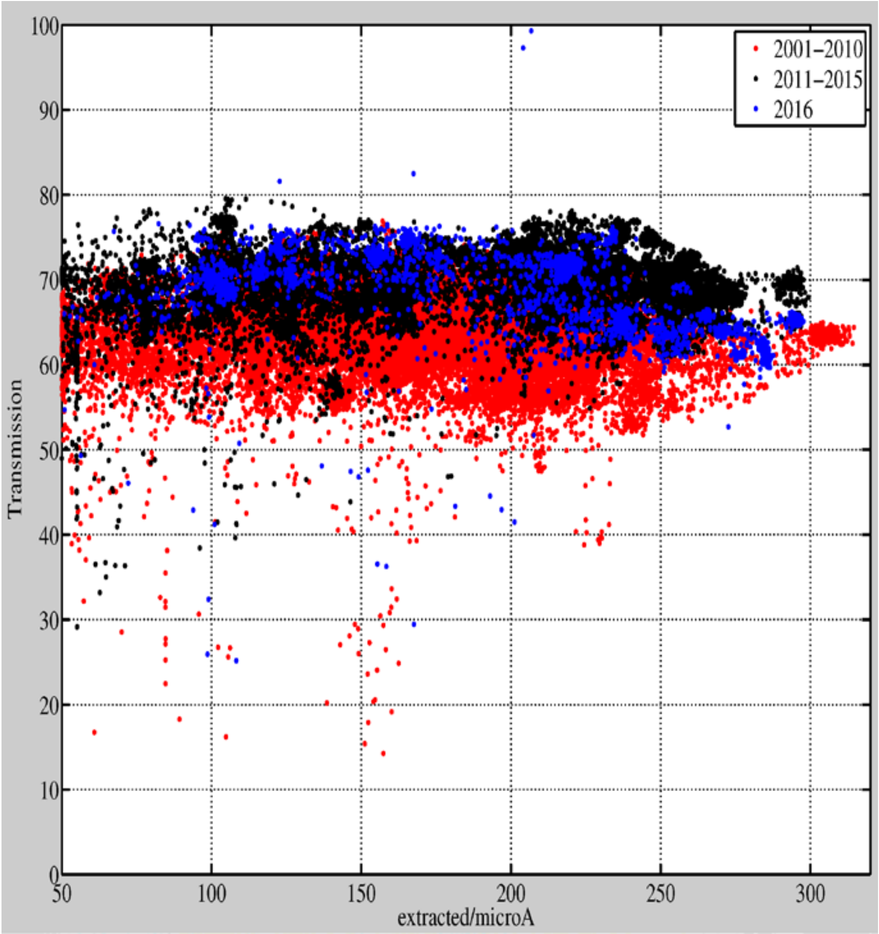
Injection Beam Transport Modelling

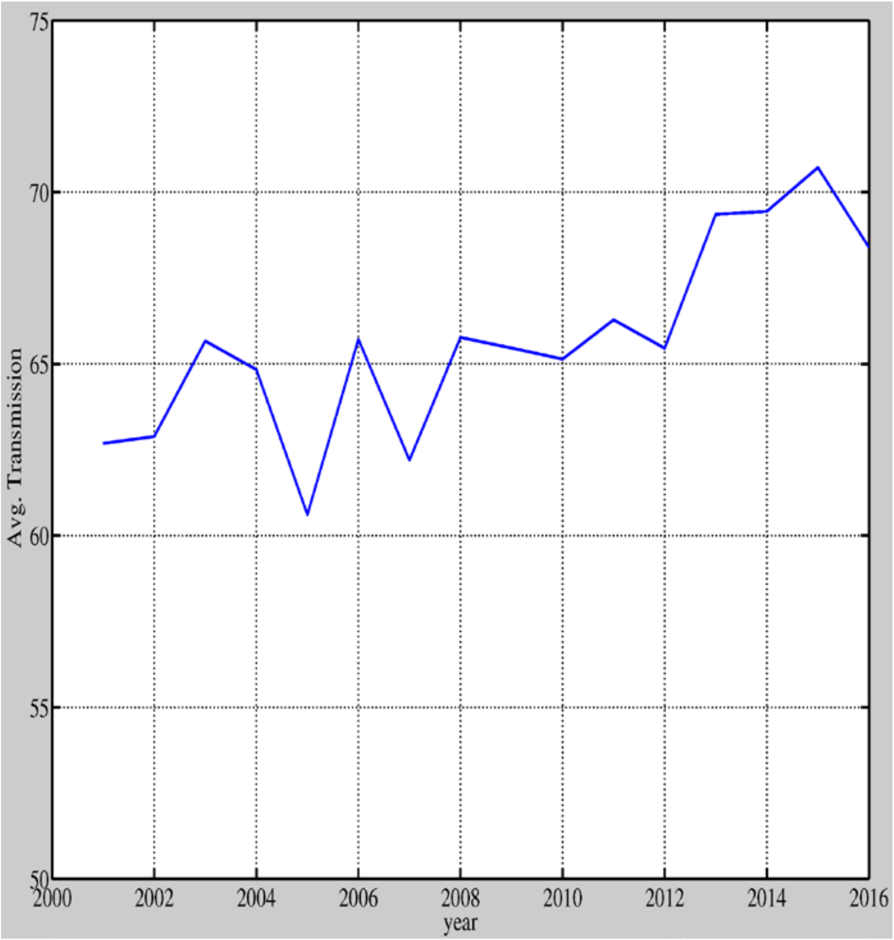


Beam envelope from H- source to buncher
Squares represent measured beam size (2 rms)

- Electrostatic steerer quadrupole effects were removed
- Accurate model of beam optics from source to cyclotron was validated
- Good matching achieved
- High Level Application (HLA) of injection line was created and passed on to operations – first at TRIUMF!

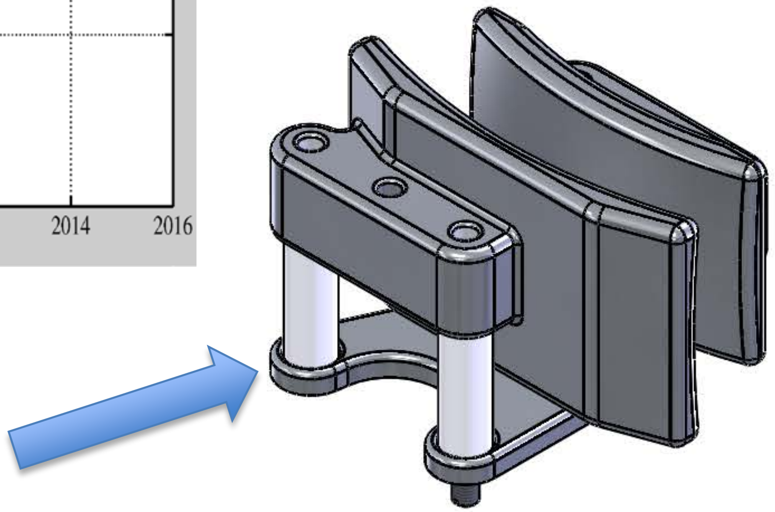
Cyclotron Transmission





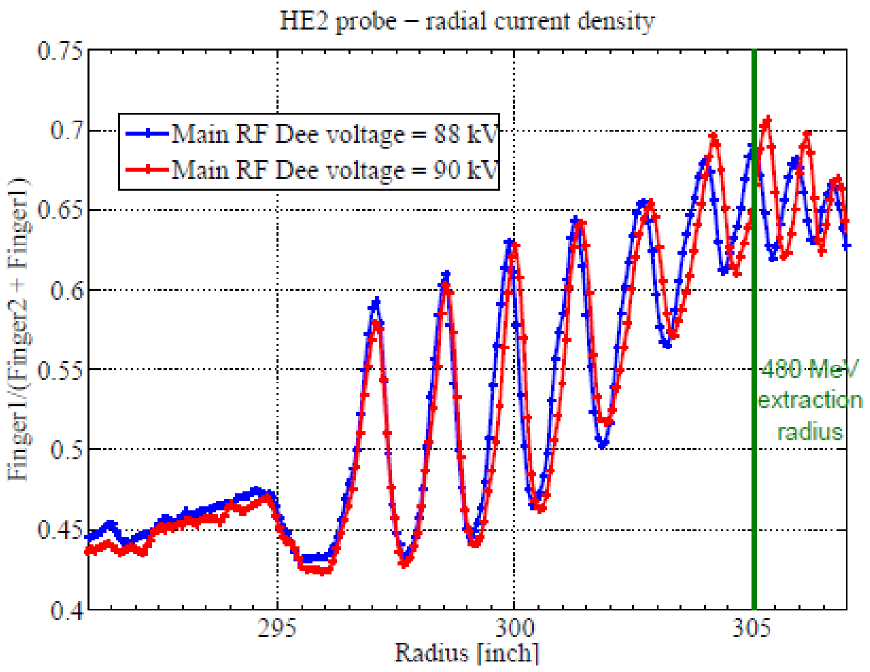
Cyclotron transmission is 70-75%; increased by ~5%:

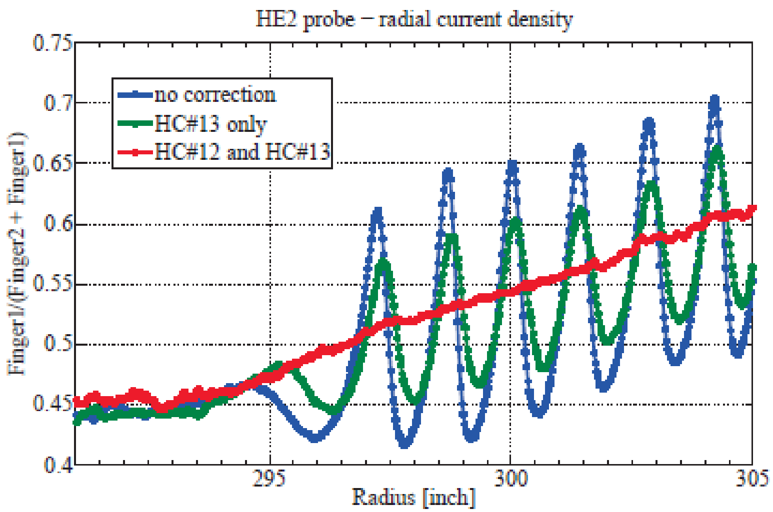
- New 12 m section of injection line (better matching to cyclotron)
- Curved electrostatic deflector at injection (added vertical focusing)

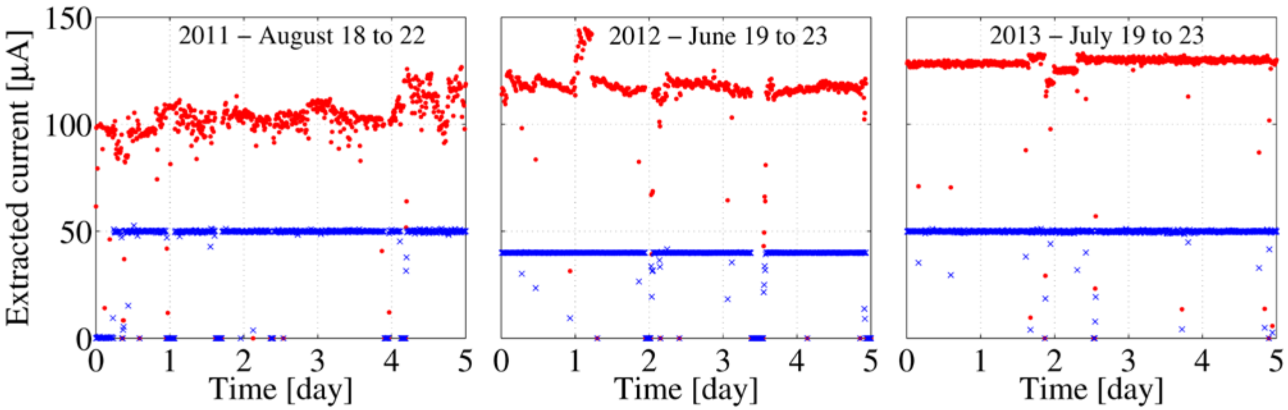


Intensity Stabilization – Phase 1

- 3 high intensity beams extracted simultaneously
- **Issue:** Intensity instabilities in all beamlines
- **Reason:** BL1A / BL2A split ratio variation caused by radial beam density oscillation induced by the ν_r = 3/2 resonance at the energy 428 MeV [3, 4] due to residual 3-rd harmonic of the cyclotron magnetic field
- **Mitigation:**
  - Pulser modulated duty cycle feedback on BL2A intensity
  - 3-rd harmonic compensation with harmonic coils 12 and 13
  - Active feedback on radial beam position by regulating 1-st harmonic component with harmonic coil 12
- **Outcome:**
  - Intensity instabilities in BL1A and BL2A within +/- 1% **- solved!**
  - Intensity instabilities in BL2C +/- 5% **- still a problem**

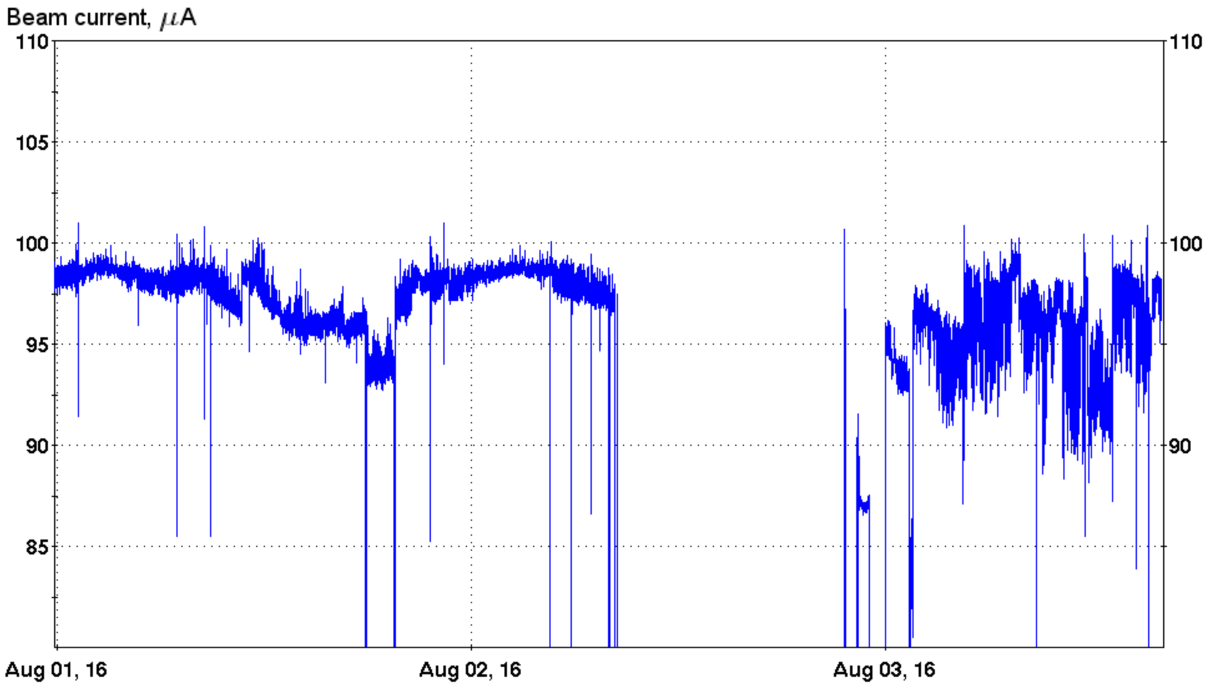




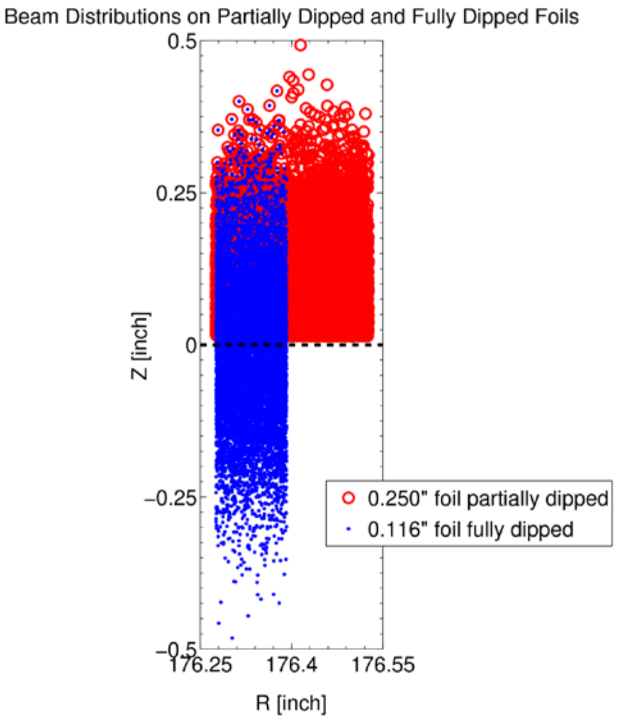


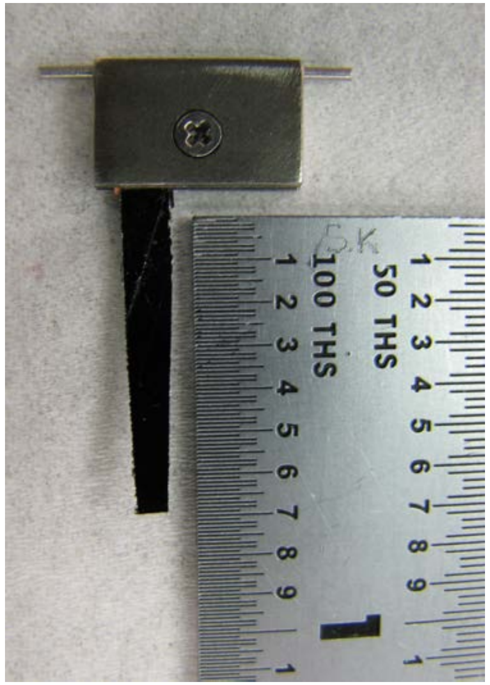
Intensity Stabilization – Phase 2

- **Remained issue:** Intensity instabilities in BL2C (+/- 5%)
- **Reason:** Not understood yet
- **Observation:** With vertical mis-steering at injection there is vertical size/position fluctuation, causing variation of extracted beam at 100 MeV with partially dipped foil
- **Mitigation:** Extraction by a narrower foil fully dipped through the beam
- **Outcome:** Fast intensity instabilities in BL2C reduced down to +/- 1%



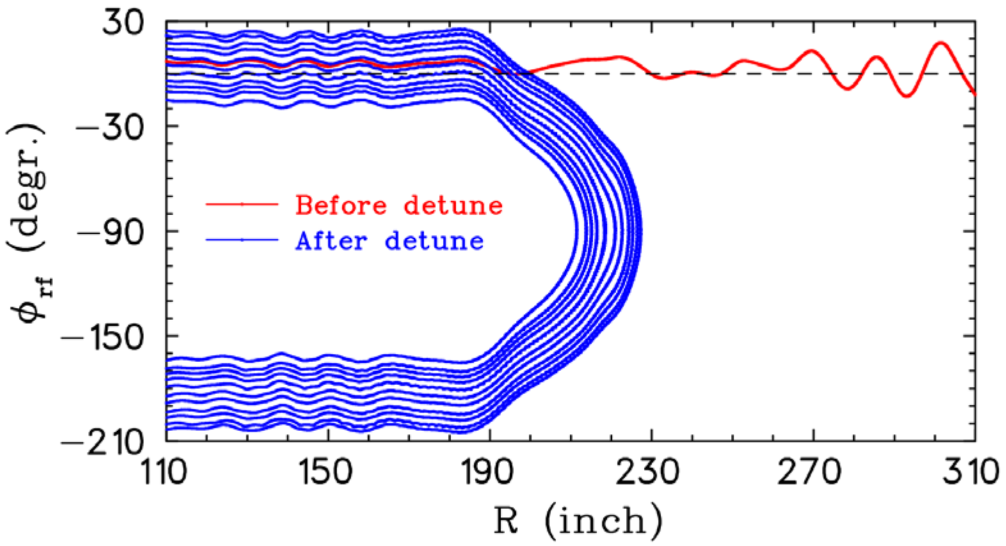
BL2C4 extracted current: left part - extraction with fully dipped foil; right part - with partially dipped foil

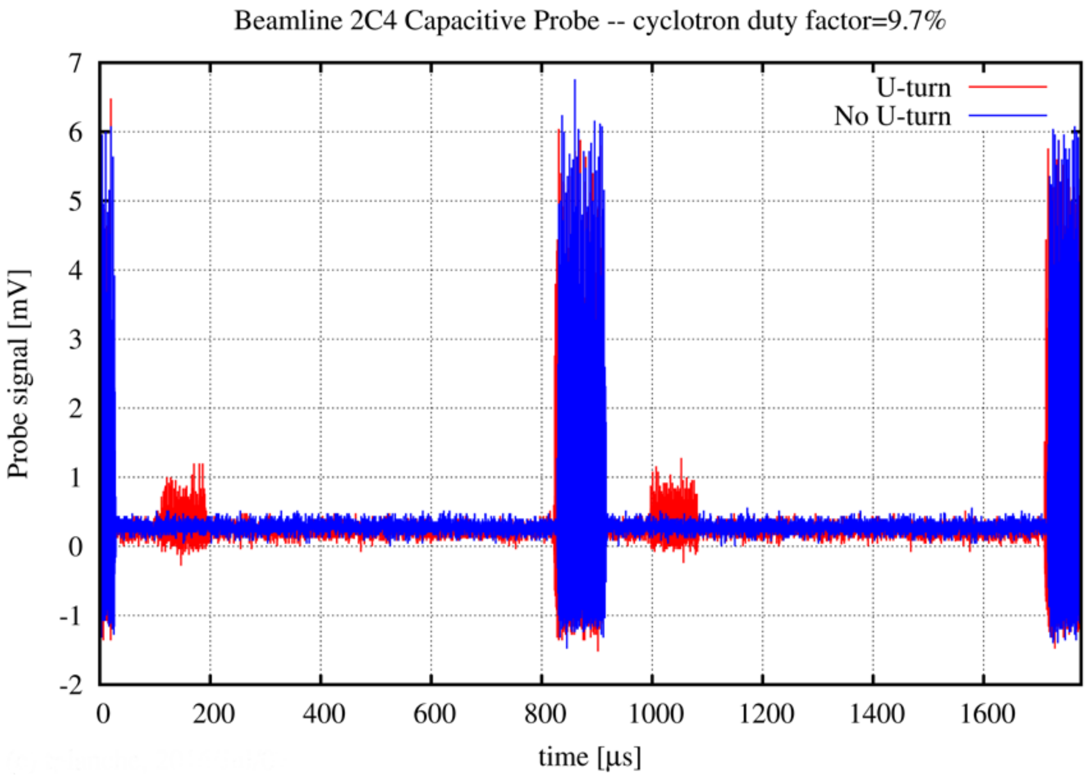




In 2013 Sr-82 Production Facility upgraded to 100 µA of protons

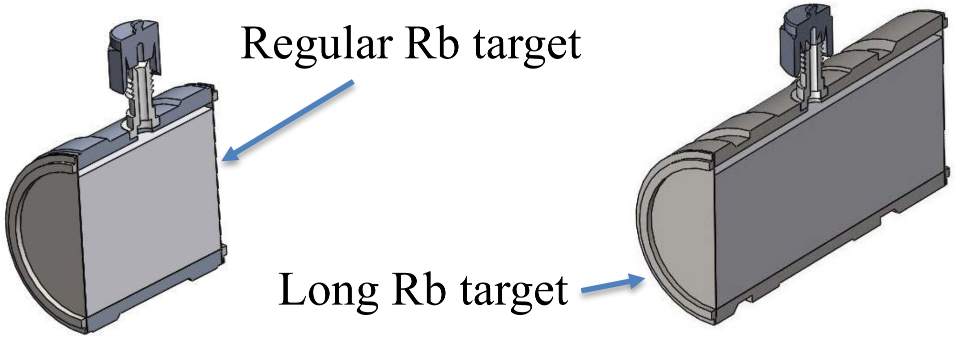
- **Need:** To run BL2C4 in a single user mode
- **Problem:** ~2% of beam bypassing widest extraction foil
- **Solution:** With 3 trim coils we made a field bump in B_z to allow a 180 degree phase slip so that the whole beam of ~50 degree phase width turns around, gets decelerated back and passes through extraction foil again



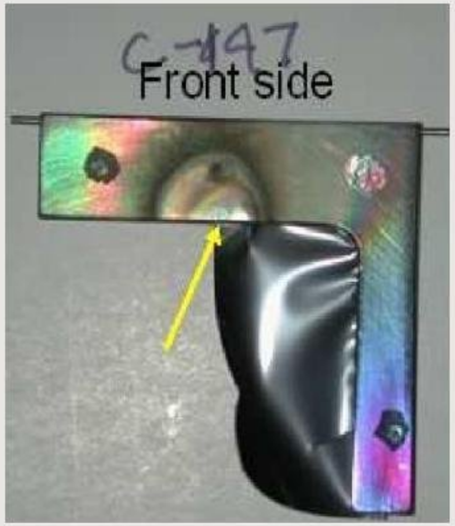


Future plans:

- Increase Sr-82 production by 50% with elongated Rb target
- Reduce radioactive gas (O-15) release into nuclear ventilation with introduction of a delay/decay line
- Optimize target cooling
- Redesign BL2C4 (~5 m) to introduce beam rastering



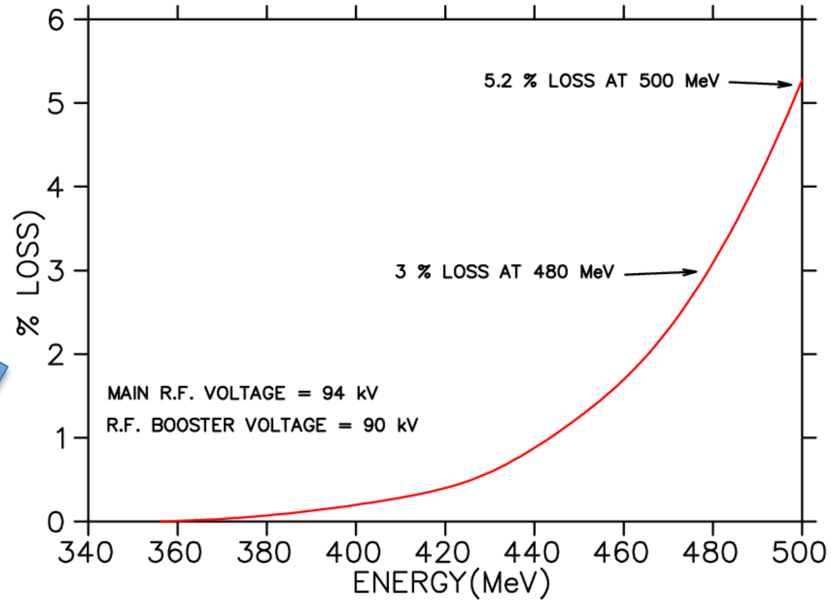
Extraction Foils Lifetime

2005	2016
	
Used Pyrolytic Graphite foil (stainless steel frame).	Highly Oriented Pyrolytic Graphite at the end of the year (tantalum frame).
Loose ^{7}Be tank contamination around extraction 1A (in counts per min.):	
4.10^{5}	2.10^{4}
Foil lifetime:	
~3 months, 50 mA hours	3+ years, 500 mA·hours

Beam Losses

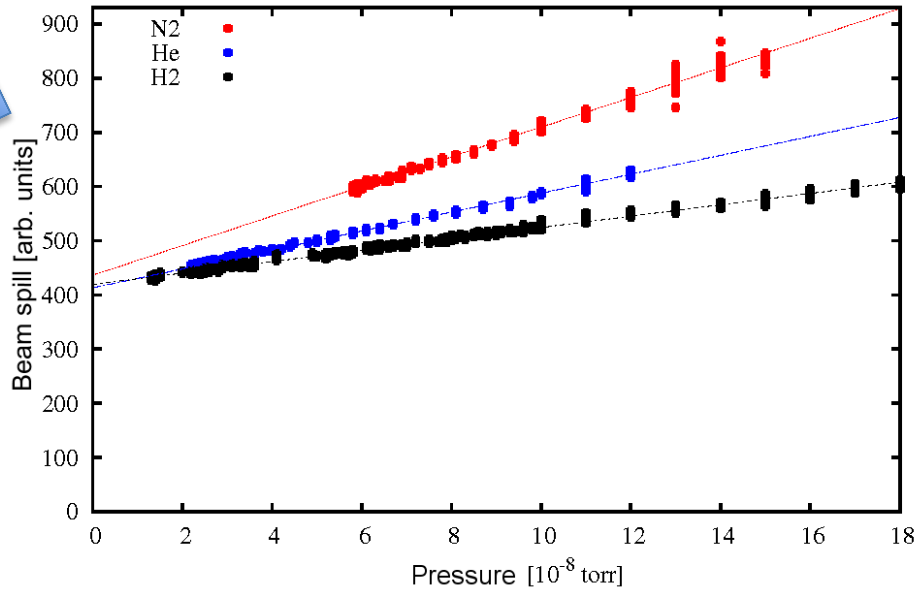
3 mechanisms leading to beam losses in the cyclotron:

1. Vertical effective emittance growth
2. Electromagnetic (Lorentz) stripping
3. Stripping on residual gas



Mitigation:

- Lorentz stripping was reduced from 5% to 3% by reducing extraction energy from 500 MeV to 480 MeV
- Cryo-pumping system upgrade: vacuum improved from $8 \cdot 10^{-8}$ to $2 \cdot 10^{-8}$ Torr.
- Studies of partial pressure of basic gases on the beam losses showed negligible impact on loss reduction beyond achieved vacuum

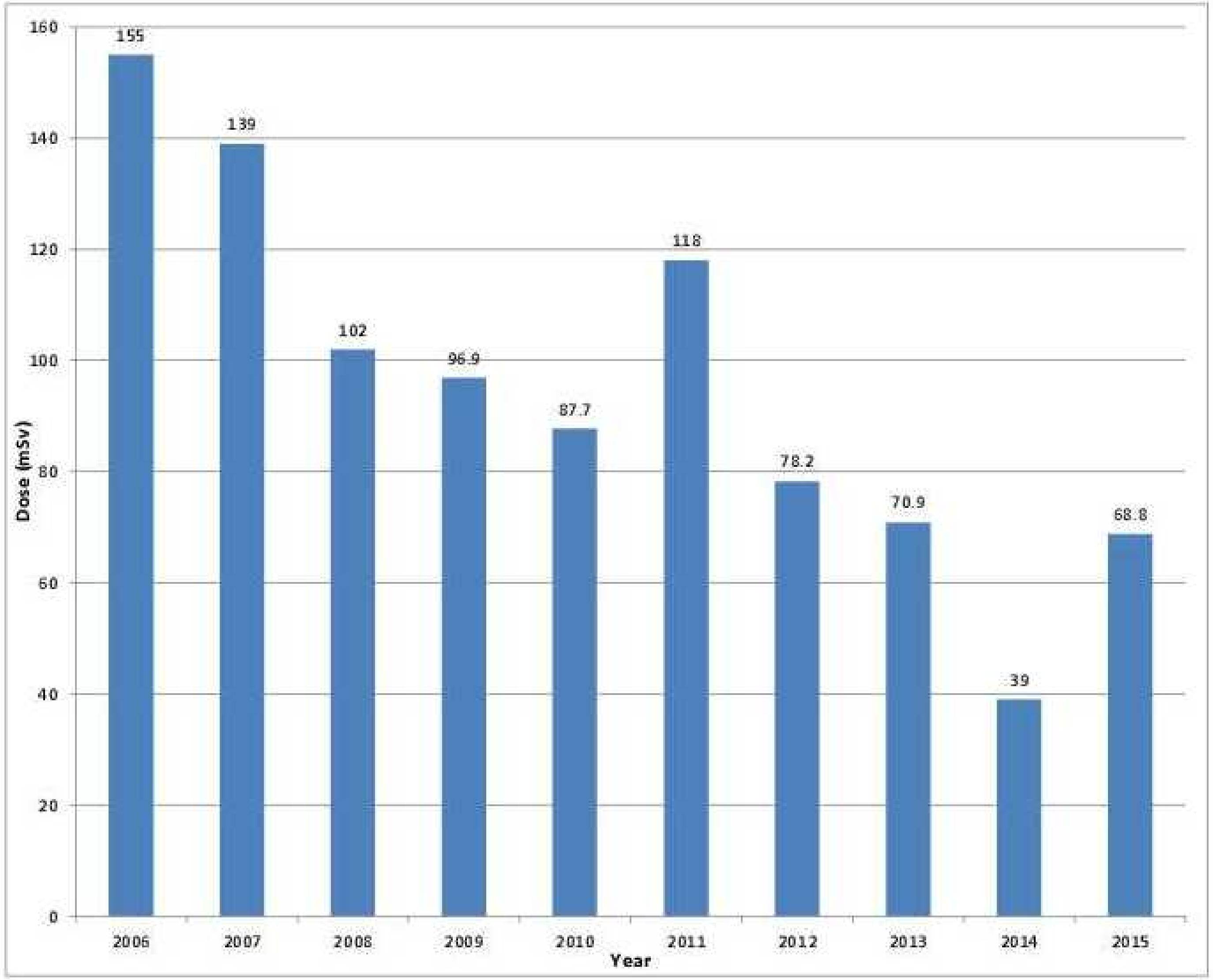


Future plans:

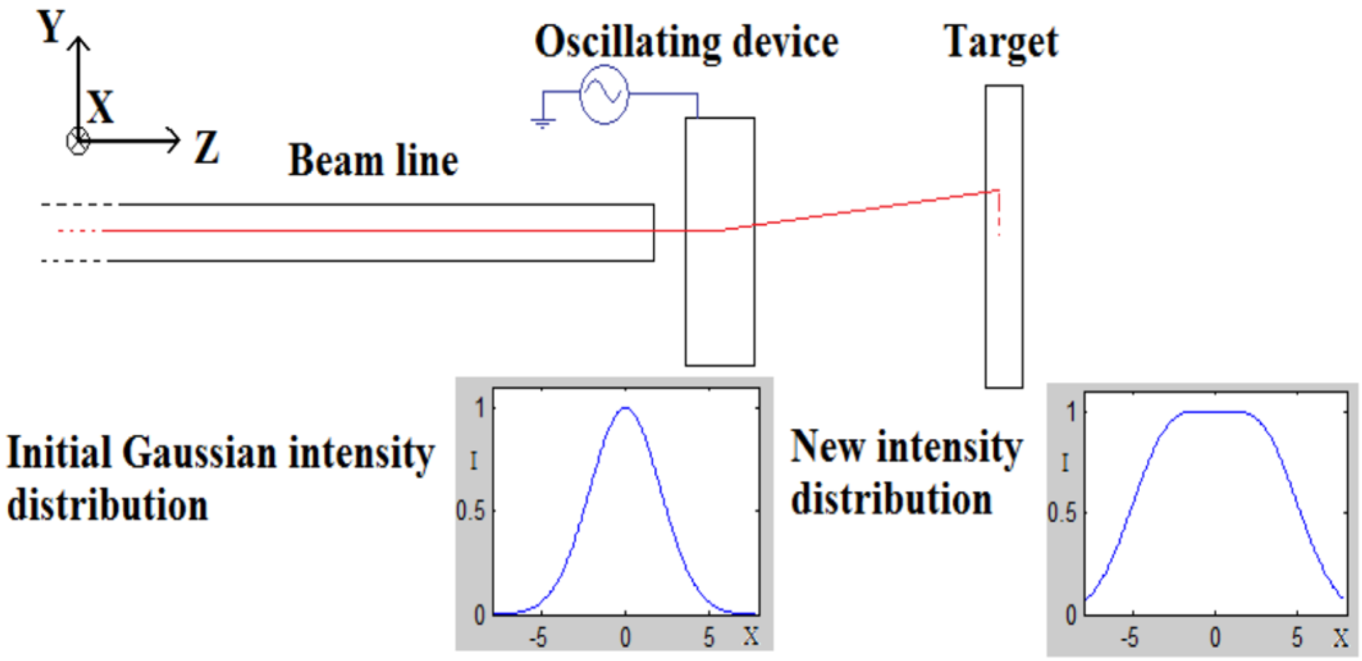
- Continue studies of beam vertical halo formation to reduce vertical tails losses down from 1.5%

Personnel exposure

Total Shutdown Dose for all TRIUMF Personnel



- Rotating a proton beam of reduced width (and smaller tails) on the ISAC targets would contribute to a more homogeneous temperature distribution across the target and enable operating at a higher average temperature.
    - Should allow a beam current increase of up to 50% of present levels
- The increased average temperature would enhance diffusion and effusion of the isotopes, and higher currents will boost production – both will contribute to higher yield of the radioactive ion beams.



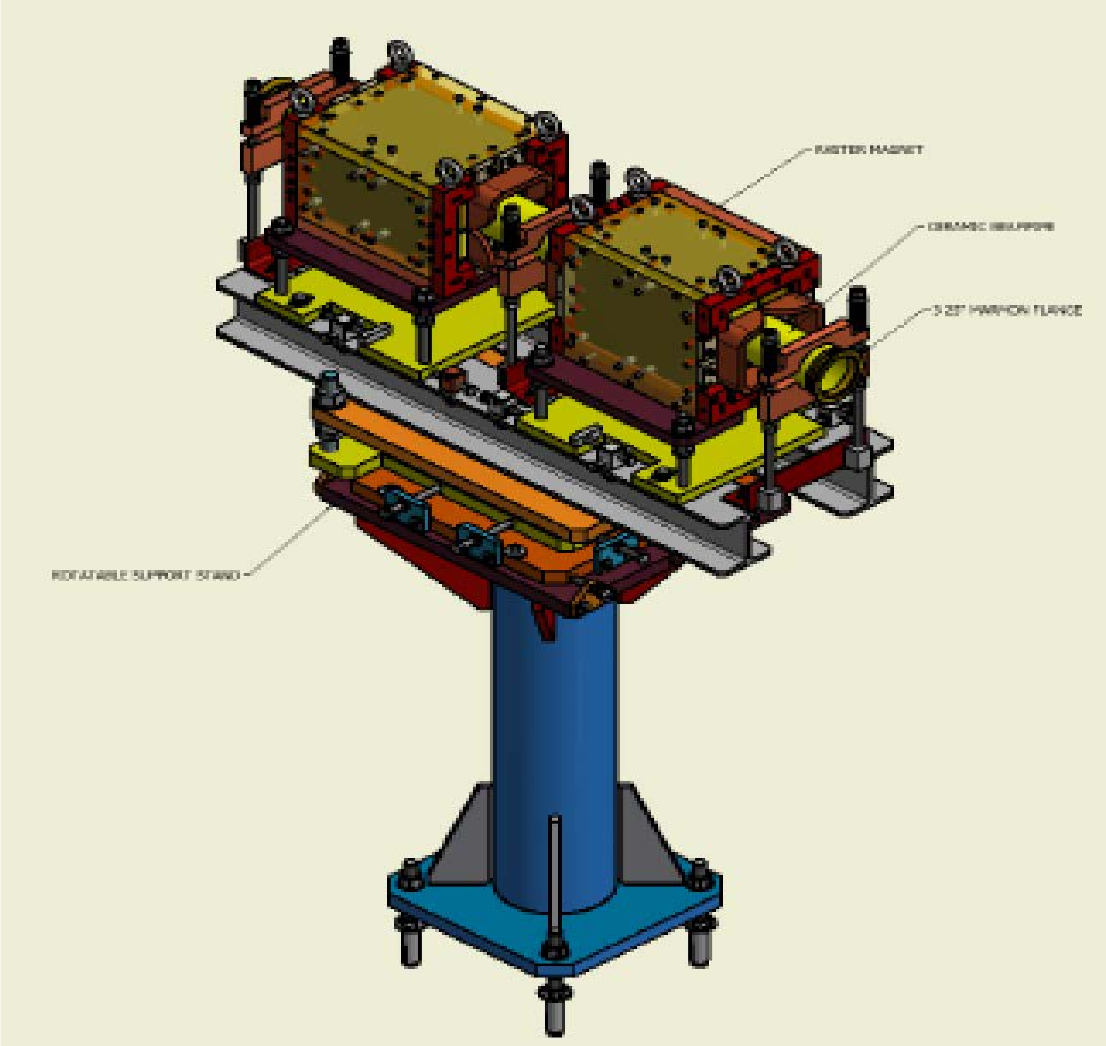
ISAC – AC Raster Magnet

Raster magnet is a ferrite H-frame type magnet (supplied by ACSI)

Components and parameters:

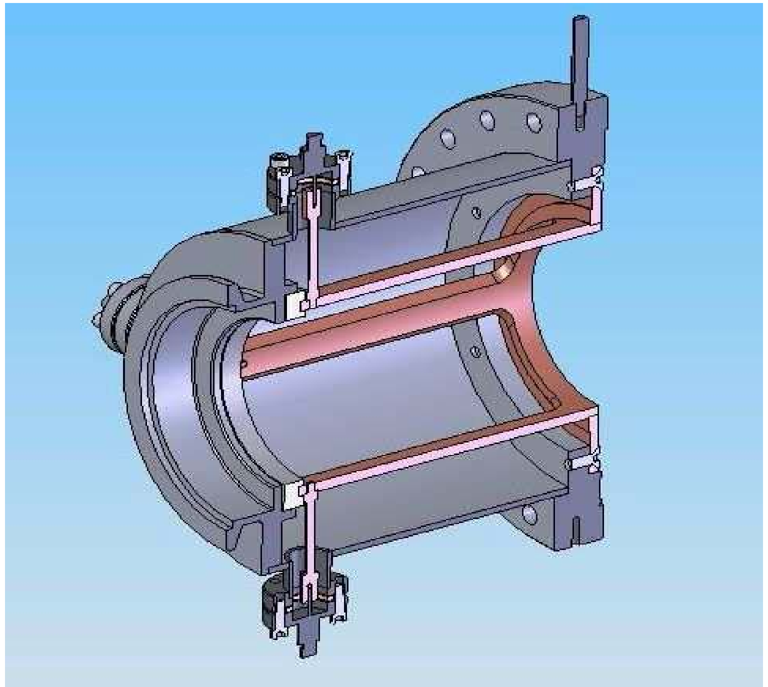
- two magnets for X and Y movements
- two power supplies with adjustable frequencies: up to **400 Hz**.
- integral field up to 150 G-m

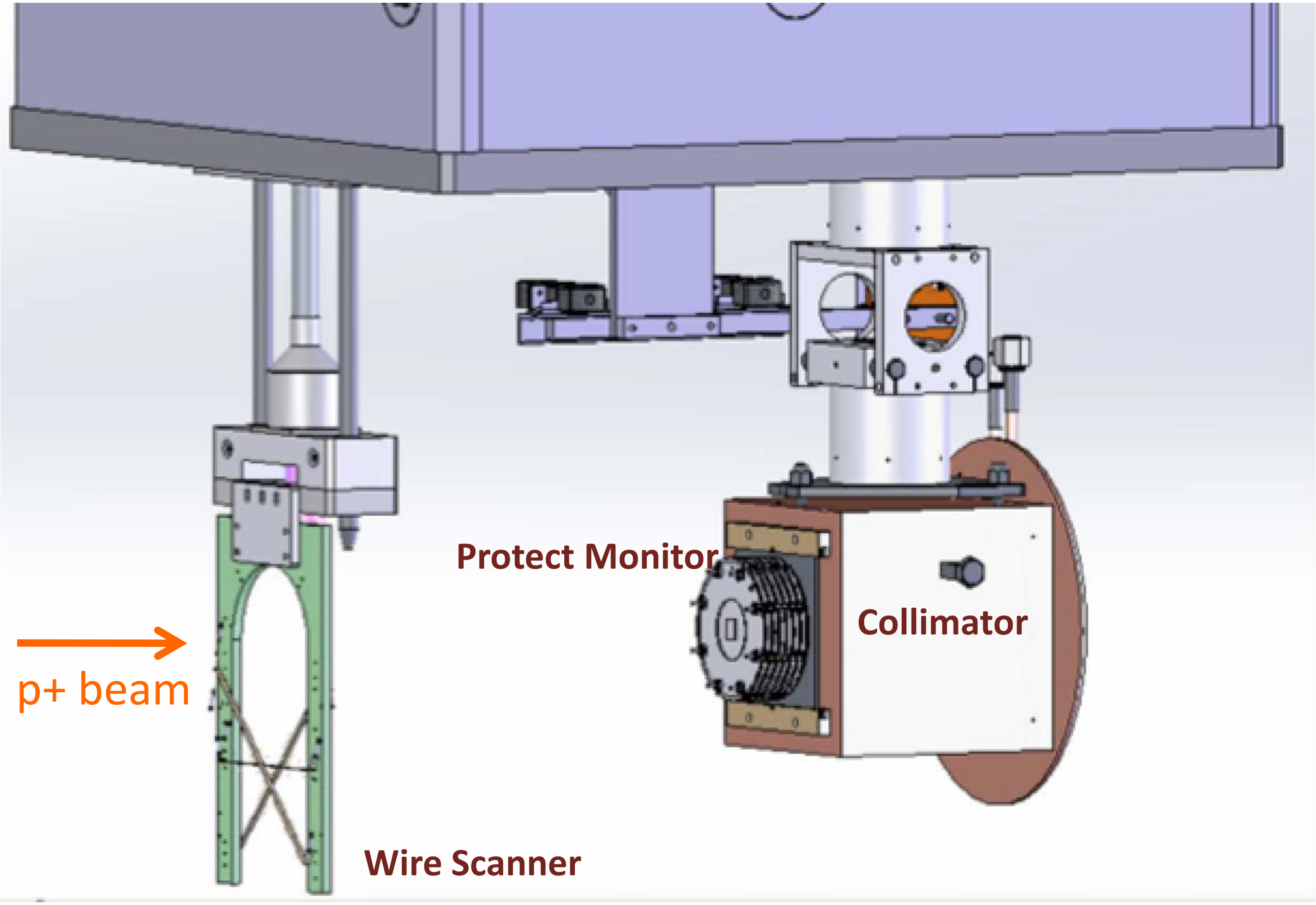
By adjusting the phases and amplitudes of the X and Y magnets a variety of rastering patterns can be achieved



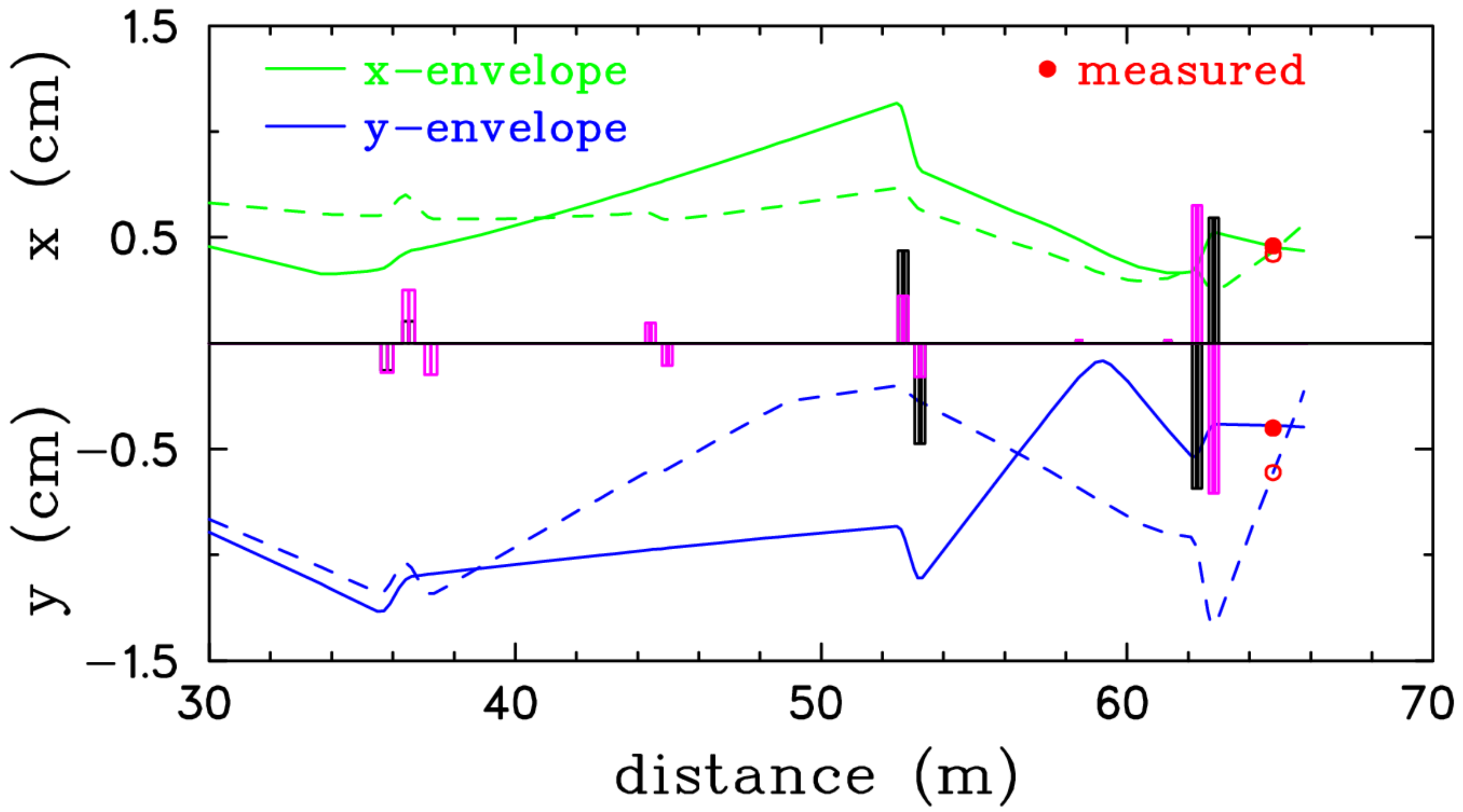
Non-intercepting Beam Position Monitor (BPM)

- Sensitivity ~2 µA
- Bandwidth ~10 kHz



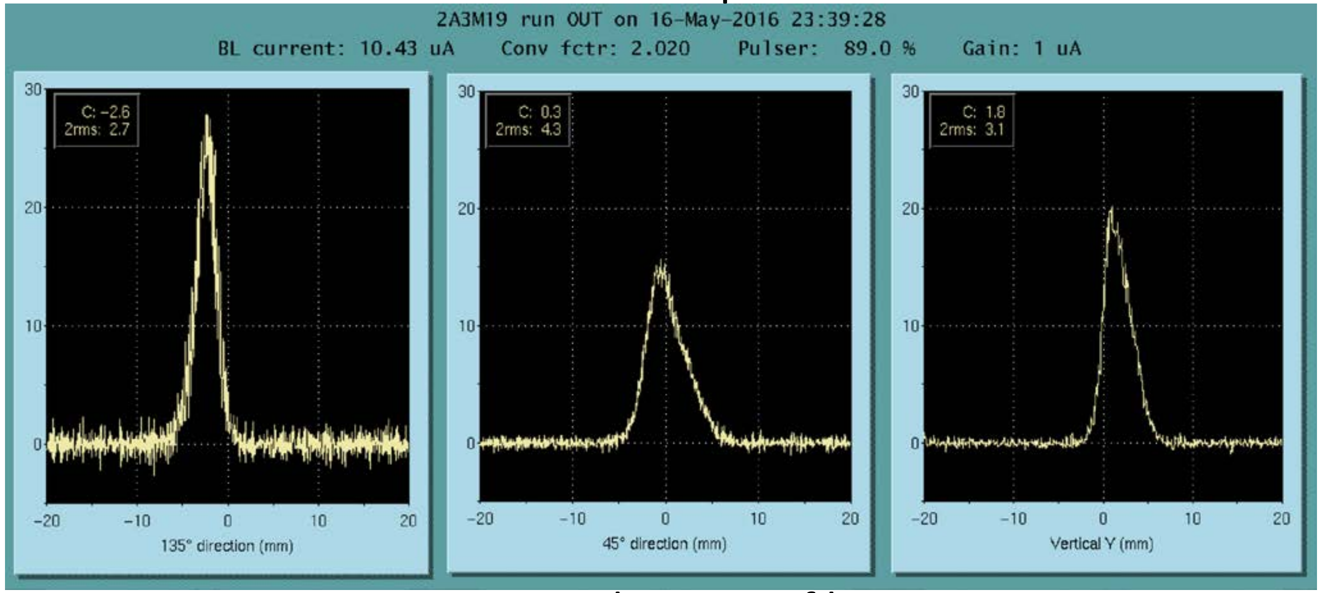


New tune features:
- Beam is parallel in last drift
- 90 degree phase advance between raster magnets and target
- 4x4mm spot size
- Easy to steer
- Available diagnostics represents very well beam spot at the target

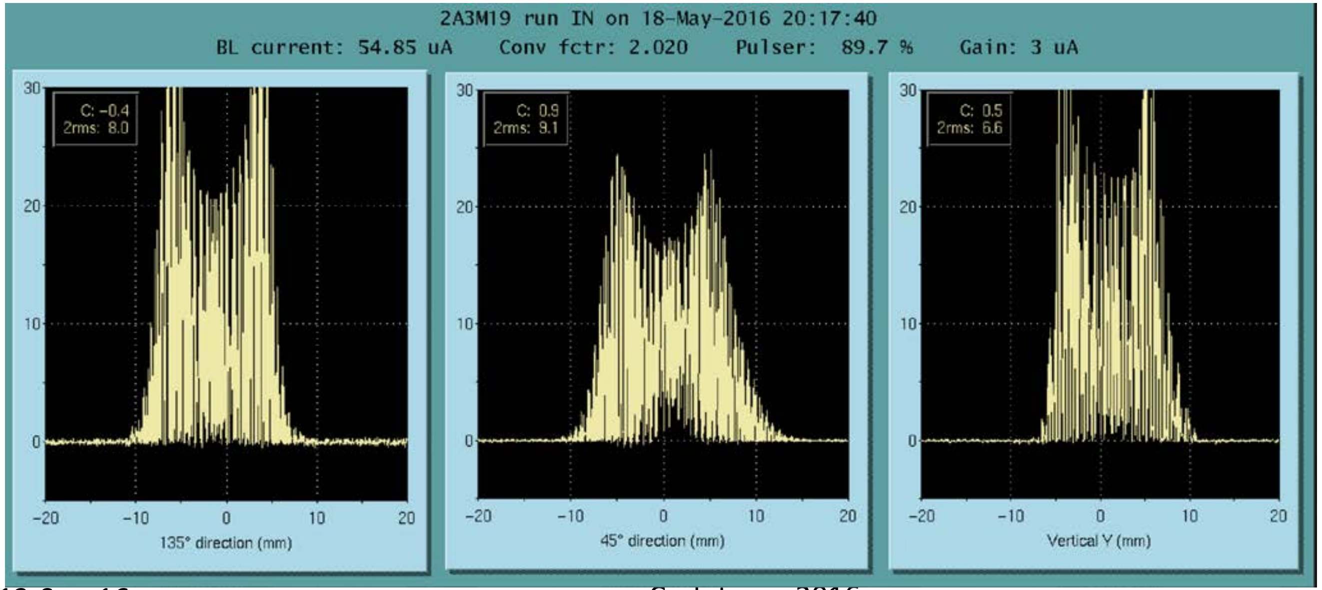


Dashed line – old tune; solid line – new tune

Static beam profile



Rotating beam profile

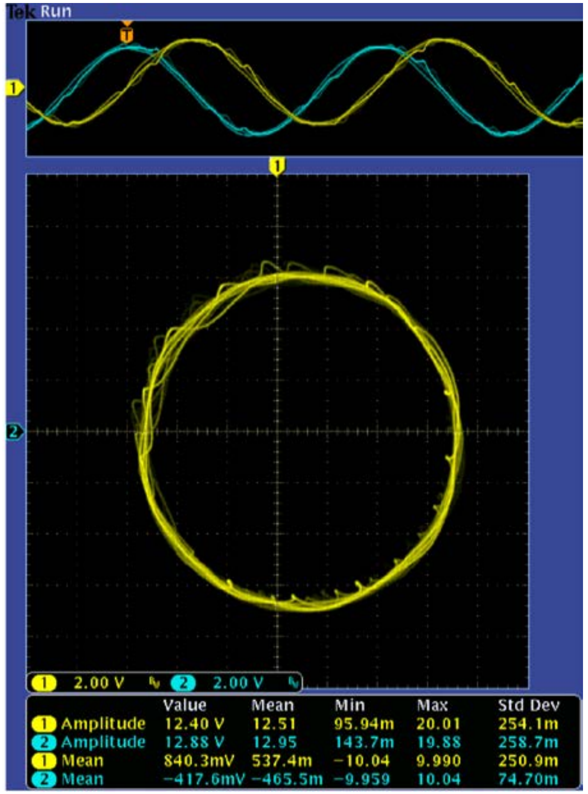


p+ = 55 µA

Instant spot size = 4x4mm

Rotating radius = 5.5 mm

Beam center trajectory on BPM



Yield Results for Ta#47 – May 2016

Yield enhancement with rotating beam

Isotope	Rot/Static	p+ [uA]	Yield [1/s]	Previous best yield from Ta [1/s]	p+ [uA]	Ratio rotating/ previous
Li11	Rotating	60	5.33E+04			2.3
	Static	40	2.36E+04	2.3E+04	65	
Li8	Rotating	60	1.37E+09			1.5
	Static	40	5.13E+08	9.1E+08	70	
Na26	Rotating	50	1.44E+07	5.9E+06	70	2.4
Na28	Rotating	50	1.32E+05	1.4E+04	70	9.4
Cs126	Rotating	50	1.29E+08	9.2E+07	70	1.4

Cyclotron upgrade major objectives:

- Replace main magnet power supply (2017)
- Increase Sr-82 production by 50% (2017)
- Develop BL1A/BL1U beam sharing for Ultra Cold Neutrons program (2018)
- Build new BL4N with extracted 100 µA (4 years)
- Increase total extracted beam to 400 µA (5-7 years)
  - Build new efficient H- source
  - Replace old injection line
  - Solve space charge issues at injection
  - Increase Dee voltage by 5-7%
  - Develop stable extraction of 4 high intensity beams
- Reduce maintenance by switching to non-serviceable components (6-8 years)
  - New inflector
  - Cyclotron probes joints
- Extend running periods between major shutdowns to >1 year

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Thank you!
Merci!

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