MUON BEAMS AT TRIUMF

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Workshop on Instrumentation
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Muon beams at TRIUMF

Outline

- The accelerator
- The high intensity proton beam
- Types of muon beams
- Beams from the 1AT1 target
  - ▷ an example: the M13 beam line
- Beams from the 1AT2 target
- Summary of muon beam properties

For more details, see the TRIUMF Users' Handbook at
http://www.triumf.ca/triumf-handbooks/

Characteristics of the TRIUMF accelerator

- Acceleration of H^- ions limits field to 0.6 T, but enables efficient proton extraction at variable energy up to 500 MeV.
- Maximum current is several hundred μA, shared among several simultaneously extracted beams.
- The RF frequency is 23 MHz, with pulses of $\sim$2 ns width every 43 ns.

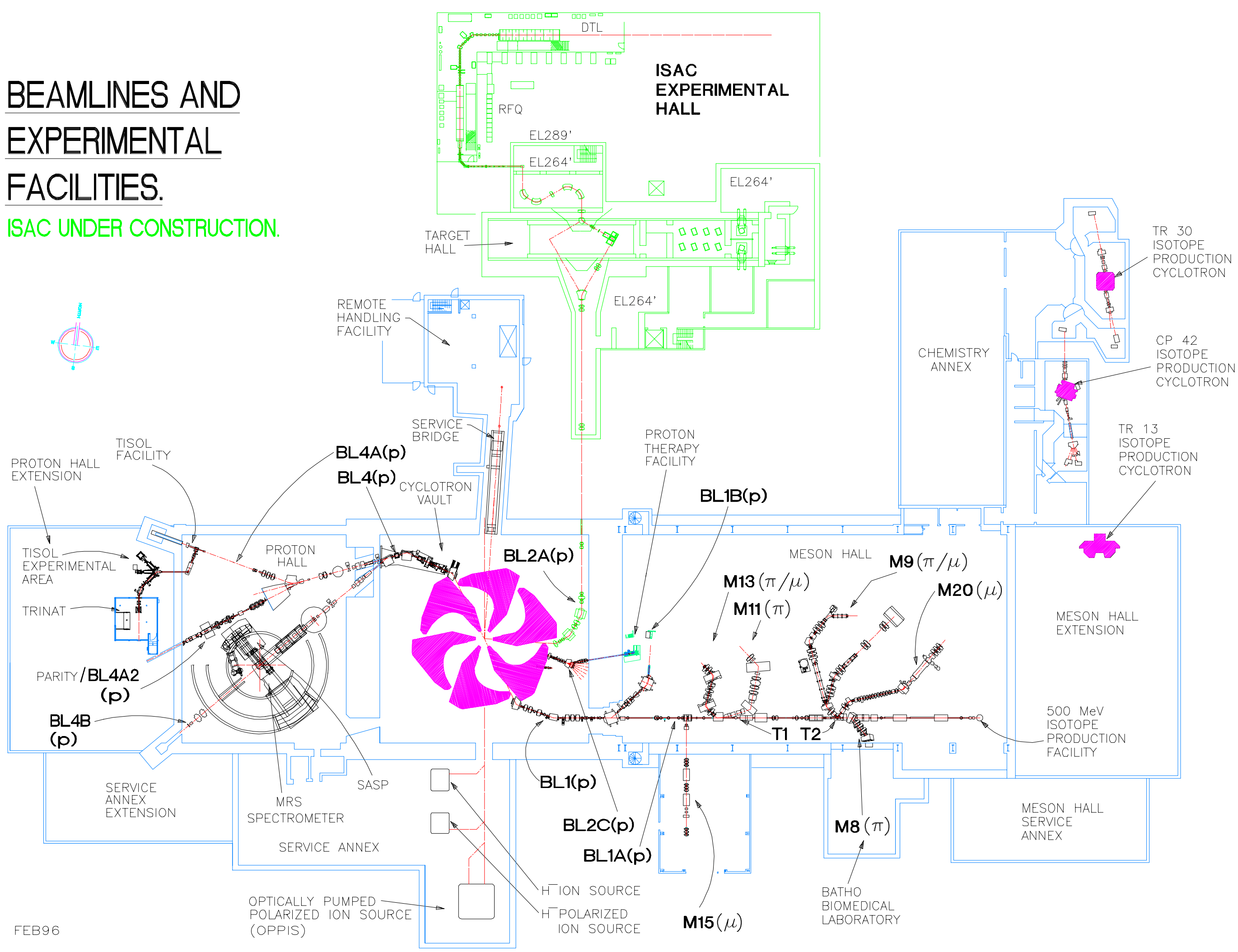

Figure 1: The TRIUMF site.

The proton beam line

- The extracted proton beam passes through two pion production targets, 1AT1 and 1AT2, each of which supplies several secondary pion and muon beam lines.
- Current for pion production at 500 MeV is limited to $\sim$150 μA.

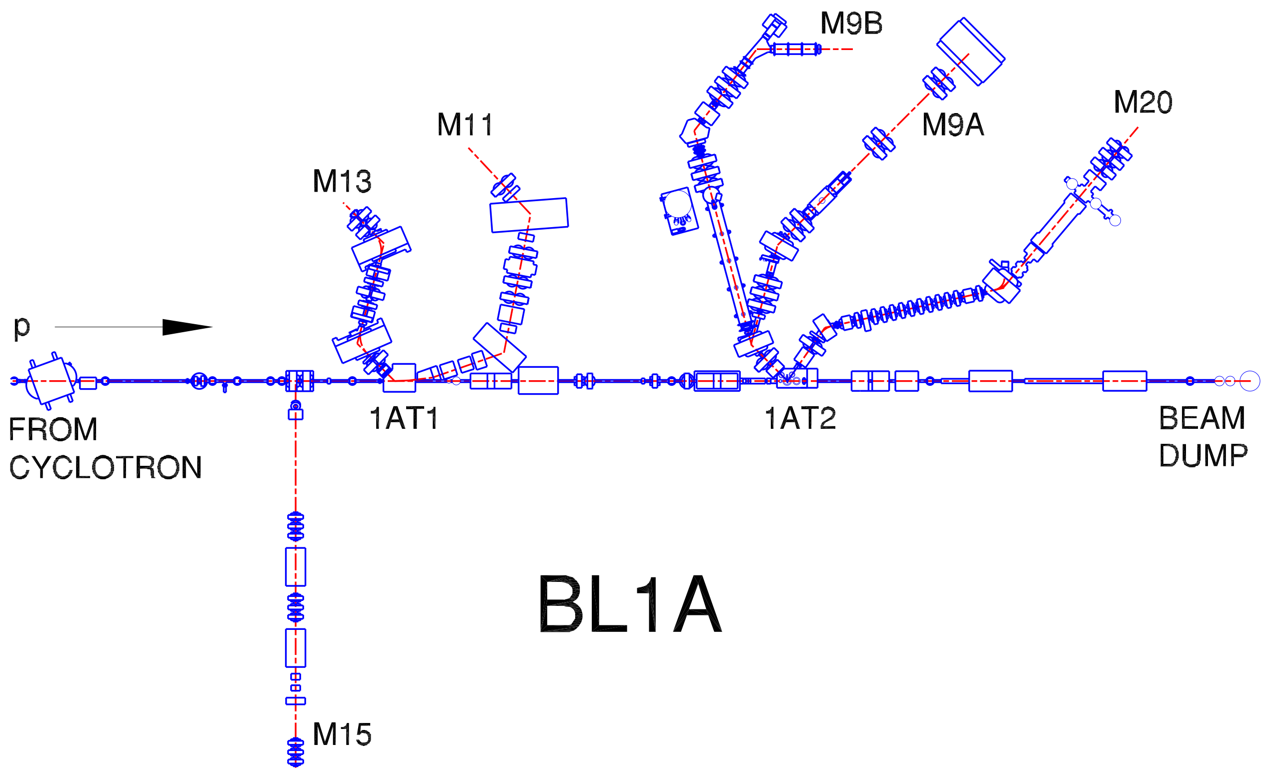

Figure 2: The high intensity BL1A proton beam line, showing production targets 1AT1 and 1AT2 and the associated secondary pion and muon beams.

Muon production: cloud muons

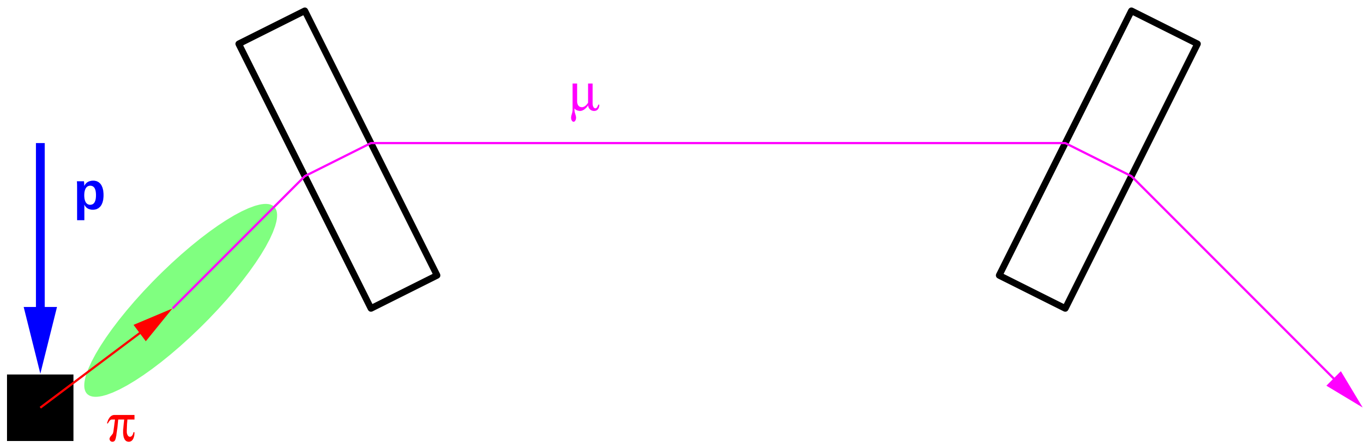

Figure 3: Cloud muon production schematic. Pions decay in the green region.

- Cloud muons:
  - From pion decay in flight, close to the production target.
  - Wide range of momentum available.
  - Source is larger than the production target.
  - Contaminated by $\pi^{\pm}$ and $\mathrm{e}^{\pm}$.
  - Polarization is low, depending on momentum and geometry.

Muon production: decay muon beams

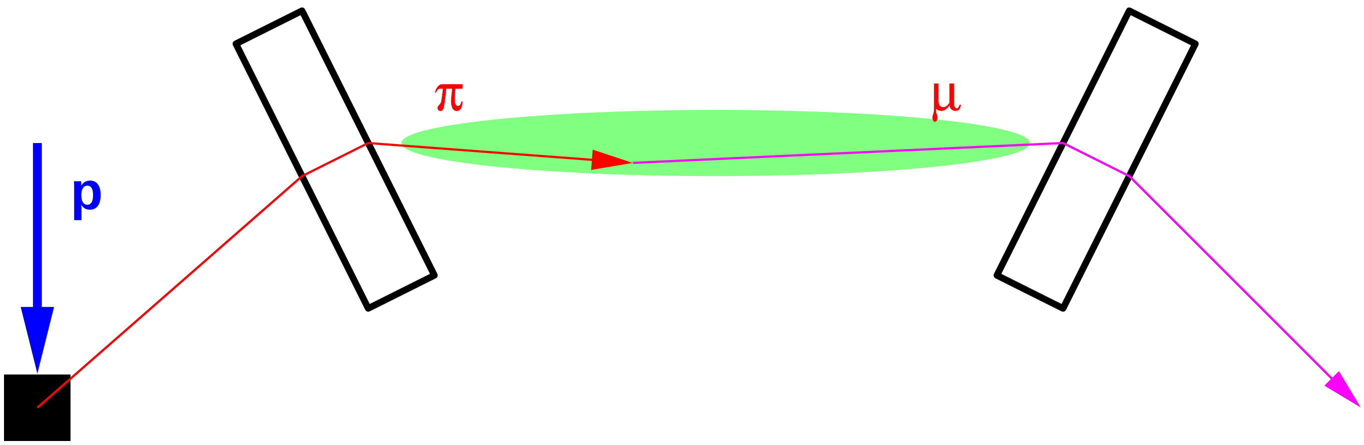

Figure 4: Decay muon production schematic. Pions decay in the green region.

- Decay muons:
  - From decay in flight of momentum-selected pion beam.
  - Source is throughout beam region between selection of pion momentum and subsequent selection of muon momentum.
  - Decay region is usually a superconducting solenoid.
  - Polarization is high and contamination with pions is low (for backward decaying muons).
  - Two or more bends following the decay section improve beam definition.

Decay muon beams: muon *vs* pion momentum

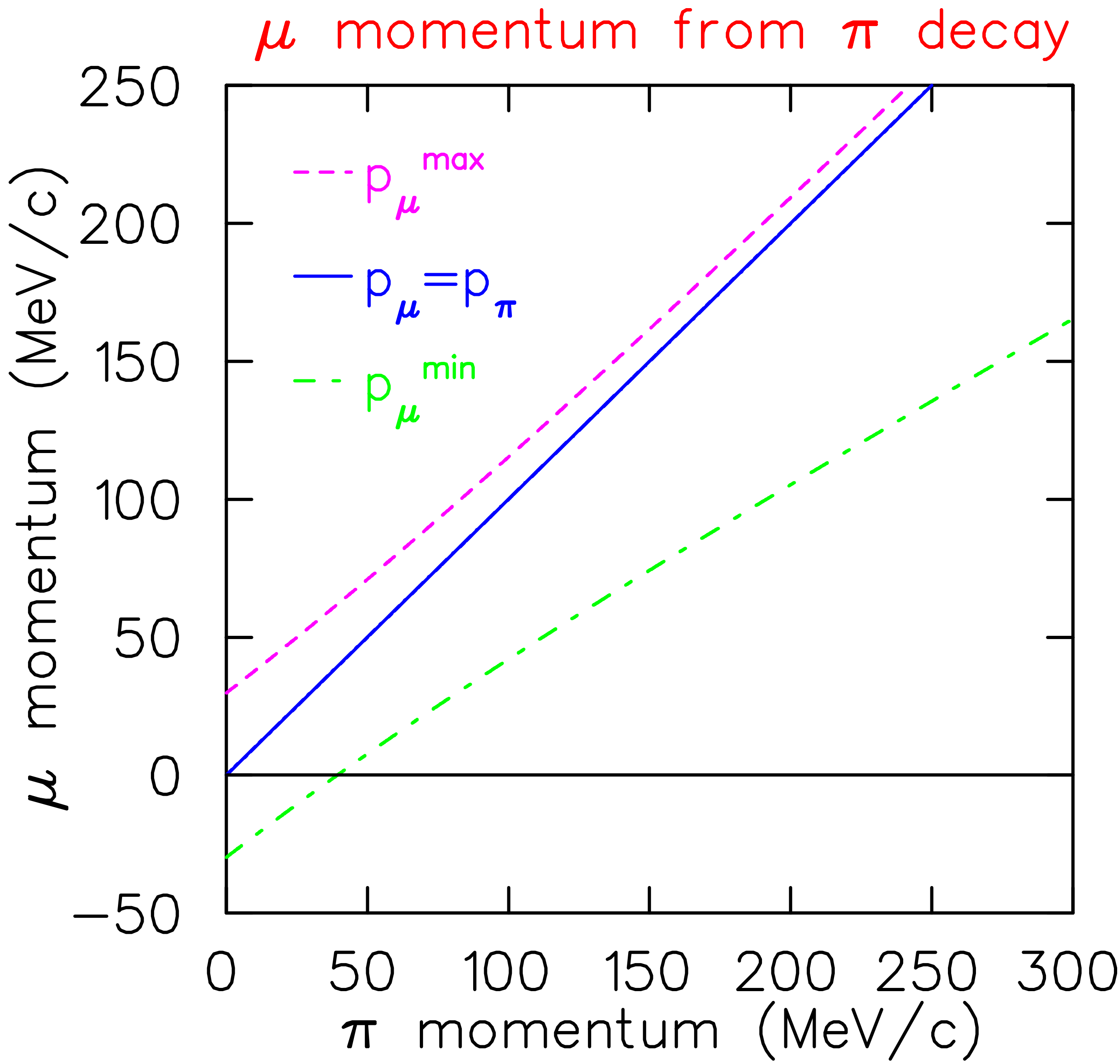

Figure 5: Decay muon momentum *vs* pion momentum, showing extremes for forward and backward muons.

Muon production: surface muons

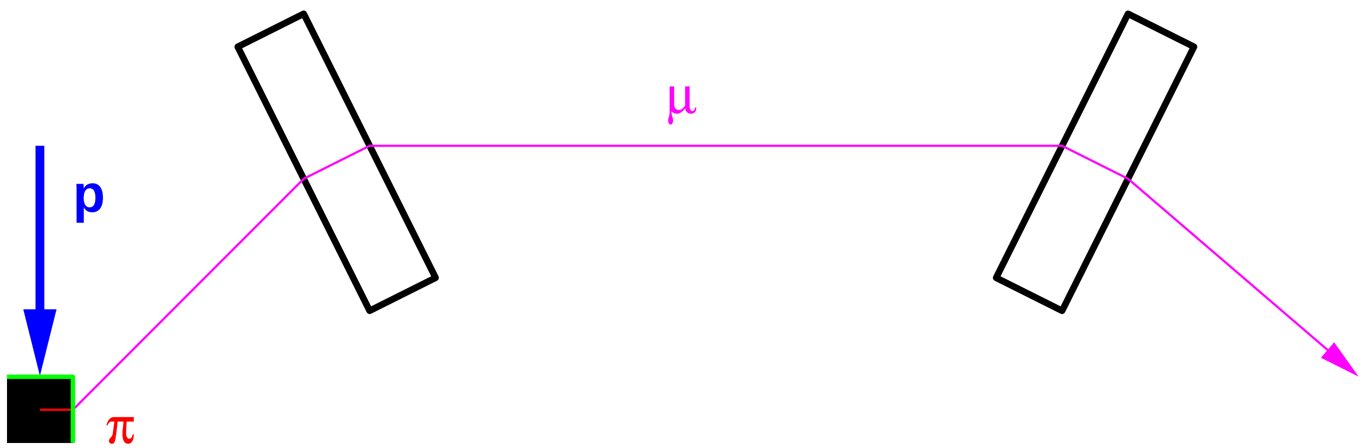

Figure 6: Surface muon production schematic. Pions decay in the green region.

- Surface muons:
  - Pions stop and decay close to the surface of the production target.
  - Source is well defined, allowing precise beam optics.
  - Polarization is near 100%.
  - μ^+ only, since π^- interact with nuclei before decay.
  - Beams are contaminated with positrons if no separation system is used.
  - Thin windows and vacuum beam transport necessary.
  - Stopping density very high due to short range ($R_\mu \sim 0.14 \text{ g/cm}^{-2}$ in carbon)

$$R_\mu \propto p^{3.5} \Rightarrow \frac{\Delta R_\mu}{R_\mu} \sim \sqrt{(3.5\frac{\Delta p}{p})^2 + (\Delta R_{str})^2}$$

See A.E. Pifer *et al.*, Nucl. Instr. and Meth. 135, 39.

Beams from the 1AT1 target: M11, M13, and M15

- Proton beam size at 1AT1 is approximately 3 mm horizontally and 7 mm vertically.
- 1AT1 target is 12 mm Be in a stainless steel water cooling jacket, or 10 mm edge-cooled graphite, on a remotely operable ladder assembly.

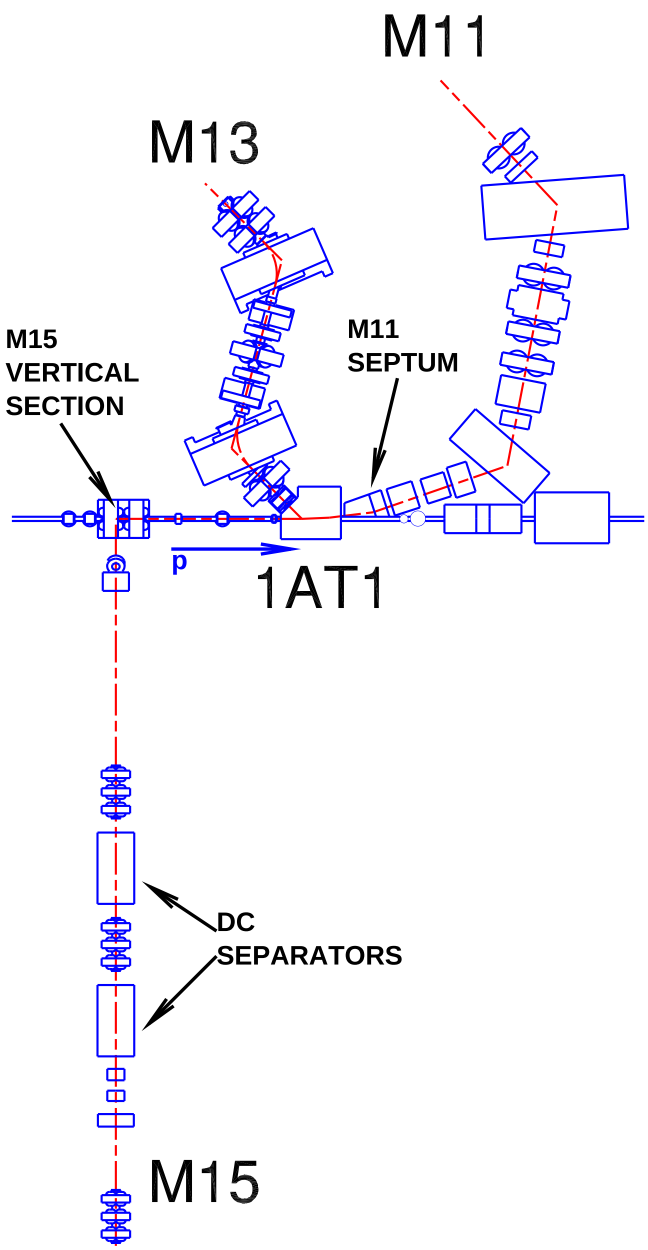

Figure 7: The 1AT1 production target and associated beam lines.

The M13 beam line

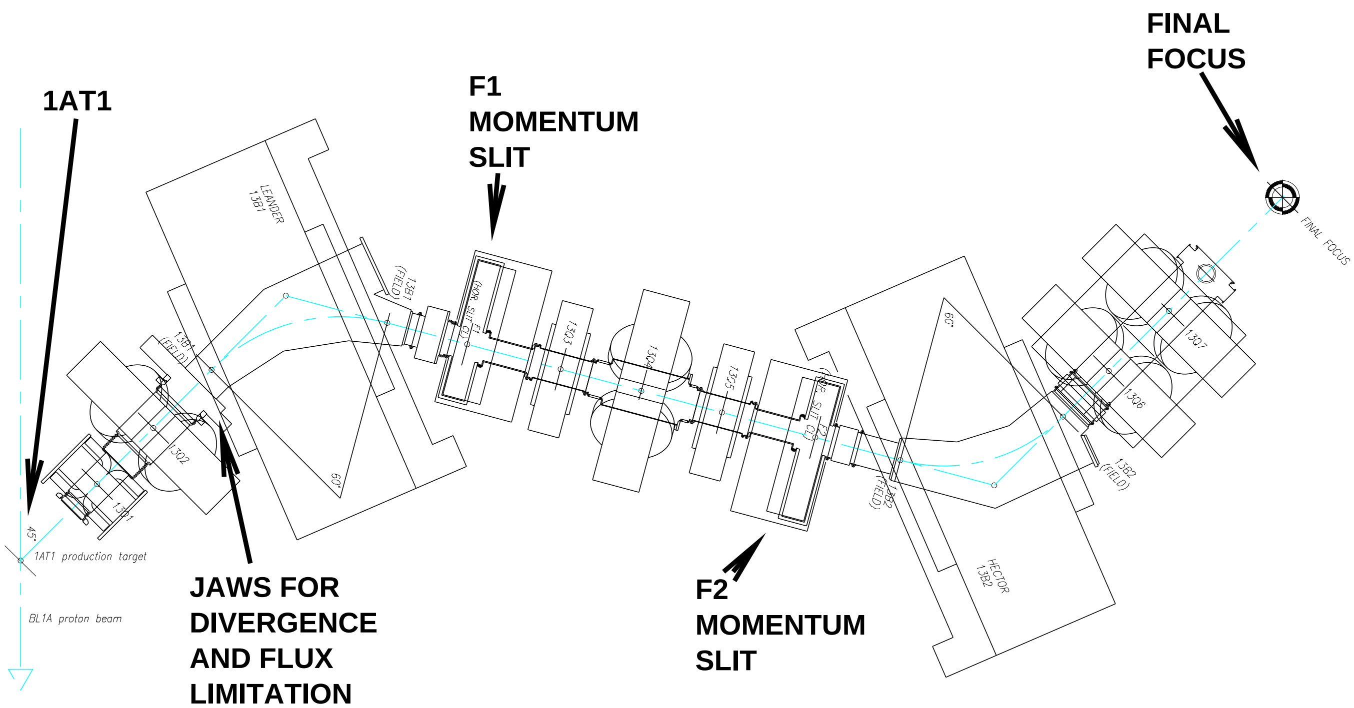

Figure 8: The M13 beam line.

- Short channel to optimize intensity of pions at low momentum.
- Secondary beam direction is 135° to proton beam.
- Simple beam transport and small production target allow good emittance definition.
- Jaws limit divergence from production target.
- Slits at two intermediate dispersed focus positions restrict momentum acceptance down to $\Delta p/p \sim 1\%$.

Beam emittances from M13

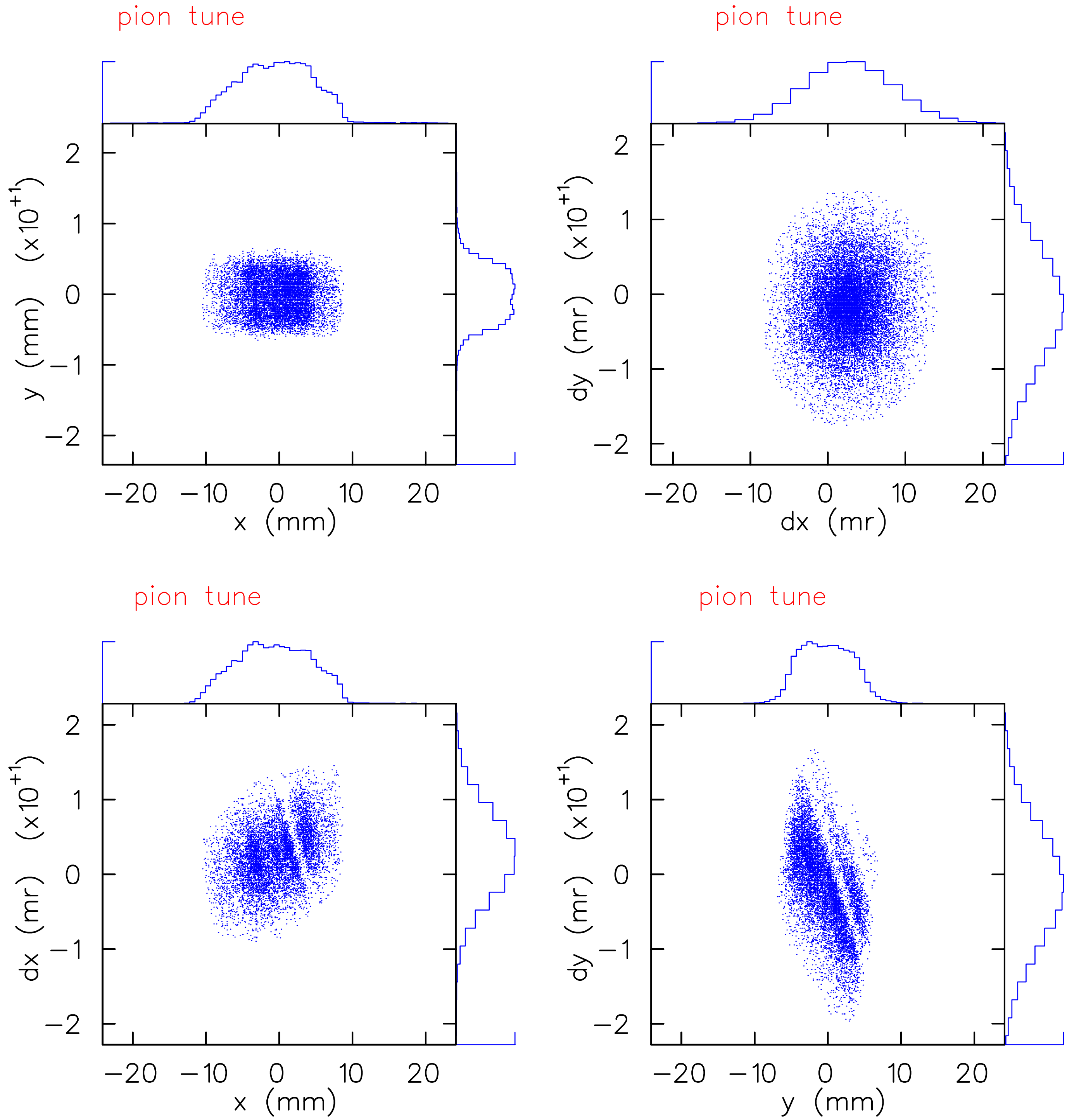

Figure 9: Beam x and y emittance plots for 120 MeV/c pions.

Particle intensities from M13

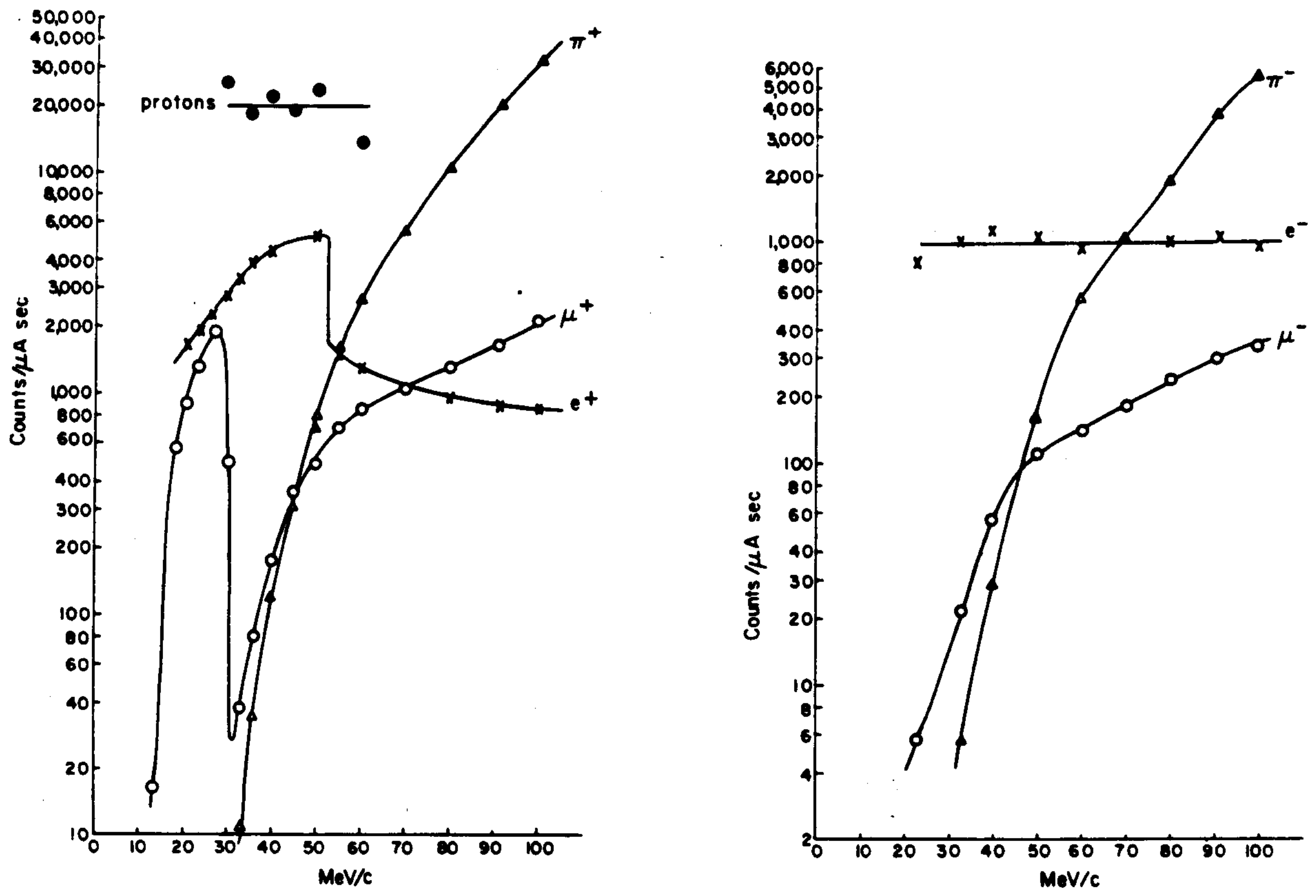

Figure 10: M13 rates for 1.45 mm graphite target.

Production of pions from 500 MeV protons is dominated via nucleon-nucleon resonances. Isotopic spin favors π^+ over π^-, resulting in higher rates for positive particles by a factor of 5 to 10.

See C.J. Oram *et al.*, Nucl. Instrum. and Meth. 179 (1981) 95.

Particle ID using TOF at higher momentum

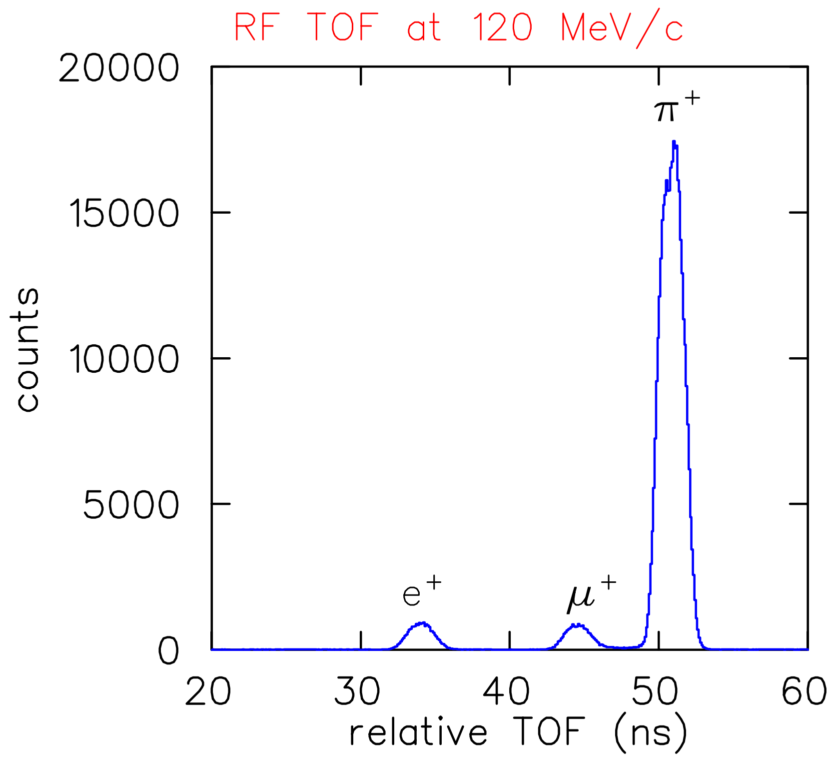

Figure 11: At 120 MeV/c, TOF for 10 m distance of production target to detector is 33 ns for e, 44 ns for μ, and 51 ns for π.

- Proton pulse width of ~ 2 ns allows separation of muons from pions, which are otherwise difficult to distinguish.
- For positive beams at higher momenta, protons and other heavy ions contaminate beams, but can usually be separated by range or by an absorber prior to the final dipole.

TOF near surface muon momentum

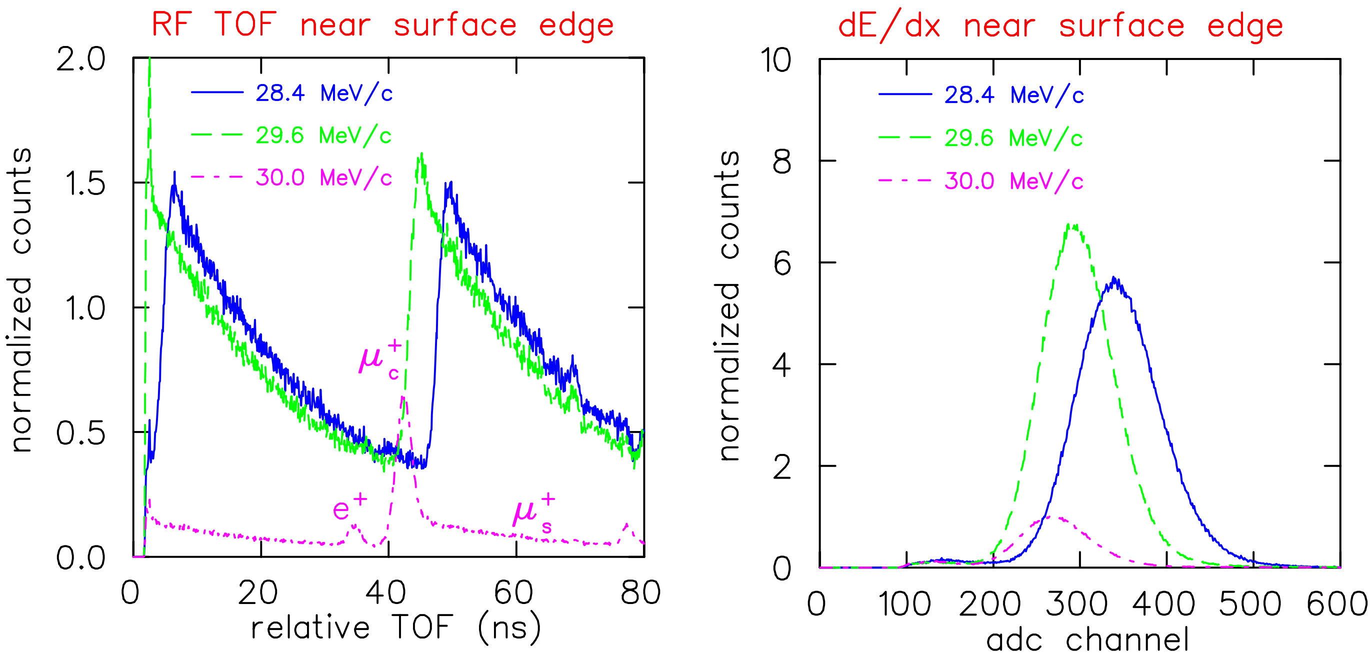

Figure 12: Time of flight (left) and pulse height in a 0.5 mm scintillator, for different beam momenta near the surface muon production edge. Below 29.8 MeV/c, muon arrival time is spread by the pion lifetime. Here they arrive just over 2 RF cycles later than positrons. The trigger discriminated against beam positrons, which normally have a higher rate than muons.

- For surface muons, time of flight is less useful, but pulse height allows separation from beam positrons, while decay length of pions reduces their intensity.
- A small contamination of cloud muons exists at the surface muon momentum, and can be removed by a TOF cut where high polarization is crucial.
- Beam positrons can be effectively removed using a crossed field DC separator (Wien filter), which is also useful to rotate muon beam polarization.

The M11 beam line

- Mainly for higher energy pion beams, using forward pion production.
- Dipole edge of primary beam quadrupole is first bending element (2.89° to 7°).
- Septum magnet bends an additional 12°.
- Divergence of accepted beam can be reduced by jaws.
- Dispersed double focus with momentum definition slits ($\Delta p/p$ from 0.5% to 5%) after first dipole.
- Absorber at dispersed focus to differentially degrade protons from pion and muon beams.

Muons from the M11 beam have been used for MUSCAT measurements at 130, 150, and 180 MeV/c.

The M15 beam line

- Mainly for surface muon beams and μSR.
- Luminosity optimized using small permanent quadrupoles near production target.
- Views production target from 135° vertical angle, $i.e.$, top front.
- Divergence of accepted beam can be reduced by jaws.
- Two bend planes, vertical and horizontal.
- Two DC crossed field (Wien filter) separators, used to reduce positron contamination and to rotate muon polarization direction from longitudinal to transverse.

Beams from the 1AT2 target

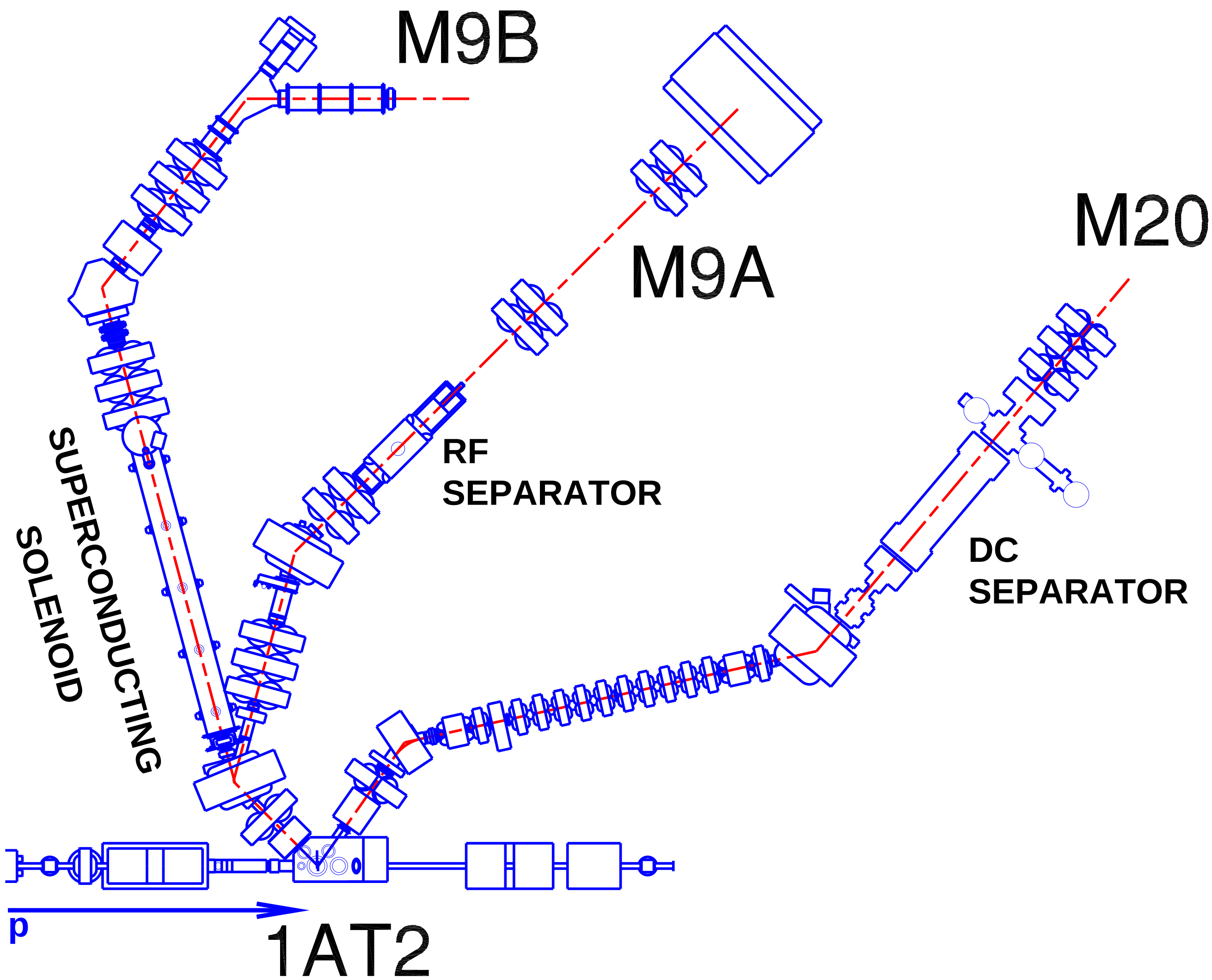

Figure 13: The 1AT2 production target and associated beam lines.

- T2 is typically 100 mm Be in a water cooling jacket.
- Greater thickness means more intensity, but larger emittances.

The M9A, M9B, and M20 beam lines

M9A:

- Delivers pions or muons to the RMC spectrometer.
- RF separation of π and e from μ near 70 MeV/c.
- High acceptance from thick target, at the expense of significant aberrations.

M9B:

- Uses a superconducting solenoid for muons from backward decay of pions.
- Short pion injection leg optimized for low energy beams.
- Two bends follow solenoid, with jaws to select emittance limits and slits to control momentum acceptance.

M20:

- Used mostly for μSR.
- DC crossed field (Wien filter) separator, used to rotate muon spin from longitudinal to transverse.
- Can be used also as cloud or decay muon (quadrupole decay section) channel.

  See J.L. Beveridge *et al.*, Nucl. Instrum. and Meth. <u>A240</u> (1985) 316.

Summary of muon beams

beam line	p (MeV/c)	intensity* at p ($10^6 s^{-1}$)	Δp/p (% fwhm)	pol^n	size h$\times$v (cm$\times$cm)
M11	50-400	1.0(+)† at 180	0.5-5	low	2.5$\times$2
		Normally a π channel, higher momentum			
M13	20-150	1.8† at 29	1-10	high	3$\times$2
		Short, simple optics			
M15	20-30	2.0† at 29	2-10	high	1.2$\times$1.6
		Mostly μ^+SR, DC spin rotator/separator, high luminosity			
M9A	30-170	25.(+)‡ at 100	4-8	$\sim$50%	8$\times$9
		RF separator, dedicated to RMC spectrometer			
M9B	20-90	1.4(−)‡ at 40	5-11	>90%	10$\times$10
		Superconducting decay channel			
M20	20-200	2.1‡ at 29	3-8	high	4$\times$3
		Mostly μ^+SR, DC spin rotator/separator, high intensity			

* For proton current of 140 μA at full Δp/p

† For production target of 1 cm graphite

‡ For production target of 10 cm Be

Table 1: Muon beams at TRIUMF. Comparisons must be made with care, since specifications are not necessarily for similar beam conditions.