# Beamline Simulation Effort for $\nu$STORM

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September 22, 2012

# Outline

1. This is a progress report on beam simulations of transportation of pions captured by a magnetic horn downstream into a muon storage ring. Including:
2. MAD8 and OptiM Simulation

   - MAD8 and OptiM are used and combined to match the optics and generate lattice input for G4Beamline
3. G4Beamline Simulation

   - Real-field plus Multi-particle tracking for transport line with reference particle tuning for the ring, and dynamic aperture calculations

# Purpose of study

1. In LOI we have proposed a pion production efficiency together with collection efficiency of 0.1 pions per proton on target, with an efficiency of 0.8 for transport, 0.9 for injection. Namely 0.072 pions per POT will be delivered to the ring;
2. Now let's look at what we can obtain according to simulation

# $\nu$STORM Target

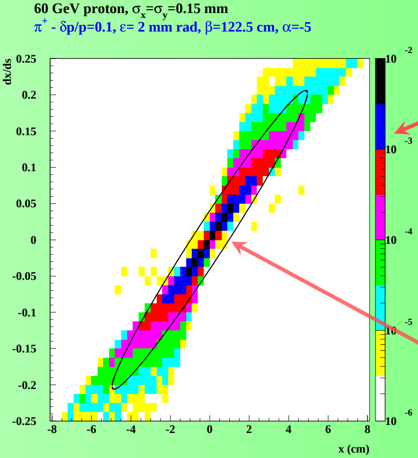
Table I. $\pi^+$ yield/POT with 60 GeV/c protons, into 2 mm radian acceptance.

| material | momentum (GeV/c) | ±15% | ±10% | ±5% | target length (cm) | density (g/cm$^3$) |
|---|---|---|---|---|---|---|
| Carbon | 3 | 0.085 | 0.056 | 0.028 | 27.3 | 3.52 |
| Carbon | 5 | 0.099 | 0.067 | 0.033 | 32.2 | 3.52 |
| Inconel | 3 | 0.131 | 0.087 | 0.044 | 19.2 | 8.43 |
| Inconel | 5 | 0.136 | 0.091 | 0.045 | 27.0 | 8.43 |
| Tantalum | 3 | 0.164 | 0.109 | 0.054 | 15.3 | 16.6 |
| Tantalum | 5 | 0.161 | 0.107 | 0.053 | 21.3 | 16.6 |
| Gold | 3 | 0.177 | 0.118 | 0.059 | 18.0 | 19.32 |
| Gold | 5 | 0.171 | 0.112 | 0.056 | 21.0 | 19.32 |

- Able to achieve ~0.11 pions per POT in ±10% momentum bin;
- Medium/Heavy targets preferred;
- Courtesy of Sergei Striganov (MARS simulation)

# Pion Phase-Space Distribution after Target

Total pions per POT = 0.137. Different color represents different intensity inside that pixel;




Pion distribution at 10 cm after target. Vertical axis: Angle; horizontal axis: Position

Pions per POT in 2 mm·rad which is the acceptance of the ring we are now considering = 0.114 (∼84%)

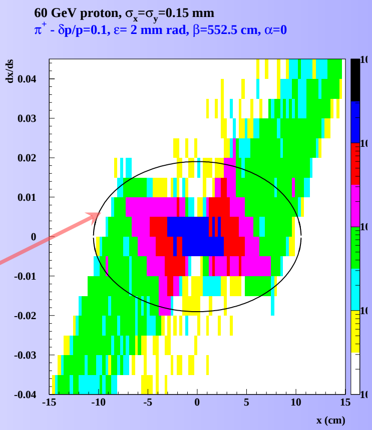
# Pion Capture

- We have looked into two schemes to capture the $\pi$'s: Lithium lens or Horn;
- A lithium lens configuration which could make capture work well according to simulation was beyond the state-of-the-art for an operating lens.
- Using a NuMI-like, 250 cm long horn seems to be a better choice$\rightarrow$**0.116** pions are collected out of 0.137 pions / POT after target(85%). In the ring's 2 mm·rad acceptance, 0.084 out of 0.114 pions / POT (74%) are collected. (See picture in next slide)

# Pion Capture(Cont'd)

Total yield of pions is 0.116 pions POT

Inside the 2 mm·rad acceptance ellipse: 0.084 pions POT are captured



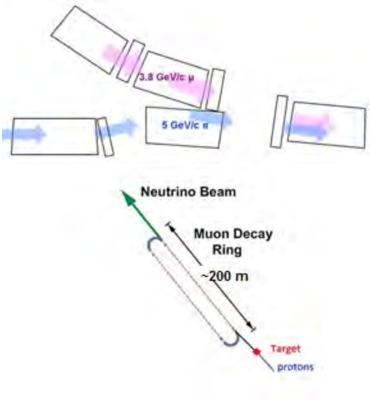

Pion distribution at downstream of the horn. Vertical axis: Angle; Horizontal axis: Position.

# Summary of target and capturing:

We were able to achieve LOI proposed 0.1 pions per POT with a Tantalum or Gold target and a magnetic horn.

# Stochastic Injection

- New injected beam separated with circulating beam by their different momenta.
- Want to store 0.1-0.2 muons / pion
- No need for a separate decay channel;
- No need for full-aperture fast kickers;
- Beam pulse as long as the Main Injector Circumference (3000 m) can be used.

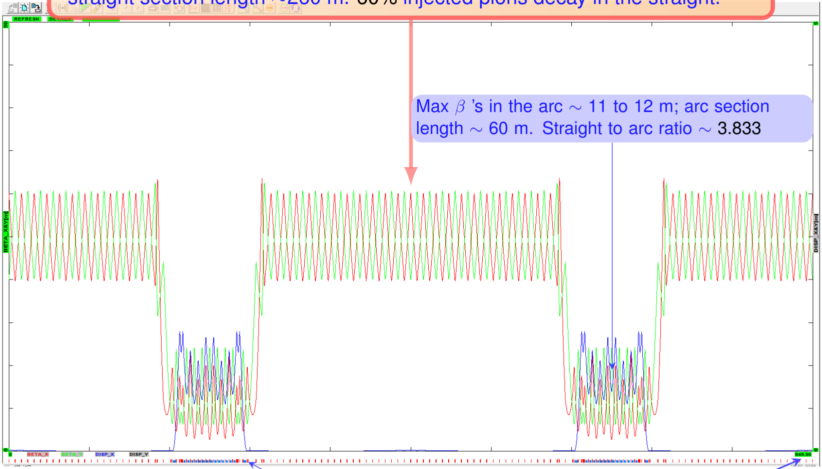


# Goals for transport line study

- Fit the beam transport in MAD8 to
  - Match C-S parameters and dispersion from downstream of the horn to decay ring straight section;
  - Lower beta functions and dispersion to decrease the beam size as much as possible;
  - Also needs to count in the cost of magnet configurations(Try to keep low gradient and keep physical sizes of quadrupoles as few as possible)
- Understand the transmission efficiency of the transport line in G4Beamline - Find the pion flux delivered to the ring;

# Matching into a symmetric FODO ring

Beta functions in straight = 20 to 30 meters (which gives beam radius size ∼0.25 m, and RMS divergence 0.0041 to 0.005. Recall that $1/\gamma \sim 0.03$); straight section length ∼260 m. 60% injected pions decay in the straight.




Max $\beta$ 's in the arc ∼ 11 to 12 m; arc section length ∼ 60 m. Straight to arc ratio ∼ 3.833

Injection-Ring common section, after which $D_x$=0, $\alpha_x$=$\alpha_y$=0, $\beta_x$=9.77 m, $\beta_y$=3.16 m

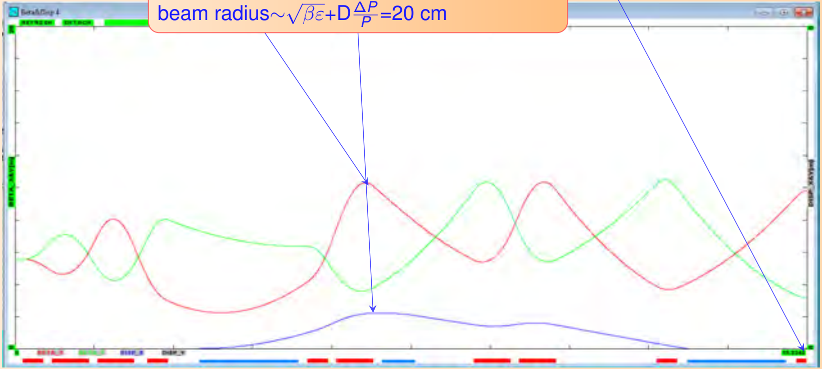
Total length of 645 meters

# Matching into my symmetric ring(Cont'd)

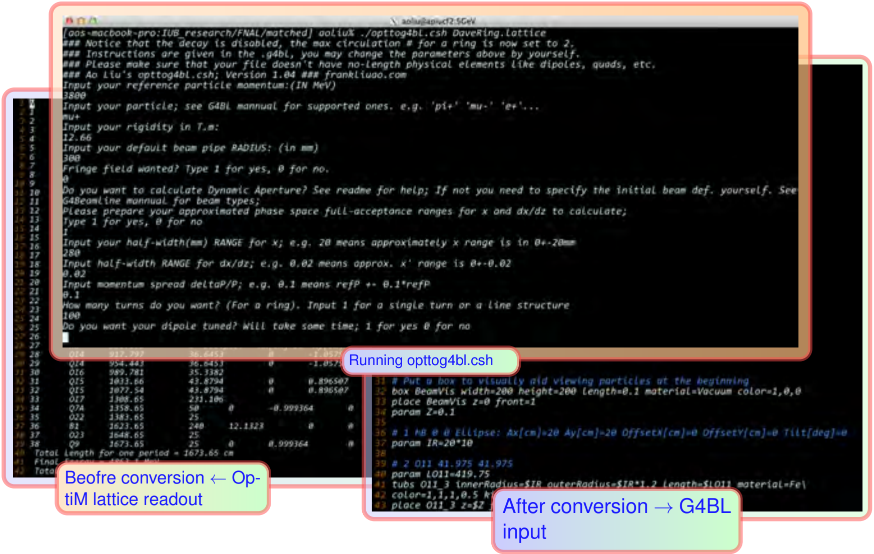
Maximum beta function around 10.3 meters

Total length of 19.2 m; time of flight 64 ns; in pion's frame 1.8 ns; fraction decayed 1-exp(-1.8/26)$\sim$6.7%

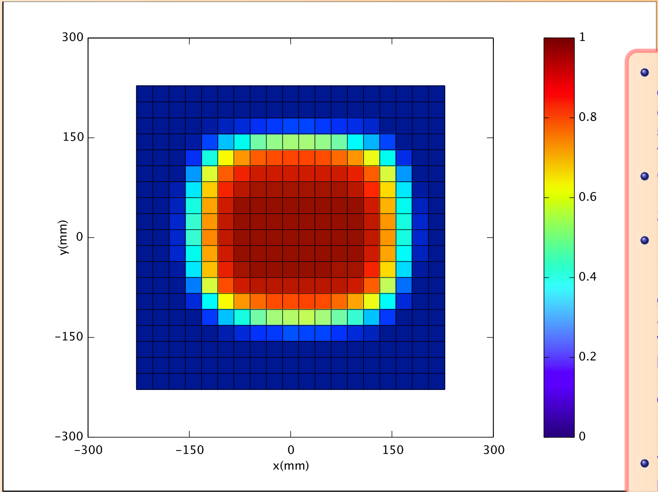
Maximum Dispersion $\sim$ 0.5 m. Approximate beam radius$\sim\sqrt{\beta\varepsilon}$+D$\frac{\Delta P}{P}$=20 cm



# Script conversion from OptiM lattice to G4BL—- opttog4bl.csh version 1.05i



# Dynamic Aperture(DA) calculation with opttog4bl.csh

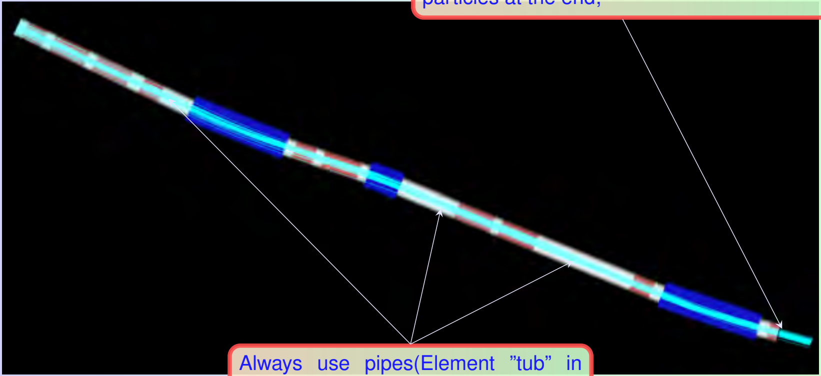



- In this figure, the DA is defined as the percentage of initial particles that can survive passing through the beamline.
- Give estimated x and x' range, then divide them to 20 divisions(steps);
- In each pixel(step), a random distribution of 1000 particles is generated, assuming x' and y' uniformly distributed within $\pm$x' range defined previously; also the momentum is uniformly distributed within the momentum spread range($\pm\Delta$P);
- The virtualdetector counts particles survived, get a percentage.

# Multi-particle tracking in G4BL

From downstream of the horn to the ring. Red blocks show Quadrupoles and blue blocks show dipoles. Cyan lines are particle trajectories.

Use a virtual detector to measure number of particles at the end;



Always use pipes(Element "tub" in G4BL) to kill particles hitting the beam pipes

# Tracking Results from Simulated Initial Pion Distribution

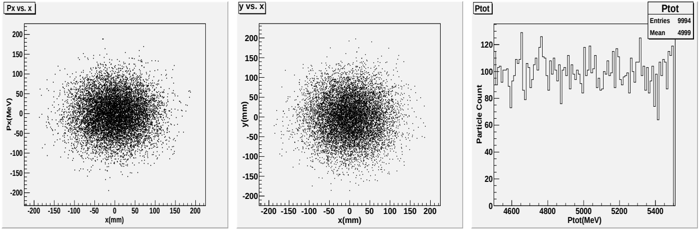
- Turn decay ON → 90% survived;
- Turn decay OFF → 96% survived −− Corresponds to the theoretical decay percentage;

10000 2D Gaussian distributed $\pi^+$'s generated by MATLAB code; RMS emittance = 0.5 mm·rad($\frac{\text{Acceptance}}{4}$); $\beta_x = \beta_y$=5.525 m, $\alpha = 0$)

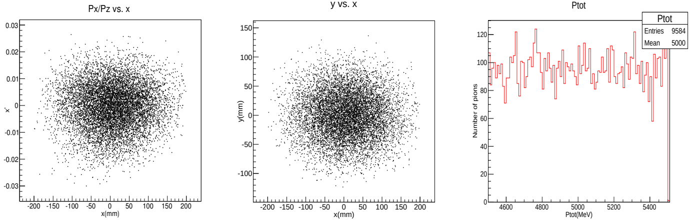
Magnets configuration(In G4BL the fringe field was turned off;)

| Magnet Name | Length (mm) | Distance to horn (From End of Magnet, mm) | Strength (T/m) | Beam pipe radius (mm) | Estimated pole-tip field (T) |
|---|---|---|---|---|---|
| Q1 | 500 | 700 | 6.09 | 200 | 1.22 |
| Q2 | 900 | 1800 | -10.18 | 200 | 2.04 |
| Q3 | 900 | 2900 | 15.37 | 200 | 3.07 |
| Q4 | 500 | 3716 | -14.77 | 200 | 2.95 |
| Q6 | 500 | 7600 | -12.06 | 200 | 2.41 |
| B1 | 2400 | 6884 | - | width=400 | 1.213 |
| QI1 | 900 | 8700 | 10.27 | 200 | 2.05 |
| B2 | 800 | 9715 | - | width=400 | 2.00 |
| QI4 | 900 | 12041 | -9.70 | 200 | -1.94 |
| QI5 | 900 | 13141 | 9.67 | 200 | 1.93 |
| Q7A | 500 | 16074 | -10 | 200 | 2 |
| B1 | 2400 | 18724 | - | width=400 | 1.213 |
| Q9 | 250 | 19224 | 10 | 200 | 2 |

# Tracking Results from Simulated Pion Distribution(Cont'd)

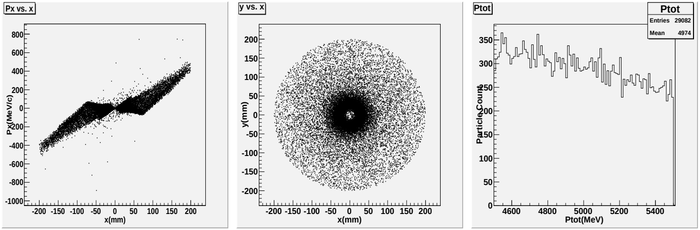



Initial beam: $\sigma_{RMS,x} = \sigma_{RMS,y} \sim 5cm$

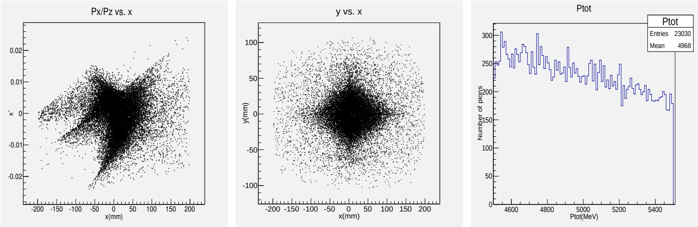



Final beam

# Tracking Results from Pion Distribution(Courtesy of Sergei Striganov) Generated by MARS




Beam at downstream of the horn

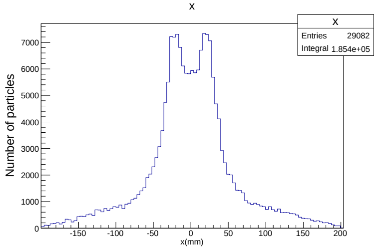


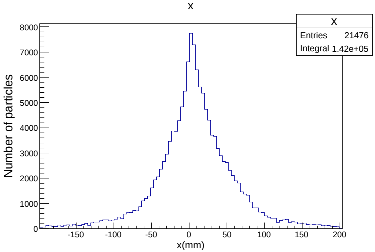

Final beam: Turn decay ON $\rightarrow$ Transmitted: 0.089/0.116=76.6%;

Turn decay OFF $\rightarrow$ Transmitted: 0.095/0.116=82%.

# X distribution of the beams shown in the previous slide.

**Note: The weight is already taken into account; Left: Distribution after downstream of the horn; Right: Distribution at the end of transport;**



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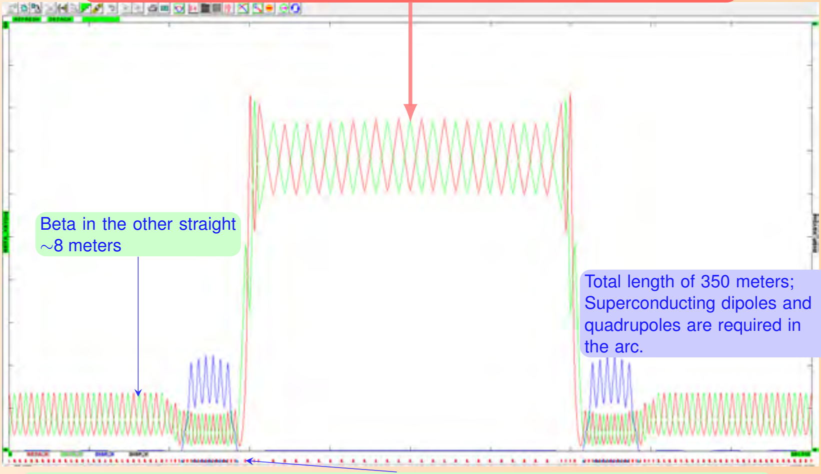
# Matching into Alex Bogacz's asymmetric ring larger beta straight

Beta functions in decay straight section ∼46 meters; straight section ∼ 150 meters. Straight to arc ratio is 6. 42% of pions decay in the straight.

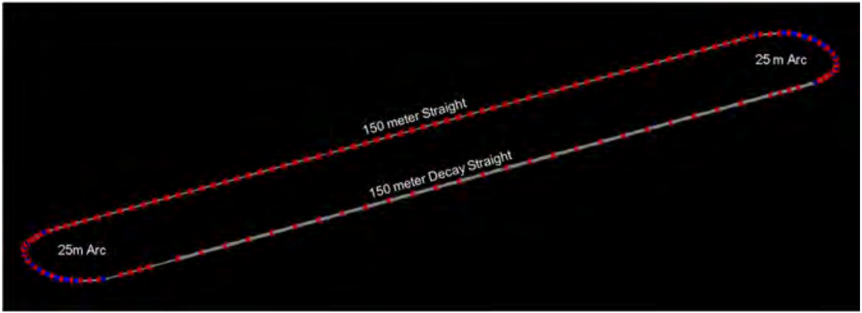


Beta in the other straight ∼8 meters

Total length of 350 meters; Superconducting dipoles and quadrupoles are required in the arc.

Injection-Ring common section, after which $D_x$=0, $\alpha_x$=-7.486, $\alpha_y$=3.07, $\beta_x$=12.57 m, $\beta_y$=28.36 m

# G4Beamline visualization of the asymmetric ring

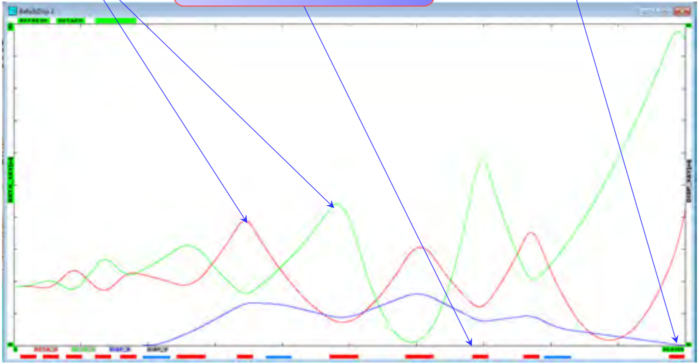


# Matching into Alex's asymmetric ring larger beta straight(Cont'd)

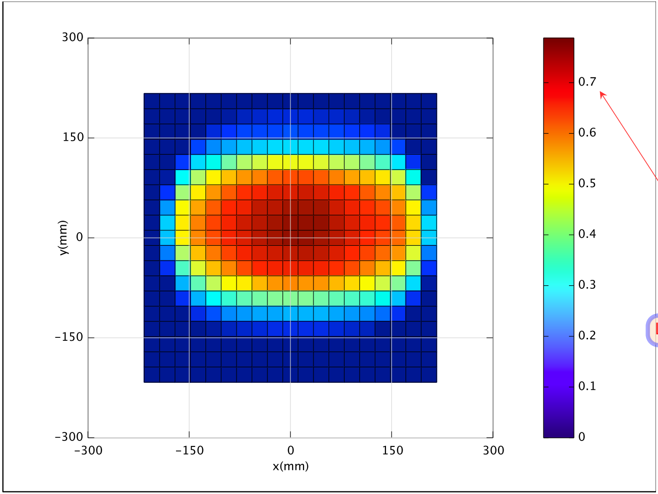
$\beta_x$ ∼11 meters, $\beta_y$ ∼14 meters, respectively.

Common section with the ring starts here

Total length of 21 m; time of flight 70 ns; in pion's frame 2 ns; fraction decayed 1-exp(-2/26)∼7.4%



# DA calculation




Lower scale colormap;

# Tracking Results from Simulated Initial Pion Distribution

- Turn decay ON → 74% survived;
- Turn decay OFF → 80% survived −− Some of the decaying particles died before decay;

Same Gaussian distributed beam as described above(10000 particles, 0.5 mm·rad RMS emittance)

Magnets configuration(In G4BL the fringe field was turned off;)

| Magnet Name | Length (mm) | Distance to horn (From End of Magnet, mm) | Strength (T/m) | Beam pipe radius (mm) | Estimated pole-tip field (T) |
|---|---|---|---|---|---|
| Q1 | 500 | 704 | 1.8 | 200 | 0.36 |
| Q2 | 500 | 1410 | -8.16 | 200 | 1.63 |
| Q3 | 500 | 2129 | 14.92 | 200 | 2.98 |
| Q4 | 500 | 3043 | -15 | 200 | 3 |
| Q5 | 500 | 3830 | 9.38 | 200 | 1.88 |
| B1 | 852 | 4886 | - | width=400 | 3.913 |
| Q6 | 900 | 5986 | -6.189 | 200 | 1.24 |
| QI2 | 500 | 7459 | 15 | 200 | 3 |
| B2 | 1200 | 8659 | - | width=400 | 2 |
| QI4 | 900 | 10745 | -12.61 | 200 | 2.52 |
| QI5 | 900 | 13092 | 10.482 | 200 | 2.10 |
| Q7 | 500 | 14790 | -26.8837 | 200 | 5.377 |
| Q9 | 500 | 16390 | 23.8548 | 200 | 4.771 |
| B1 | 852 | 17367 | - | width=400 | 3.913 |
| Q7A | 500 | 20920 | -8.042 | 200 | 1.608 |

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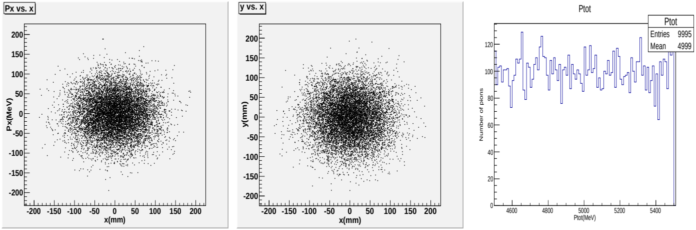
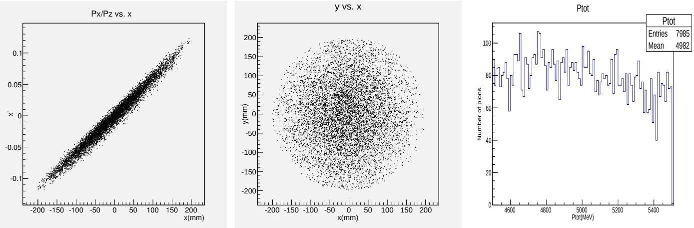
# Tracking Results from Simulated Pion Distribution(Cont'd)

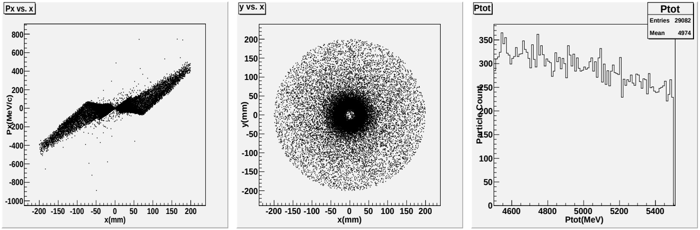



Initial beam

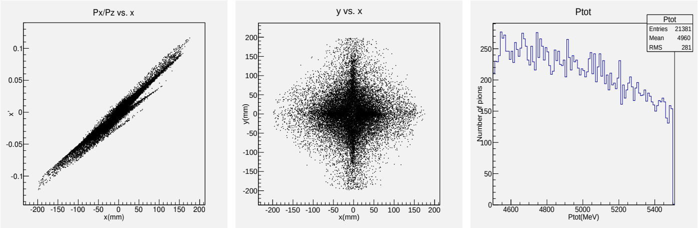



Final beam

# Tracking Results from Pion Distribution Generated by MARS




Beam at downstream of the horn

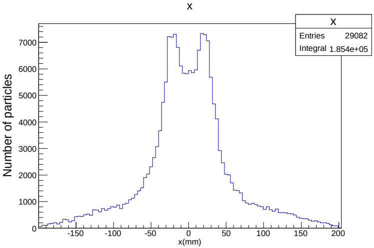


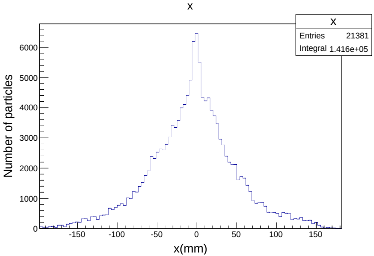

Final beam: Turn decay ON → Transmitted: 0.0822/0.116=71%;

Turn decay OFF → Transmitted: 0.0886/0.116=76.5%.

# X distribution of the beams shown in the previous slide.

**Note: The weight is already taken into account; Left: Distribution after downstream of the horn; Right: Distribution at the end of transport;**



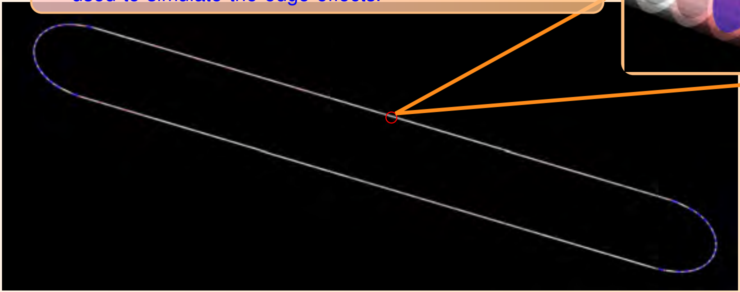
# Summary of transport line study

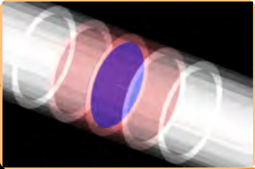
We were able to achieve LOI- proposed 0.072 pions per POT that can be injected to the ring, according to the simulations of transport lines corresponding to our current ring scenarios.

# Ring Simulation using G4Beamline

- Use a particlefilter(blue) at the beginning namely the end of the ring to limit the number of turns;
- Use a virtualdetector at the end of the ring to trace particles for each turn;
- Use a beamlossntuple to record the loss of each particle;
- Converted by opttog4bl.csh from OptiM: automatically connected to be a ring; if dipole edge effects are considered, genericbends rather than sectordipoles are used to simulate the edge effects.

A degree larger than 360 may cause an overlap of the last element and the first one, which results in failure of particlefilter killing.(Can view the angle from OptiM-Orbit)





# First trial of simulation of the ring

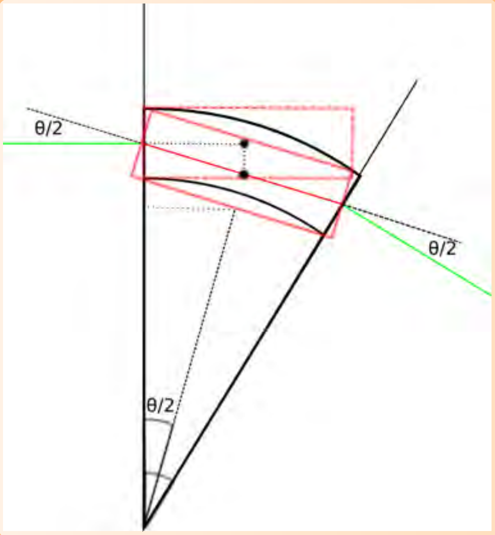
- Starting with my ring since the dipoles are pure sector dipoles;
- The initial C-S parameters: $\beta_x$=30 m, $\beta_y$=20 m, $\alpha_x = \alpha_y = 0$
- Choose RMS emittance = $\frac{Acceptance=2mm\cdot rad}{4}$=0.5 $mm \cdot rad$, different momentum spread($P_0$=3800 MeV)
- Simulation time will be long since there are hundreds of elements in one turn. Thus only 50 muons were used to perform the first step study.
- 100 turns = 64556 meters $\rightarrow$ 215.2 microseconds $\rightarrow$ 5.98 $\mu s$ in muons' view $\rightarrow$ $e^{-(5.98e-6)/(2.2e-6)}$=0.0659 survived assuming no loss but only decaying;

(30 cm radius magnet aperture)

| Transmission | 1 turn | 100 turns |
|---|---|---|
| $\frac{\Delta P}{P_0}$=0 | 41/50 | 41/50 |
| $\frac{\Delta P}{P_0}$=0.1 | 34/50 | 25/50 |

(No chromaticity correction) Tunes crossed resonance lines for larger momentum spread; would consider adding sextupoles soon.

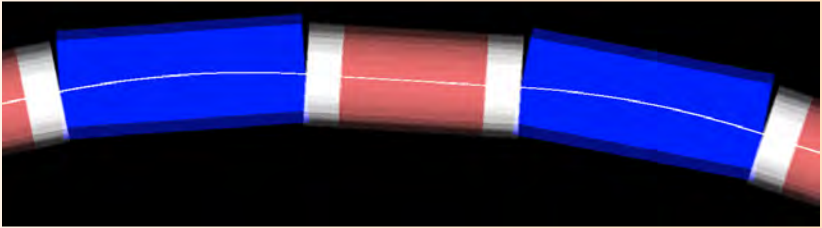
# Automating ring beamline conversion with dipoles having edge effects




- Sector dipoles → rectangular dipoles
- Real length(a line) is shorter than the sector arc length in optics design;(Need to consider that in G4Beamline)
- Center of the rectangular dipole should displaced by the amount shown(both horizontally and vertically);
- Rotation angle of the dipole is always half of the bending angle.

# Tuning the dipoles

To make sure the reference particle circulates the ring in a single circle rather than forming an envelope, we need to tune the dipoles to center the reference trajectory. To do this both the dipole field and the centerRadius of its corresponding cornerarc can be adjusted, to minimize the transverse reference offset and angle.



# Transmission for Alex's Ring beamline

Transmission slightly lower compared to the previous ring scheme (This ring requires even larger aperture in the decay straight, since $\sqrt{\beta\varepsilon}$ $\sim$31 cm already at max beta positions) – there is still no sextupole chromaticity correction. Also need to be further inspected.

(30 cm radius magnet aperture)

| Transmission | 1 turn | 100 turns |
|---|---|---|
| $\frac{\Delta P}{P_0}$=0 | 35/50 | 34/50 |
| $\frac{\Delta P}{P_0}$=0.1 | 29/50 | 10/50 |

# Conclusions

- Two transport lines for the current FODO ring schemes have been developed, they are able to achieve $\sim$ 0.085 pions / POT including decay;
- A SHELL script has been written to automate the conversion from OptiM lattice to G4BL input format, and is being updated based on specific requirements;
- The ring simulation using G4BL has been started and several different scenarios will be further tested.