U.S. DEPARTMENT OF ENERGY

Fermilab

Project X Based Muon Factory

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APT Seminar

Fermilab

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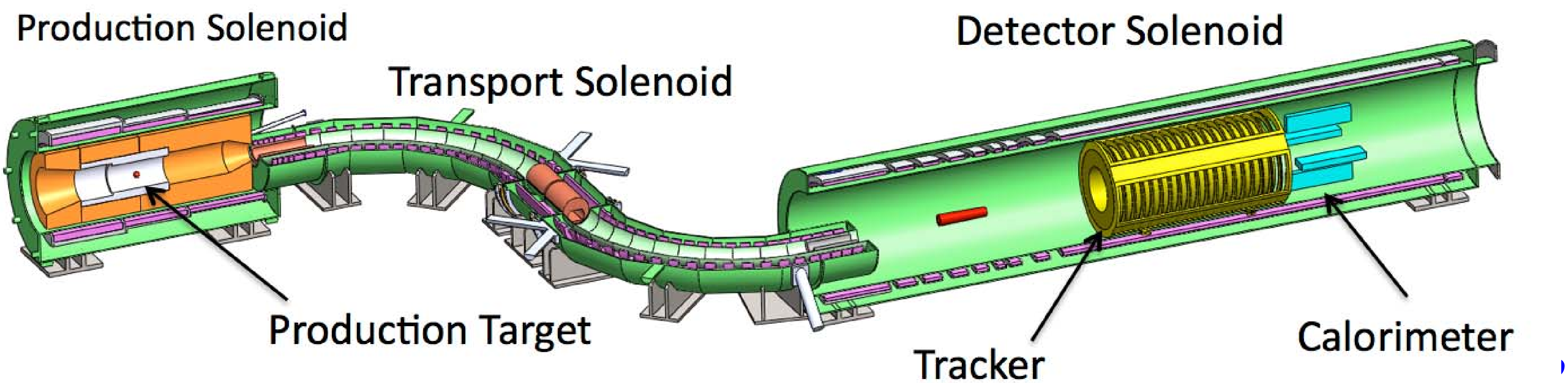
Present μ-to-e

- Conversion – 2.1·10^{-3} ($dN_p/dt=2.4\cdot10^{13}\ s^{-1}$, P=25 kW, $dN_\mu/dt=5\cdot10^{10}\ s^{-1}$)
- Extinction <10^{-10} (sensitivity $6\cdot10^{-17}$(90% C.L.))
- Target (gold, L~16 cm, r=0.5 cm, water cooled)
  - Total power - 25 kW
  - Power left in the target – 2 kW
- Secondary target
  - 17 Al discs, 0.2 mm thick, 5 cm apart, tapered radii – r_d = 8.3 → 6.53 cm
- Magnetic fields
  - Production solenoid: 5T -> 2.5 T, internal radius 0.75 m (reflection of muons)
  - Transport solenoid – 2 T
  - Detector solenoid : 2T -> 1T (reflection of electrons with negative $p_{||}$)



Major Requirements to a New Generation μ-to-e Experiment†

- ~100 times better than μ-to-e
  - single event sensitivity $2\cdot10^{-19}$ (or $6\cdot10^{-19}$ at 90% CL)
    - ⇒ $5\cdot10^{18}$ muons: 2 years of $2\cdot10^{7}$ s each
    - ⇒ $1.2\cdot10^{11}$ muons/s or 2.5 times of μ-to-e
    - ⇒ Conversion ≥ $6\cdot10^{-5}$ (3 GeV beam with 1 MW power)
  - Pc < 20 MeV i.e. E_{kin}<1.9 MeV (stopped in 0.4 mm Al foil)
  - Extinction <10^{-14} for pions; no antiprotons
  - Short pulse: t < 10 ns
  - Detector is located underground (≥12 m)
- Short pulse and very good extinction imply that the beam transport has to be in an isochronous beam line
  - Drastic reduction of transverse and longitudinal acceptances
    - ⇒ 1 MW Project X power should be helpful
- Limitation of maximum energy to <1 MeV points out to the muon deceleration as a possible choice

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† Bernstein & Prebys, July 26, 2011

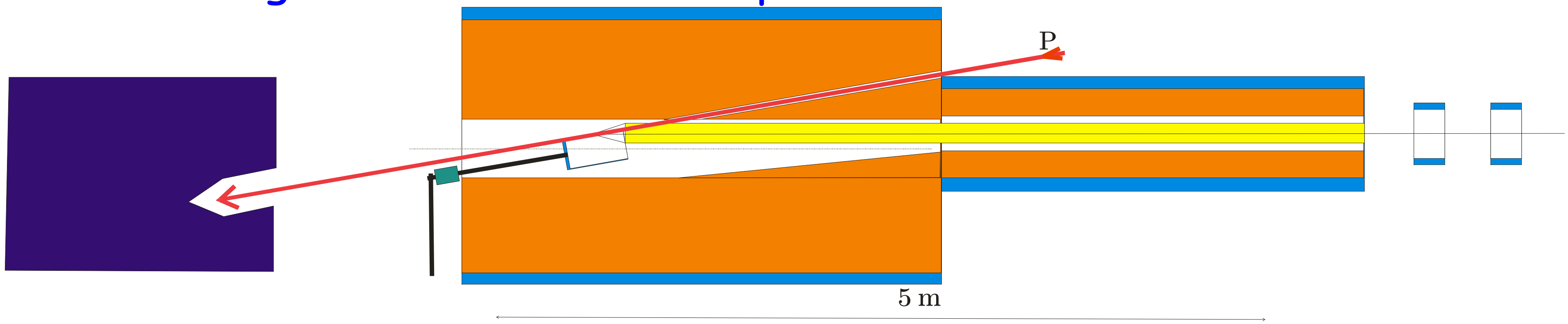
Questions to be addressed

- Target or how to handle the beam power
  - Required shielding
  - Target shape and material
  - Target cooling
- Particle distributions and emittances of pions and muons
  - Effect of magnetic field strength and line acceptance
  - Distribution changes at conversion of pions to muons
- Phase space manipulation for muon beam
  - Which area of the phase space we would like to use
  - Matching between the target and the decay solenoid
  - Deceleration and ionization cooling
- Beam transport and background suppression
    - Beam transport in isochronous beam line
    - Deceleration versus ionization cooling

- *This talk should not be considered as a proposal for a project It rather discusses major limitations and possible ways of their mitigation*

Target

- The target length should be ~1.5 of nuclear interaction length
  - ⇒ Carbon ~60 cm
  - ⇒ Tantalum ~15 cm
- The beam leaves ~10% of its energy in the target;
  - ⇒ ~100 kW for 1 MW power
  - ♦ 90% goes to the beam dump



- Relative to pulsed beam the CW beam drastically reduces stress in target

Target cooling

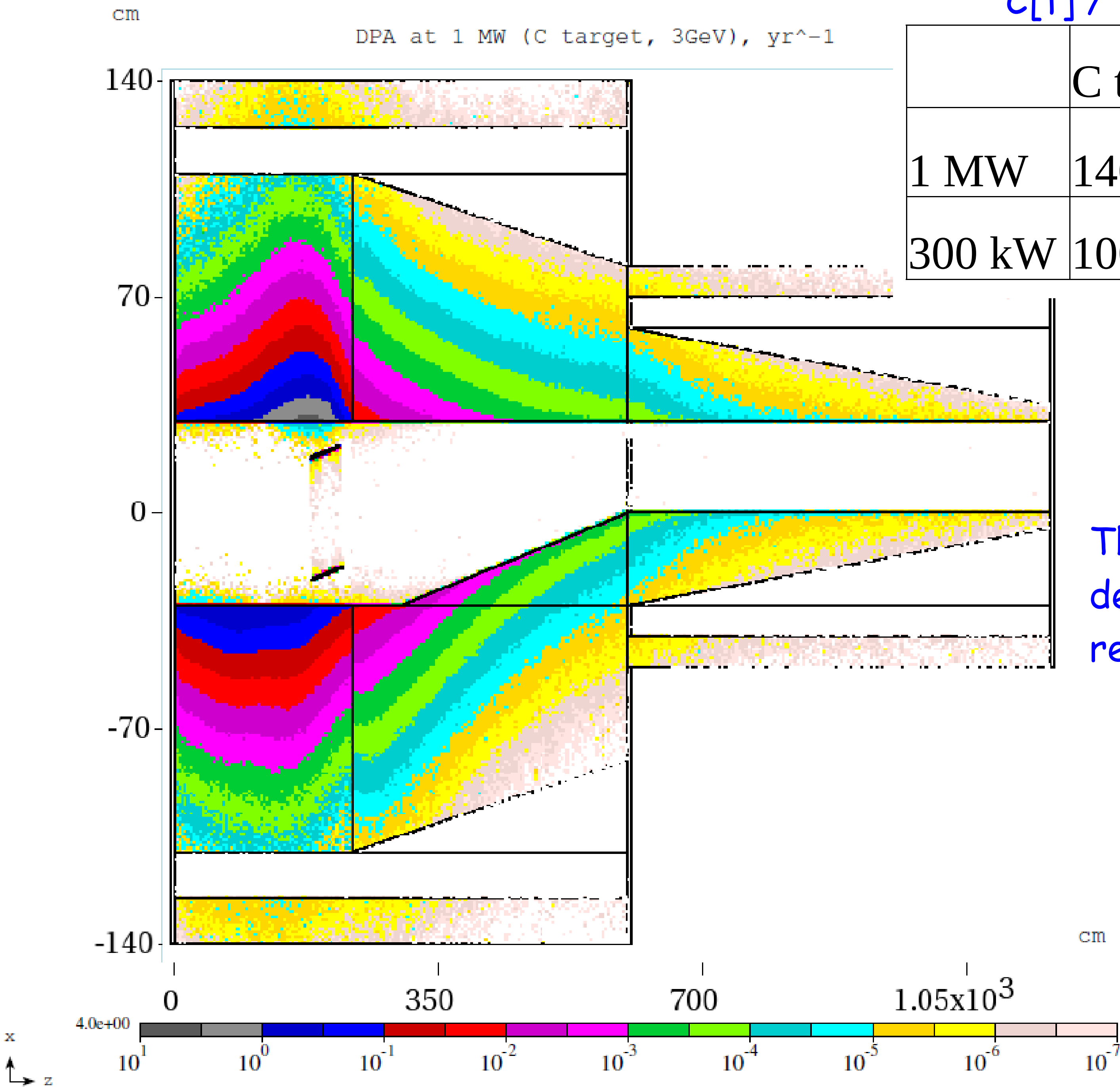
- For 1 MW beam power the power left in the target is ~ 100 kW
  - Heat cannot be removed from pencil target: dP/dS~2 kW/cm^2 for R~0.5cm
  - Relative to this an oxidation and repairs look as an easy problem
- Two possibilities
  - Liquid metal stream (muon collider)
    - Looks expensive
    - Reliability, safety and repair issues
  - Rotating cylinder cooled by black body radiation
    - PSI uses a rotating graphite target at 1 MW beam power
    - Tantalum, R=10 cm, d=0.5 cm, L=15 cm, 400 rev/min

      $\Rightarrow$ T $\approx$ 3000 K (melting T = 3270 K), ΔT $\approx$ 50 C
    - Graphite (C), R=10 cm, d=0.5 cm, L=40 cm, 60 rev/min

      $\Rightarrow$ T $\approx$ 1800 K (melting T = 3270 K), ΔT $\approx$ 50 C
    - For C temp. looks OK but we still have to address

      $\Rightarrow$ Bearing lifetime under radiation (rotation)
- Any solution requires vacuum windows to separate target from the beam => 1 MW windows
    - Do we need to have the target in vacuum?

Effects of radiation



Shielding estimate

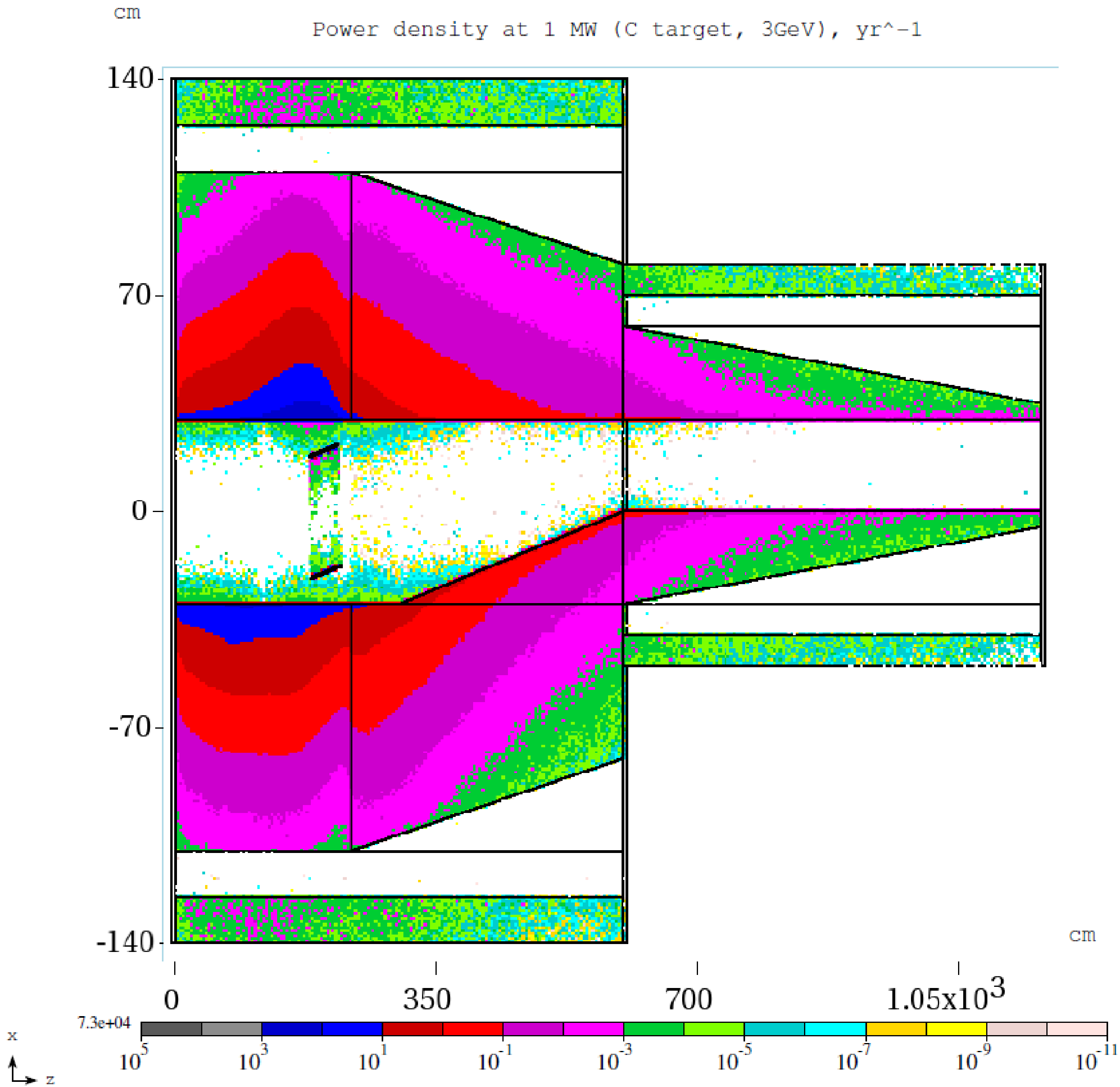
C[t] / W[t] /Rmax [cm]

	C target	Ta target
1 MW	140/80 (110)	180/100 (125)
300 kW	100/55 (95)	110/65 (100)

This preliminary absorber design satisfies typical requirements for SC coils

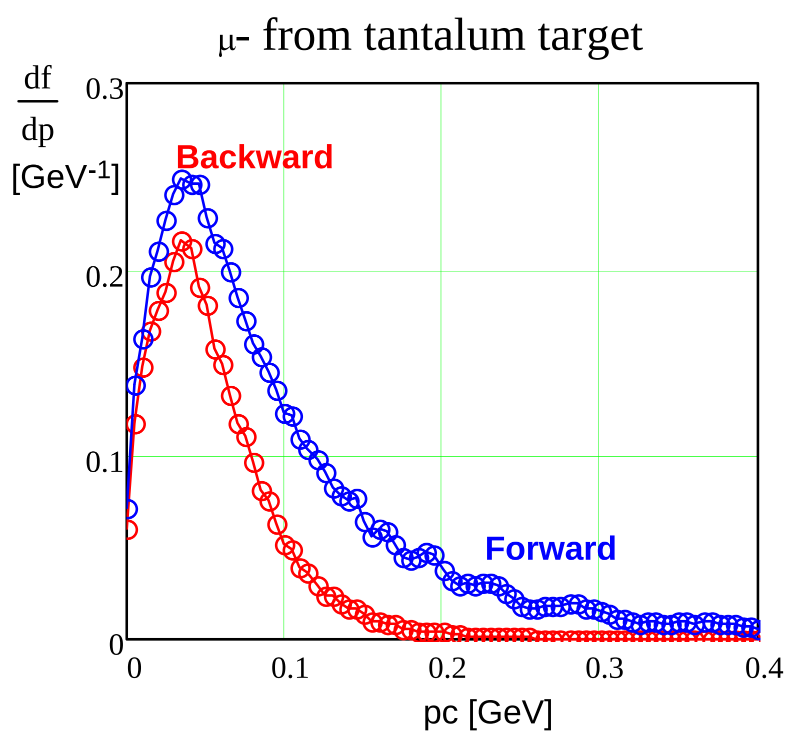
- peak DPA 1E-5 yr^-1)
- power density (3 μW/g)
- absorbed dose 60 kGy/yr
- Dynamic heat load is 10 W

Effects of radiation (continue)



Muon's longitudinal distribution (per 1 GeV of proton energy)

- 3 GeV/c (E_{kin}=2.2 GeV) proton beam (this choice is supported by measurements)
  - ♦ $\sigma_x = \sigma_y$ = 1 mm – parallel beam, proton multiple scattering unaccounted



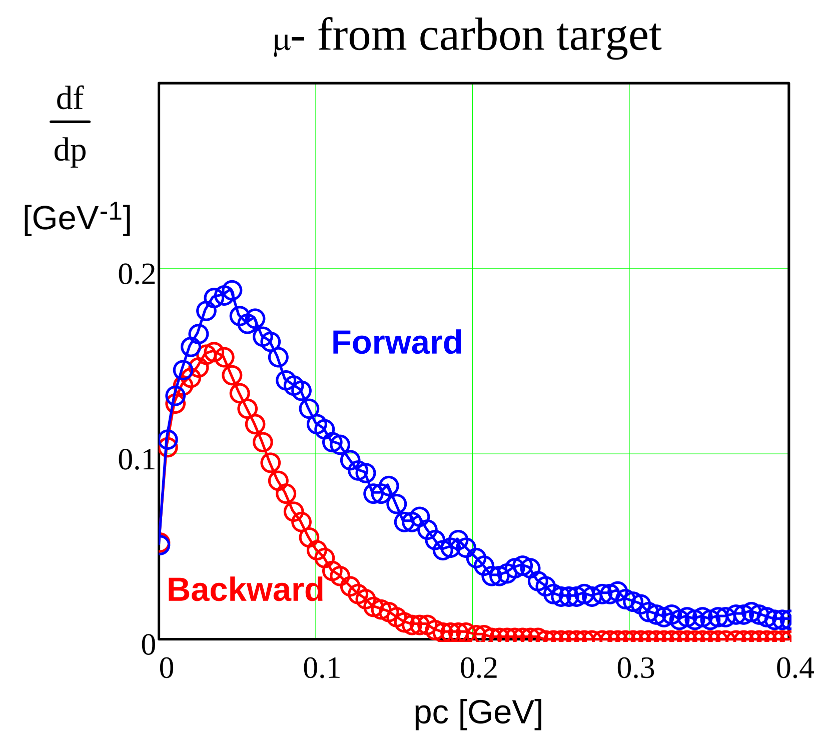
Tantalum hollow cylinder (Pc=3 GeV)

R_{out}=20 cm, ΔR=5 mm, L=16 cm, θ=300 mrad

Total muon yield at ±10 m

Forward – 1.4% per proton GeV

Backward – 0.73% per proton GeV



Carbon hollow cylinder (Pc=3 GeV)

R_{out}=20 cm, ΔR=5 mm, L=40 cm, θ=200 mrad

Total muon yield at ±10 m

Forward – 1.3% per proton GeV

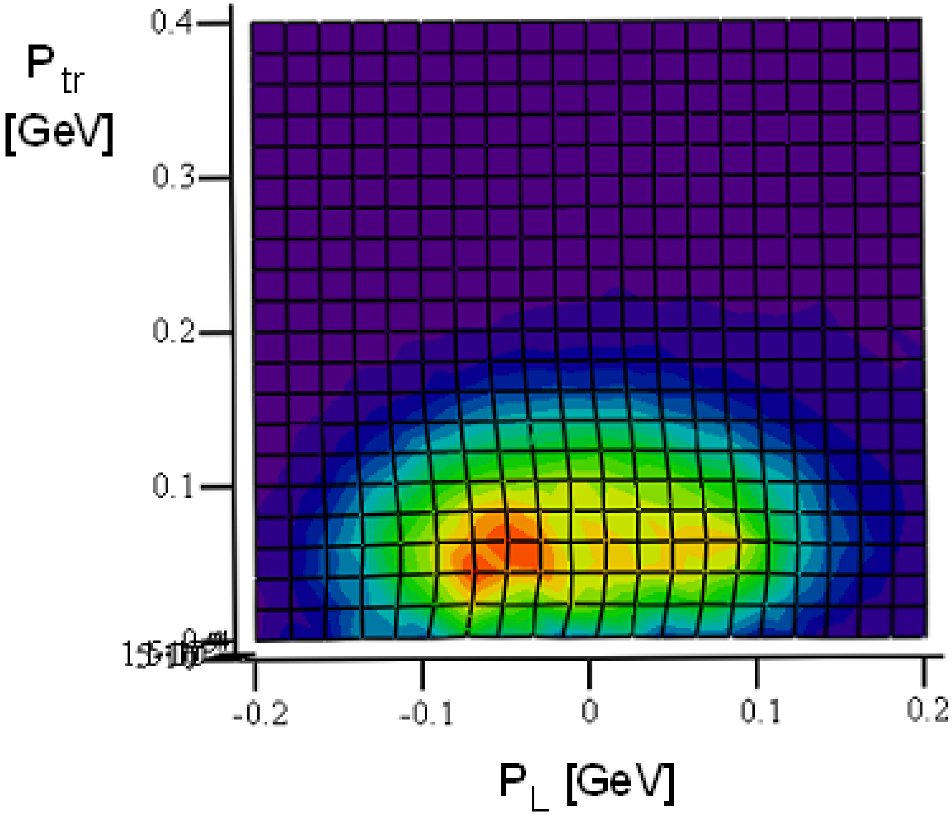
Backward – 0.59% per proton GeV

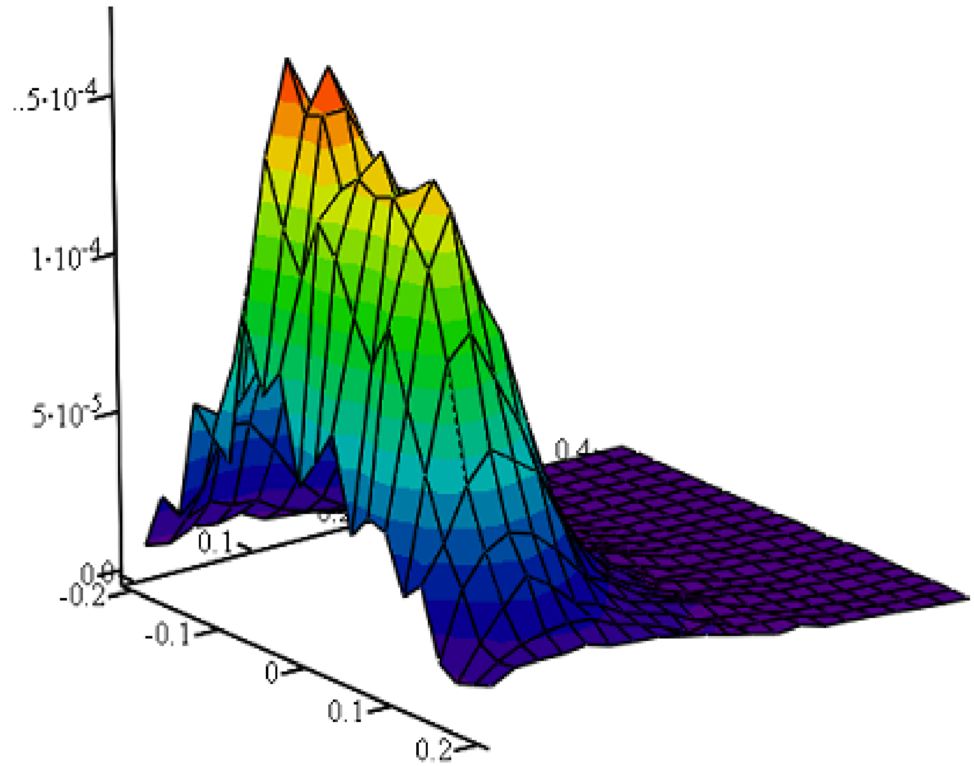
- Small difference between forward and backward muons for Pc<50 MeV

Muon's longitudinal distribution (contunue)

- Compared to a pencil like target a hollow cylinder target has smaller muon yield by more than factor of 2
  - But it allows one to use much larger beam power
- For Pc<100 MeV the carbon target has smaller yield but
  - Less problems with cooling due to larger length
  - It also makes less neutrons
- Beam damp inside solenoid would be a formidable problem therefore below we assume:
  - Backward muons
  - Carbon target
- We also assume the proton energy of 2.21 GeV
    - For $E_{kin} \in [2, 8]$ the production of slow muons per unit beam power weakly depends on the beam energy

Pion distribution over momentum





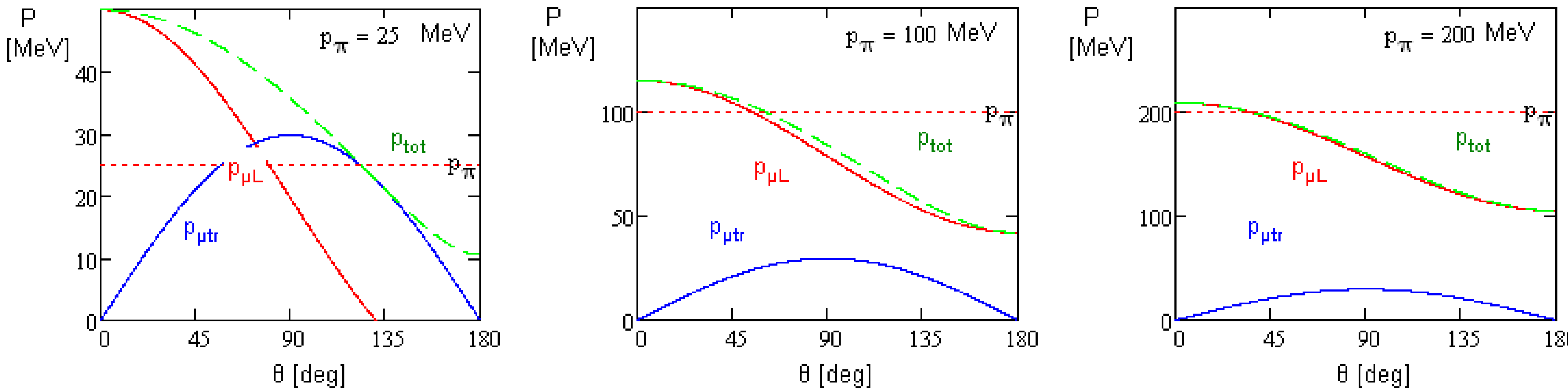
Pion distribution over momentum, d^3N/dp^3 ,
Nickel cylinder, L=10 cm, r=0.4 cm; no magnetic field
Total production: forward 5.3% p_GeV^{-1}; backward – 2.9% p_GeV^{-1}

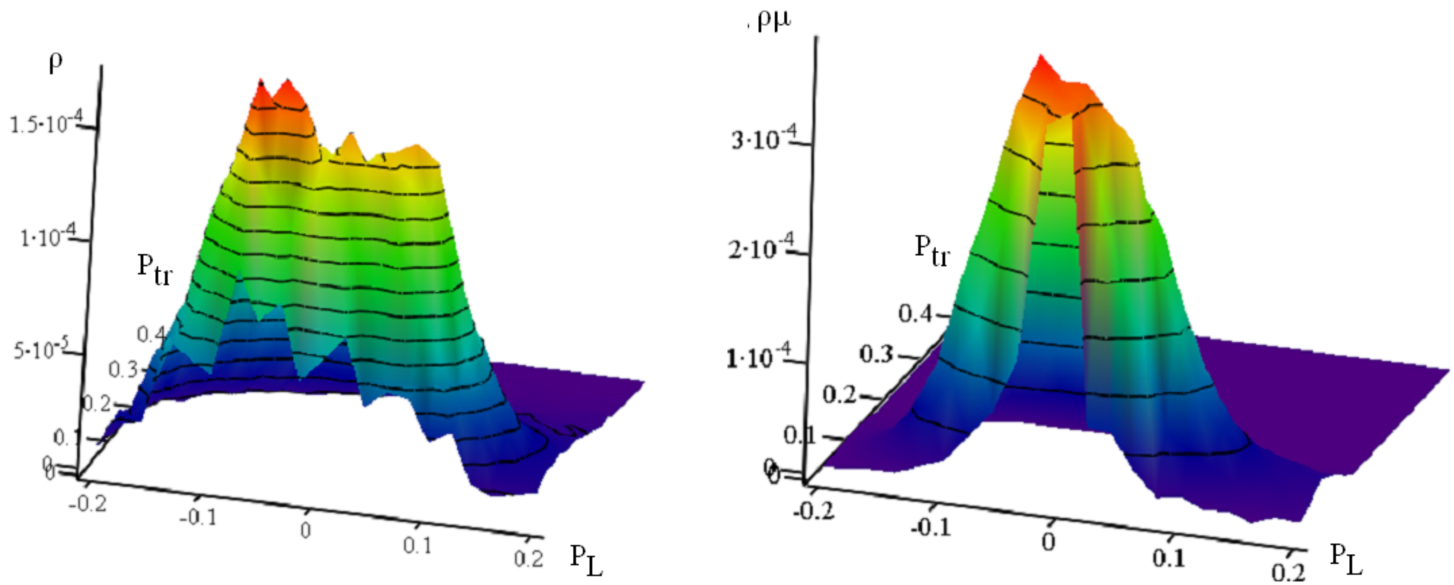
- Pion distribution is close to the Gaussian one with σ_p = 100 MeV/c
- Distribution function approaches zero due to particle deceleration at the target surface: $f(p_\perp) \propto p^3 / \left(p^4 + p_r{}^4\right)^{3/4}, \quad p_r \approx \sqrt[4]{m_\mu{}^3 \delta r \left(dE/dx\right)_0 / c}$
  where $\left(dE/dx\right)_0$ is the energy loss at $\beta = 1$ (~1.6 MeV/(g/cm^2)); $p_r \approx$20 MeV/c

Muon distribution over momentum

- After decay a muon inherits the original pion momentum with Δp correction depending on the angle of outgoing neutrino, Δp_{cm}=29.8 MeV/c
- For most of pions (p > 60 MeV/c) a decay makes a muon with smaller *p*

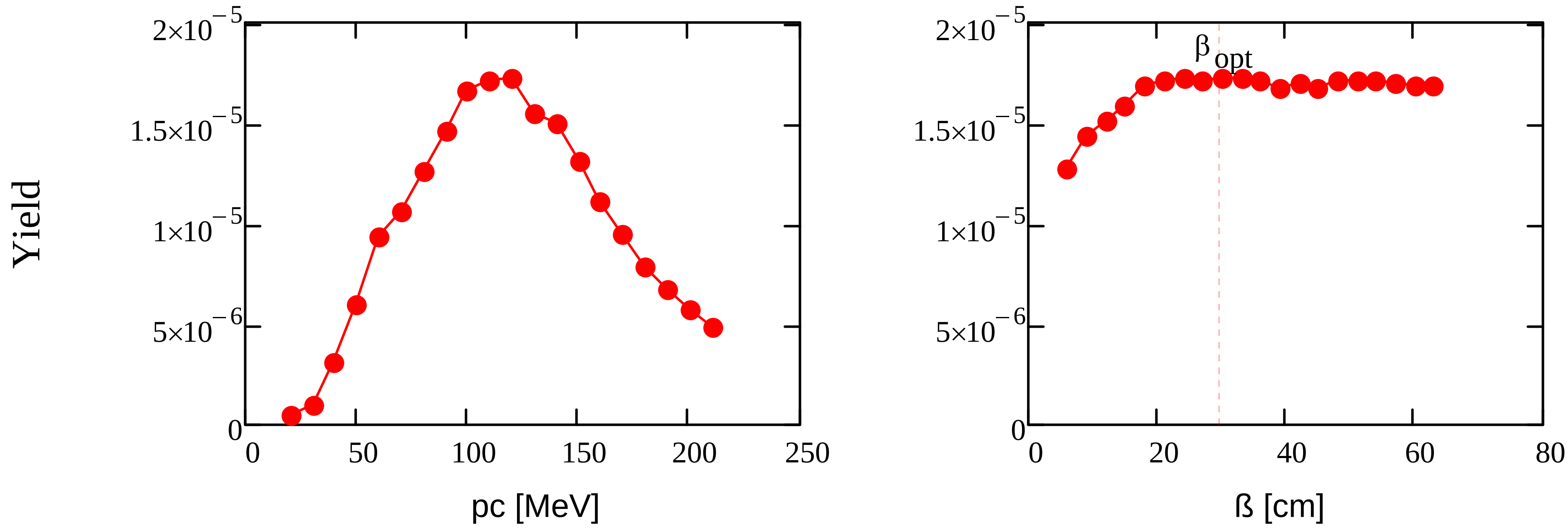
$\Rightarrow$ Momentum spread in μ-beam is smaller than in π-beam





Muon yield into the beamline finite acceptance

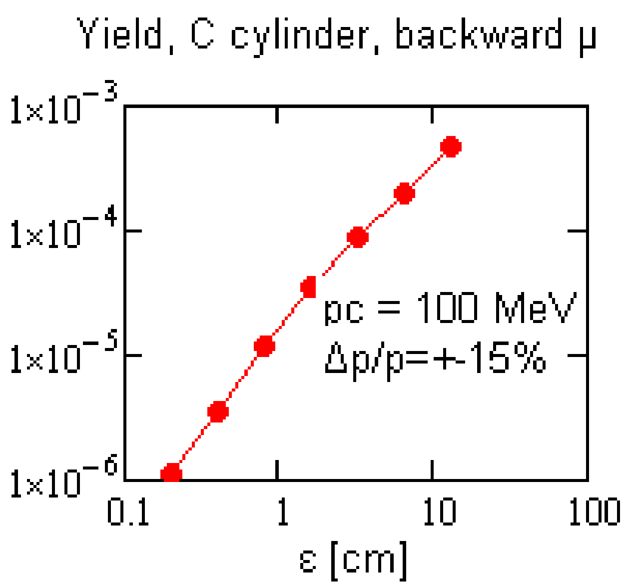
- Issues related to the beam transport in a "normal" beam line
  - Isochronous transport requires bends and soft focusing, Q_x~1
  - Beam line limits maximum acceptance and momentum spread to $\varepsilon \approx$ 0.3-3 cm, $\Delta p/p \approx \pm 0.15$
  - We can match the beam line to the decay solenoid so that to maximize the capture $\Rightarrow \beta_{opt}$
    - Weak dependence on β for small ε
    - Strong suppression of small energy muons (pc<50 MeV) due to deceleration in medium

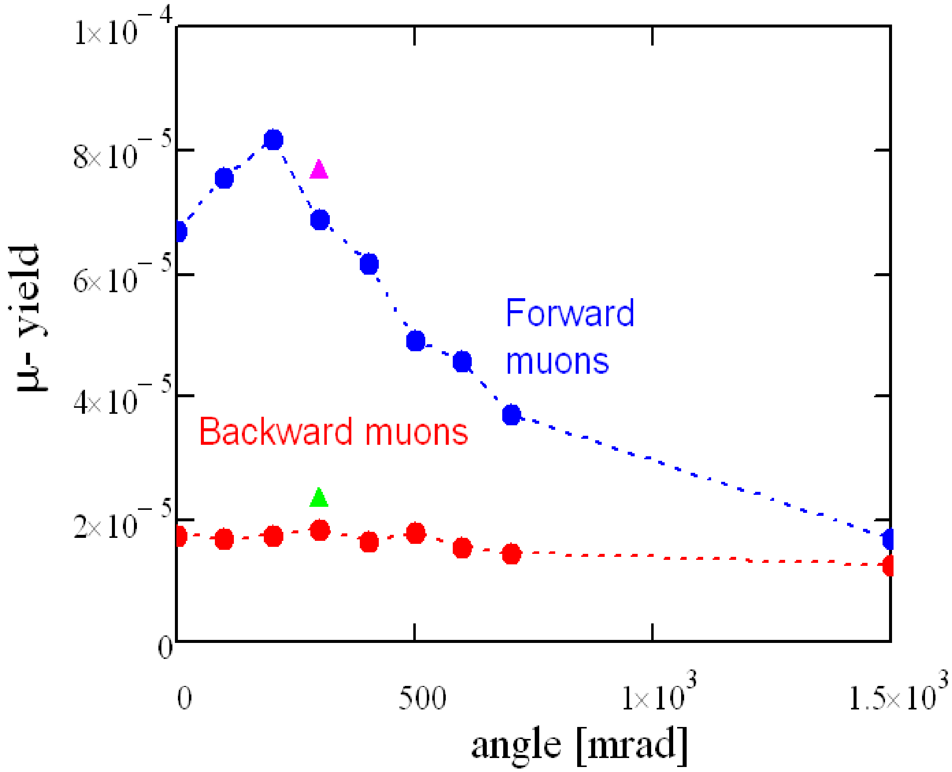


Graphite target, backward muons, $\varepsilon_x = \varepsilon_y$ = 1 cm, $\Delta p/p = \pm 0.15$, θ = 200 mrad, B=2.5 T.

Muon yield into the beamline finite acceptance (continue)

- Pions are produced with zero angular momentum and muons inherit this property
  $\Rightarrow$ Absence of x-y correlations after beam exit from magnetic field
  $\Rightarrow$ Beam line axis has to coincide with solenoid axis
- Yield is proportional to B_{target}
  - 2.5 T $\rightarrow$5 T would double the yield
- Yield is $\propto \Delta p/p$ (for $\Delta p/p \ll 1$)
- Yield is $\propto \varepsilon^{1.5}$

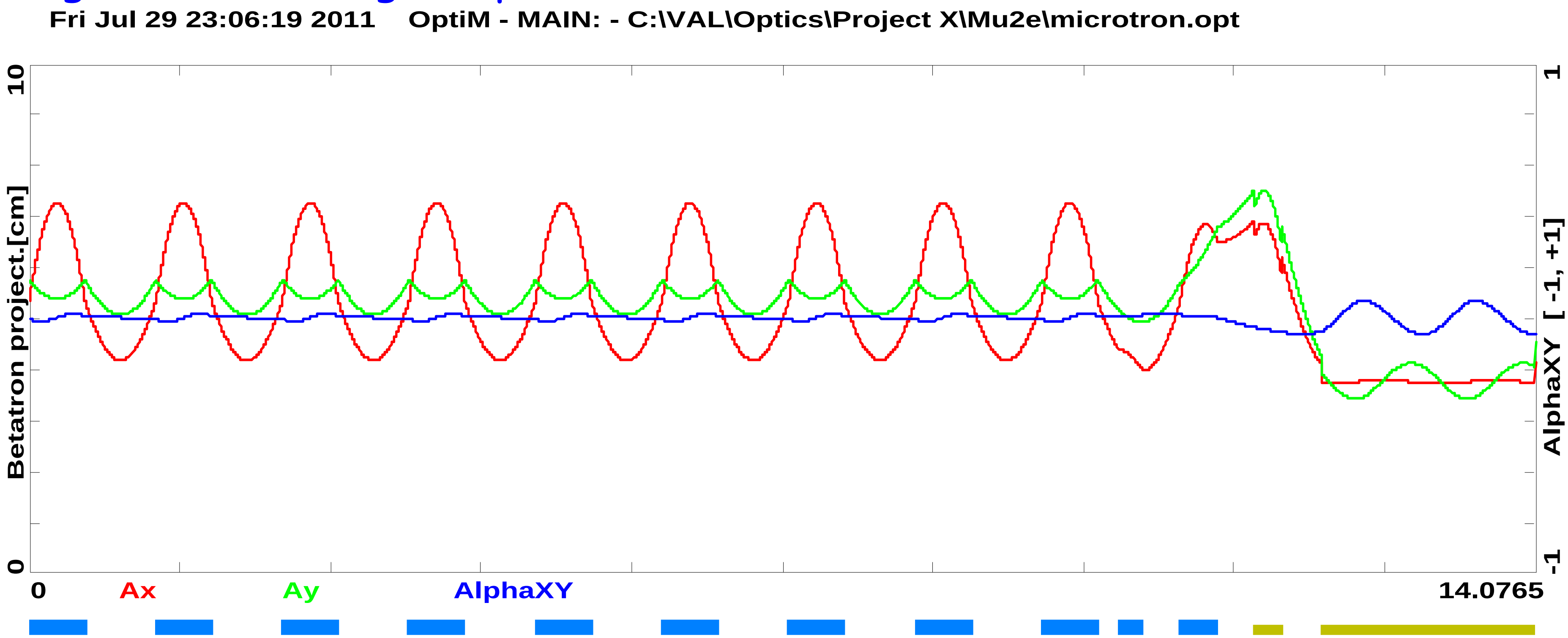




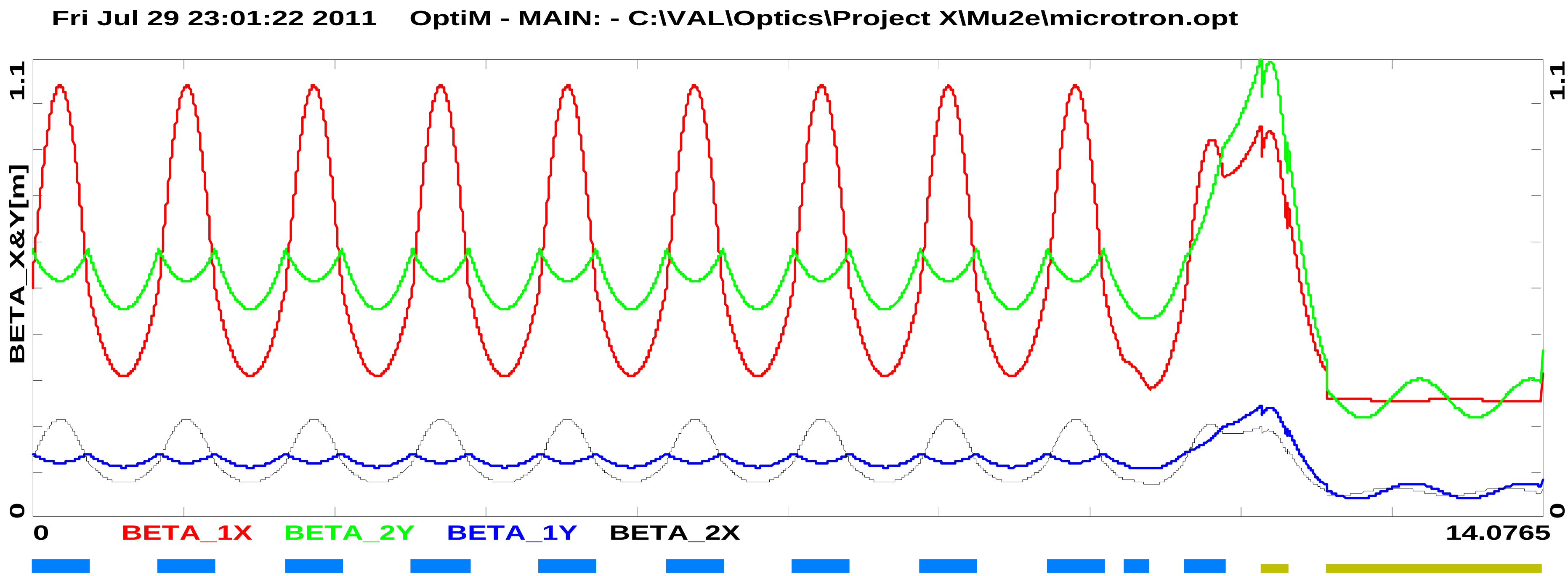
Dependence of muon yield on target angle relative to magnetic field for carbon target into the following phase space: $\varepsilon_x=\varepsilon_y=1$ cm, $\Delta p/p=\pm 15\%$,
Optimal momenta are: 100 MeV/c for backward and 200 MeV/c for forward muons
Triangles show results for tantalum target

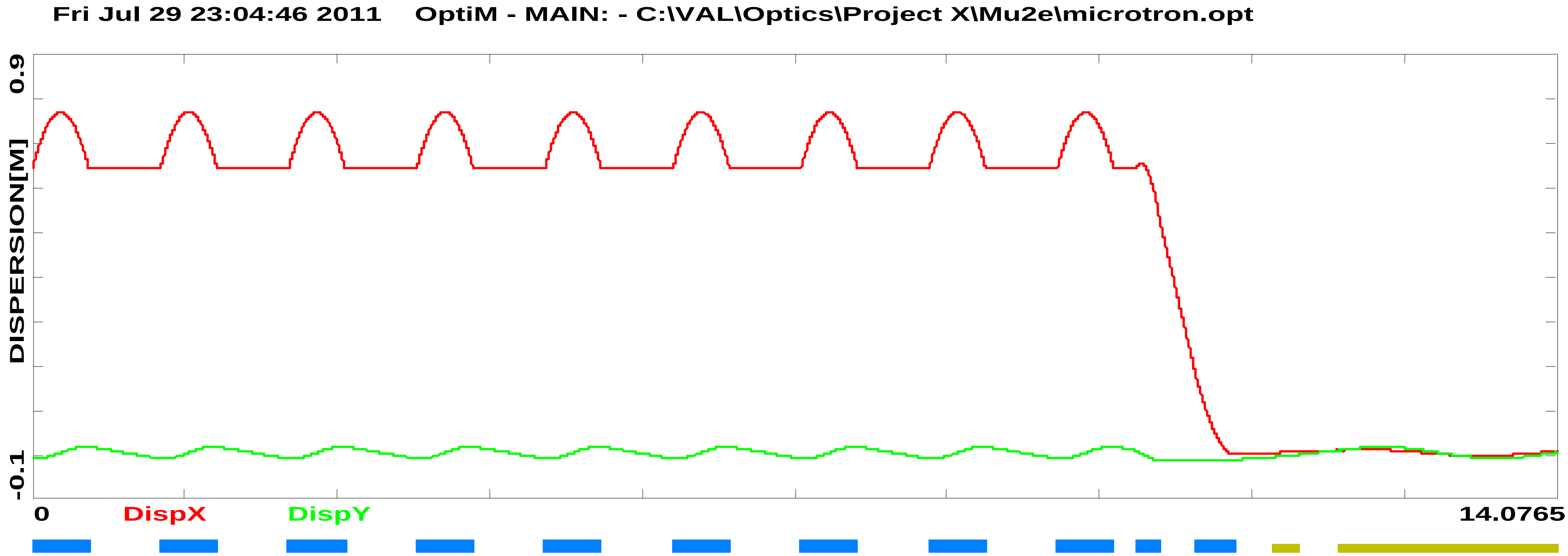
Beam transport in Helical Transport Line

- The line consists of downward spiral
  - matched to the production and detector solenoids with two dipoles and one or two solenoids at each end
- One revolution includes 4 dipole magnets: B=5 kG (Pc=50 MeV), L=52.3 cm, R=33.3 cm, gap 13 cm, good field region width: ±15 cm
- The line acceptance 0.41 cm; Momentum spread ±0.15, it descends with angle of 2.591 deg, step of the helix is 23.973 cm



Betatron beam envelopes for helix and match to the detector solenoid. Acceptance 0.41 cm





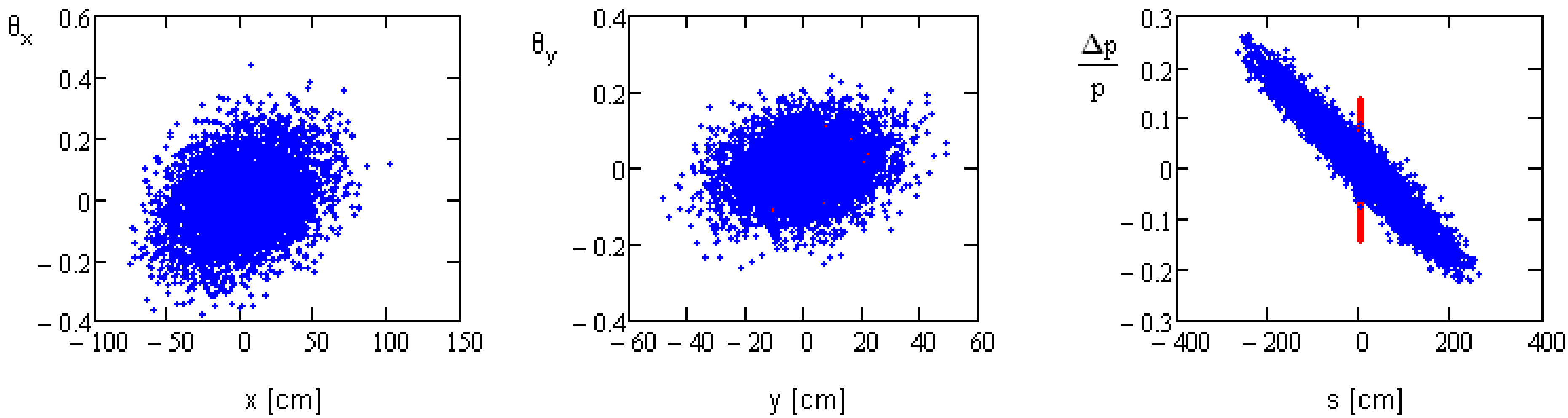
4D beta-functions (top) and dispersions (bottom) for helix and match to the detector solenoid

Beam transport limitations

- To match the yield requirement of $\sim 10^{-4}$ we need to have a line with acceptance of ~3 cm (backward muons from carbon target)
  - Similarity of optics yields: $\varepsilon \propto a \propto \beta_{x,y} \propto R_0$
  - Isochronicity requires soft focusing, Qx ~ 1
  - Magnetic fields are reduced with increase of R_0 making magnet price affordable
  - Total length and number of turns is determined by required pion extinction (~70 m for 50 MeV/c and extinction of 10^{-14})

Possibilities with Deceleration

- Deceleration in electro-magnetic structure results in the adiabatic antidumping, with consequential 6D emittance growth $\propto p^{-3}$, i.e. 8 times for every factor of 2 in momentum
- Deceleration in the material looks much better at large p ($p \geq m_\mu$) but behaves the same way ($\propto p^{-3}$) for non-relativistic particles
  - even worse than it if multiple scattering is important (large $\beta_{x,y}$ at absorber)
  - Redistribution of damping decrements in realistic simulation partially helps but does not address the problem



$g_L \equiv 1$ $\quad \kappa_{scat} \equiv 1$

$\mu_x \equiv 2\cdot\pi\cdot 0.25$ $\quad \mu_y \equiv 2\cdot\pi\cdot 0.25$ $\quad D \equiv 150$ cm $\quad \varepsilon_x \equiv 3$ cm

$\beta_x \equiv 200$ cm $\quad \beta_y \equiv 200$ cm $\quad D_p \equiv 0.0$ $\quad \varepsilon_y \equiv 3$ cm

$\alpha_x \equiv -0.3$ $\quad \alpha_y \equiv -0.2$ $\quad M_{56} \equiv 0$ $\quad \sigma_p \equiv 0.15$

$\kappa_{eff} = 0.281$

$\frac{\varepsilon x_{fin}}{\varepsilon x_{in}} = 6.89$ $\quad \frac{\varepsilon y_{fin}}{\varepsilon y_{in}} = 2.54$ $\quad \frac{\sigma p_{fin}}{\sigma p_{in}} = 1.758$

Conclusions

- Requirements on the total muon flux accepted into a beam line can be met for muons with momenta ~100 MeV (E_{kin}=40 MeV)
- Requirements on isochronicity can be met
- Number of muons at low energy is reducing fast
  - Deceleration results in about the same yield decrease as the direct capture would do
  - Changes in the target design look as a promising avenue

$$f(p_\perp) \propto p^3 / \left(p^4 + p_r^{\,4}\right)^{3/4}$$

$$p_r \approx \sqrt[4]{m_\mu^{\,3} \delta r \left(dE/dx\right)_0 / c}$$

  - Small emittance of Project X will be helpful
    - Convergent beam
    - Mitigation of multiple scattering for protons in the target