Muon Task Force

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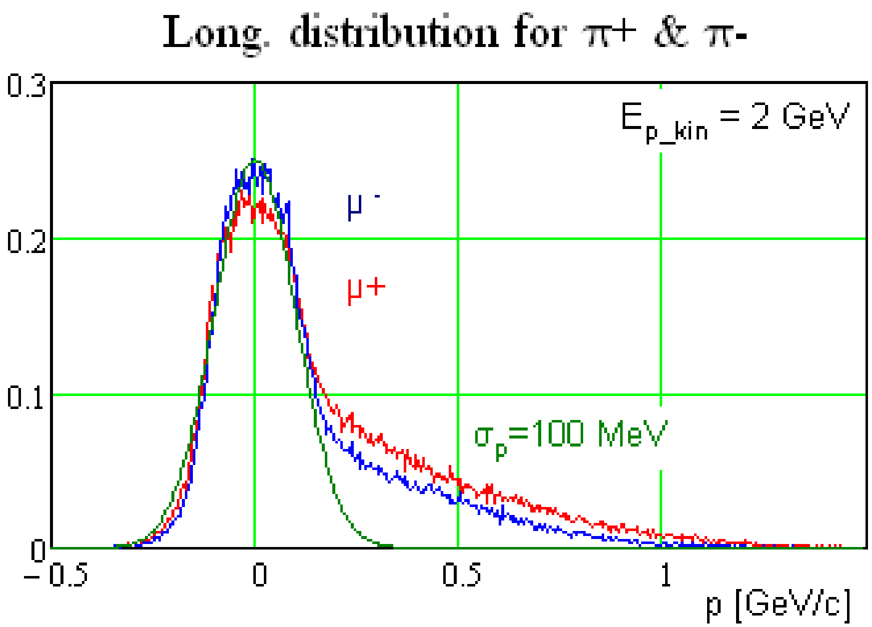
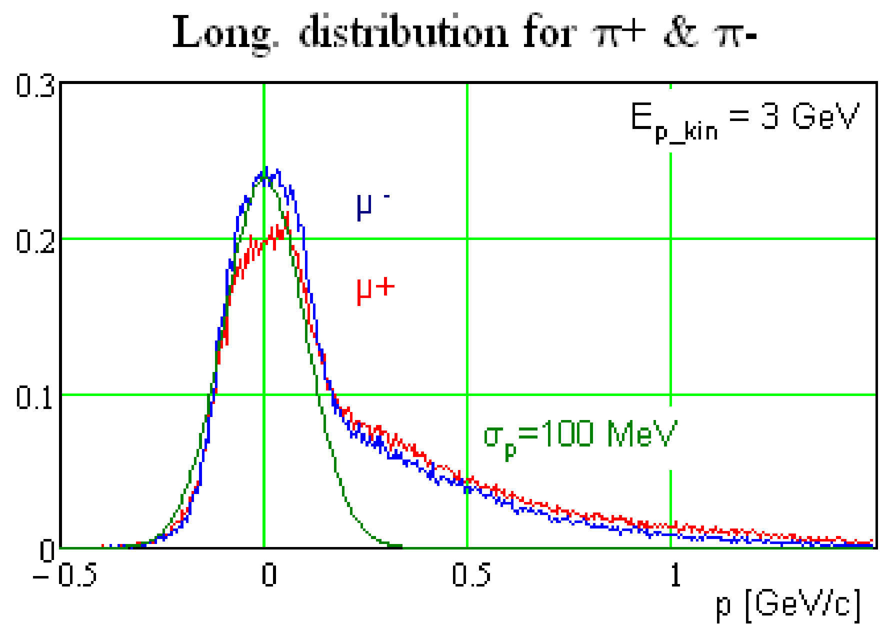
Objective

- Project X can deliver ~1 MW beam
  - Factor ~40 larger than the power expected in μ-to-e
- How to use this power?
  - How should the target look like?
- Which additional possibilities for experiments can we obtain?
  - Achievable muon flux
  - What else can be done to improve experiments with stopped muons

Pencil-like target

Pion distribution over momentum for Nickel target





Longitudinal distribution function $(df/dp_{||})/E_{p\_kin}$ [c/GeV^2]

Nickel cylinder, L=10 cm, r=0.4 cm; no magnetic field

Total production per unit energy of incoming protons

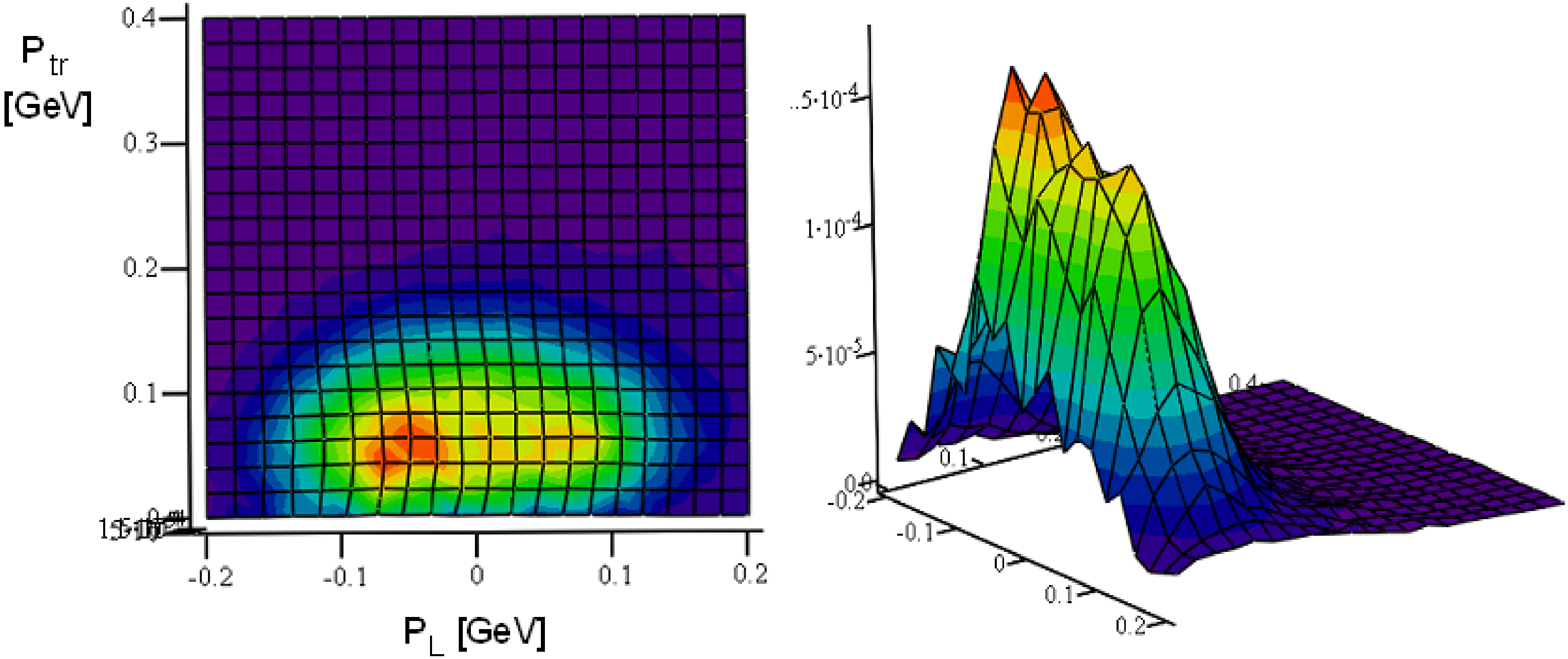
Ekin=2 GeV: forward 5.3% p_GeV^{-1}; backward – 2.9% p_GeV^{-1}

Ekin=3 GeV: forward 6.3% p_GeV^{-1}; backward – 2.8% p_GeV^{-1}

- Longitudinal pion distribution is close to the Gaussian one, $\sigma_p \approx$ 100 MeV/c
- Central part of distribution has weak dependence on the incoming proton energy in the range [1-8] GeV
  - High energy tail grows with proton energy

Pencil-like target (continue)

Pion distribution over momentum for Nickel target (continue)



Pion distribution over momentum, d^3N/dp^3 ,
Nickel cylinder, L=10 cm, r=0.4 cm; no magnetic field

- Distribution function approaches zero due to particle deceleration at the target surface

Pion deceleration due to ionization lass

For $\gamma\beta \in [0.1,\ 1]$ one can write $\dfrac{dE}{dx} \approx \dfrac{1}{\beta^2}\left(\dfrac{dE}{dx}\right)_0$

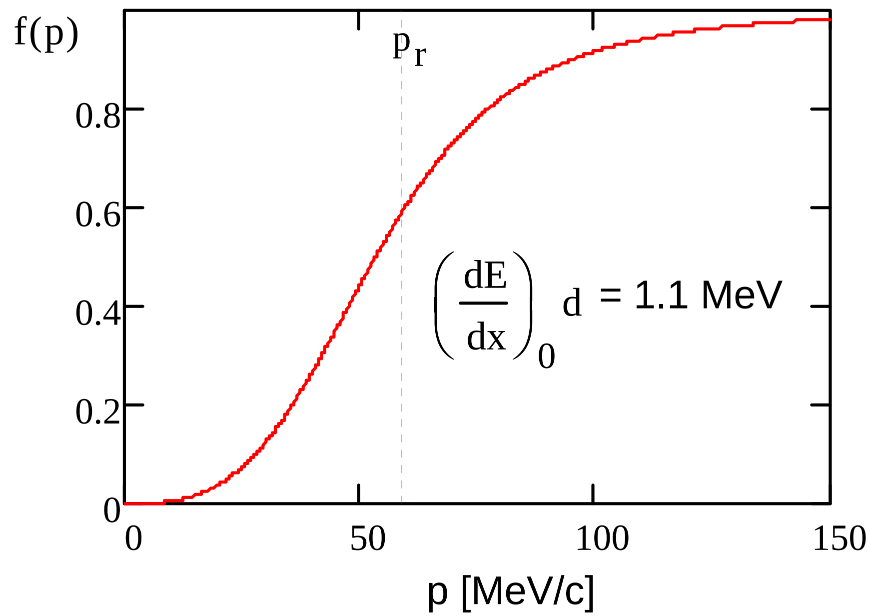
For non-relativistic case $E = m_\pi c^2 \beta^2 / 2$ => $p_{fin}{}^4 \approx p_{in}{}^4 - 4 m_\pi{}^3 c^2 \left(\dfrac{dE}{dx}\right)_0 L$

Distribution function change is: $f(p_{fin}) = \dfrac{f(p_{in})}{dp_{fin} / dp_{in}}$

Combining one obtains:

$$f'(p_{fin}) \propto p_{fin}{}^3 / \left(p_{fin}{}^4 + p_r{}^4\right)^{3/4}$$

where: $p_r \approx \sqrt[4]{4 m_\pi{}^3 c^2 L \left(dE/dx\right)_0 / c}$



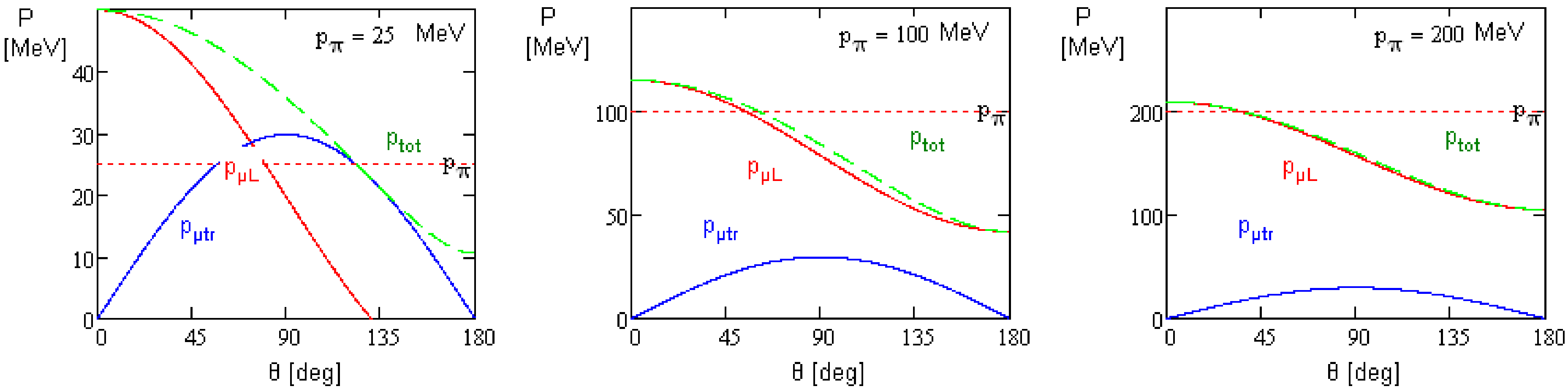
- p_r has comparatively weak dependence on medium properties

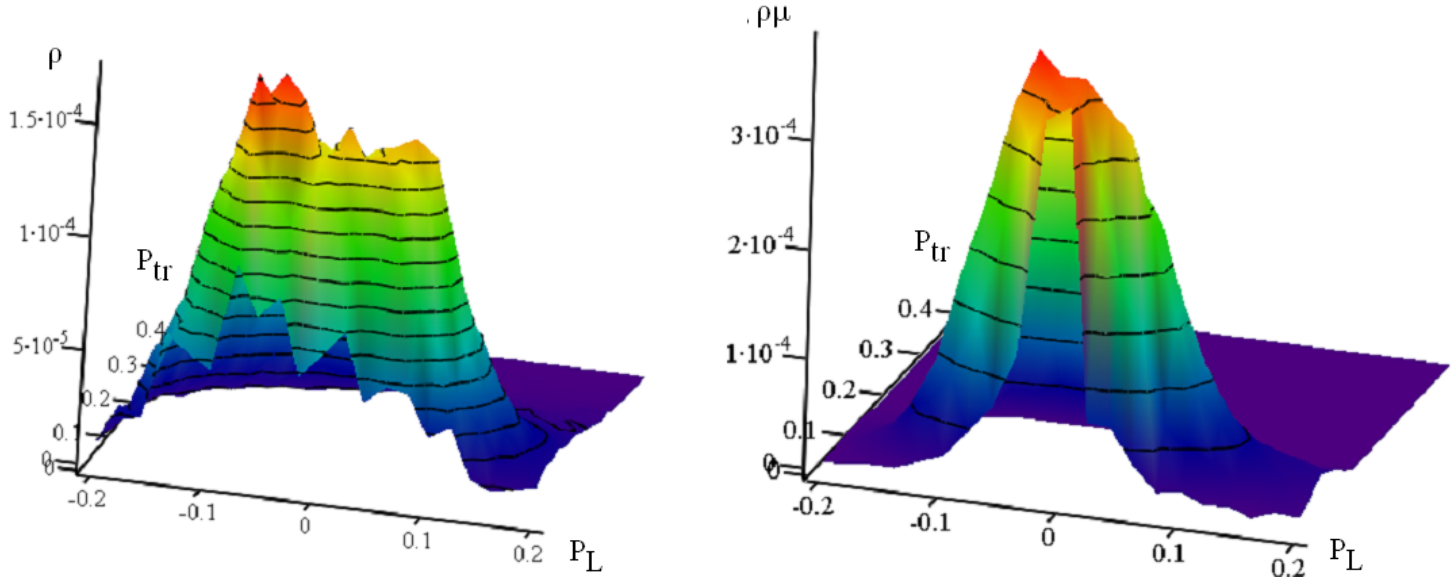
  $(dE/dx)_0$ ~1.6 MeV/(g/cm^2)); $p_r \approx 1$ MeV/c for $L \approx 1$ mm

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*

⇒ Momentum spread in μ-beam is smaller than in π-beam





Phase Density and Emittance of Muon Beam

- Pions
  - For short target, $L_{t\arg} < F$, (antiproton source)

$$\beta^*_{opt} \approx \frac{L_{t\arg}}{6} \quad \Rightarrow \quad \varepsilon \approx \frac{L_{t\arg}}{6}\sigma_\theta^{\ 2}$$

  - For small energy pions this approximation does not work, i.e $L_{t\arg} \geq \beta$
    - In this case
      - $\varepsilon \approx \beta\sigma_\theta^{\ 2}$ where $\beta = \dfrac{2pc}{eB}$
      - and beam emittance does not depend on the target length

      ⇨ Phase density of pions is proportional to the magnetic field
- Muons
  - To reduce emittance growth due to pion decays the pions are transported in a solenoidal magnetic field
  - Pions are produced in the solenoid center

    ⇨ they have small angular momentum
  - Pion decays have little effect on the angular momentum and the beam emittance

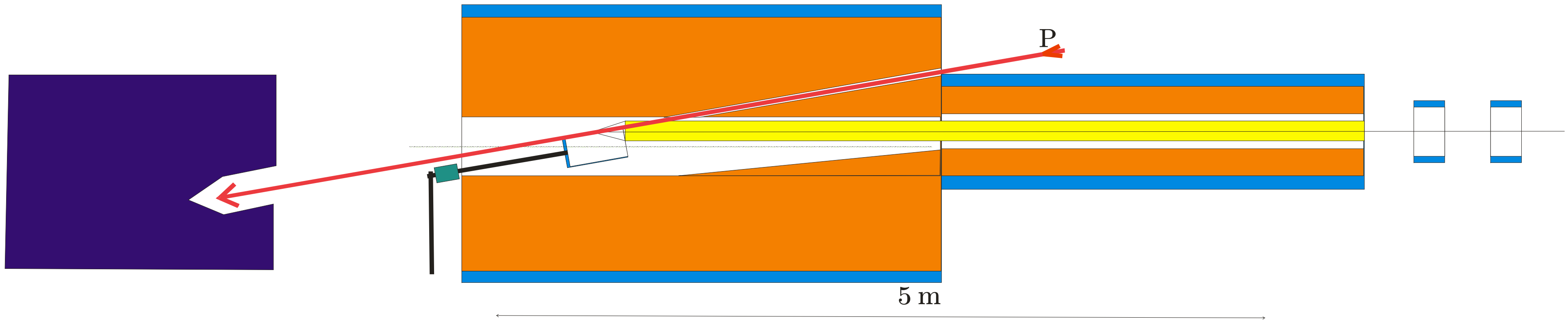
    ⇨ Phase density of the muons is proportional to pion density and, consequently,

    ⇨ the number of muons in given phase space is proportional to the magnetic field

    ⇨ and muons do not have x-y correlations after exiting the solenoid

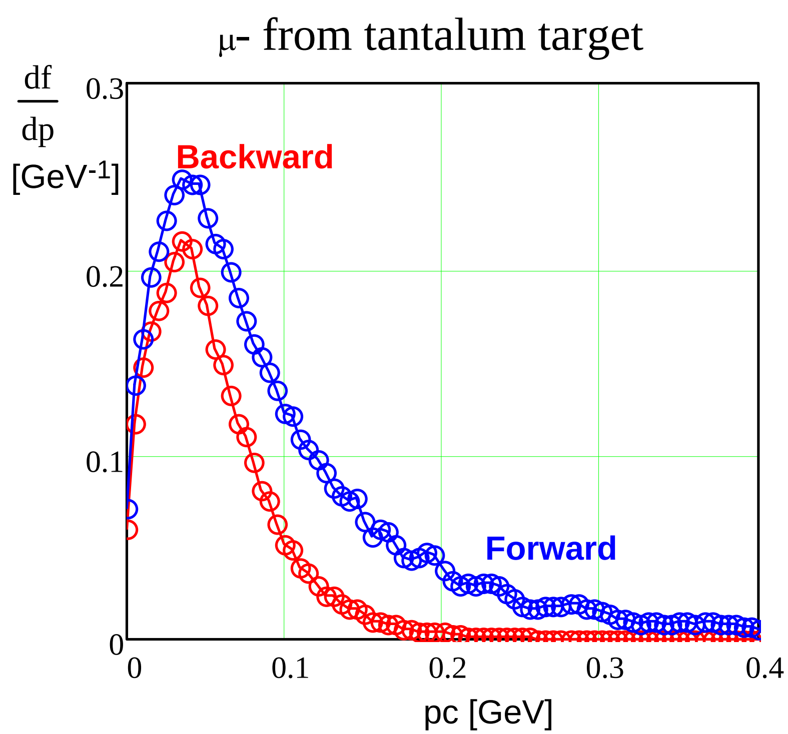
Muon yield from cylindrical target

- Large beam power prohibits to use pencil-like target in high power application with small energy beam (few GeV)
  - Liquid jet-target is intellectually attractive but has severe problems with safety and repairs
- Cylindrical rotating target looks as the most promising choice
  - Carbon (graphite) and tantalum targets were considered



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



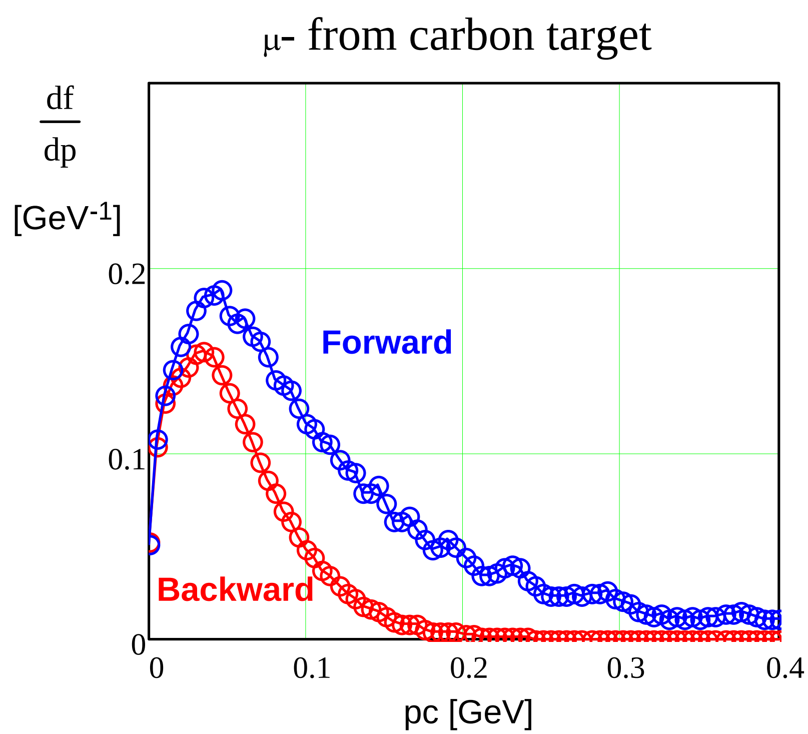
Tantalum hollow cylinder (Pc=3 GeV)

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

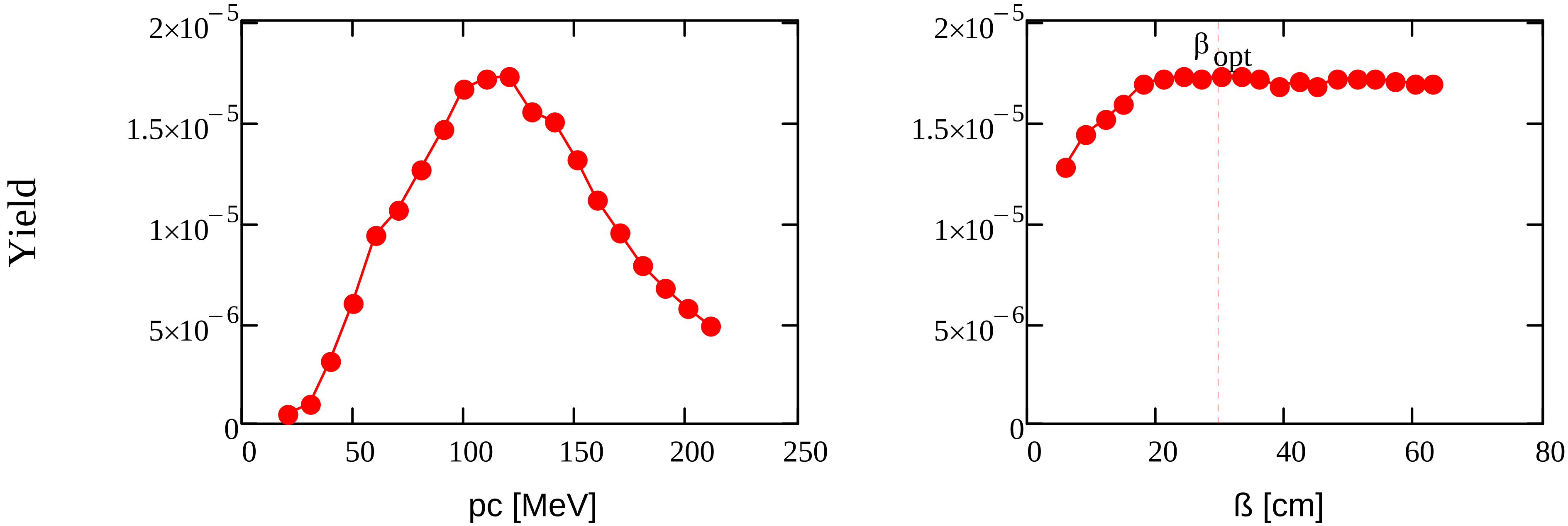
- Small difference between forward and backward muons for Pc<50 MeV

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 (this choice is supported by experimental data)
    - For $E_{kin} \in [2, 8]$ the production of slow muons per unit beam power weakly depends on the beam energy

Muon yield into a beamline with finite acceptance

- In some applications beam transport in a beam line is desirable
- It allows
  - Isochronous transport preventing beam lengthening
  - but it significantly reduces the acceptance and momentum spread
- Below we assume that the beam line limits maximum acceptance and momentum spread to $\varepsilon \approx$ 0.3-3 cm, $\Delta p/p \approx \pm 0.15$
  - Beam line can be matched to decay solenoid to maximize the capture $\Rightarrow \beta_{opt}$

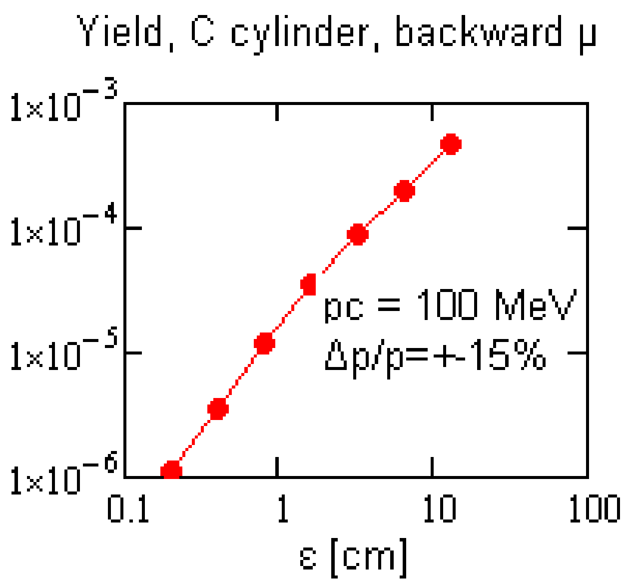


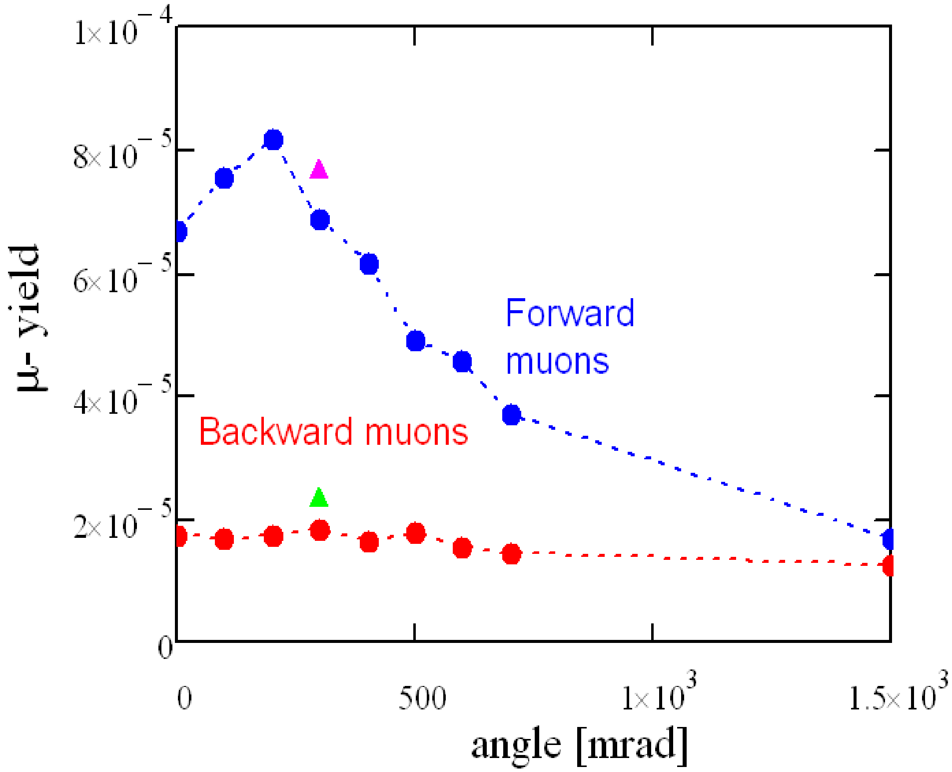
Graphite cylindrical target, backward muons, $\varepsilon_x = \varepsilon_y$ = 1 cm, $\Delta p/p = \pm 0.15$, θ = 200 mrad, B=2.5 T.

- For small emittance the dependence of muon yield on β–function is weak
- Strong suppression of small energy muons (pc<50 MeV) by deceleration in medium

Muon yield into the beamline finite acceptance (continue)

- Absence of x-y correlations after beam exit from magnetic field requires axial symmetric exit from solenoid $\Rightarrow$ i.e. the beam center has to coincide with solenoid axis
- Yield is proportional to B_{target}
  - 2.5 T →5 T would double the yield
- Yield is $\propto \Delta p/p$ (for $\Delta p/p \ll 1$)
- Yield is $\propto \varepsilon^{1.5}$



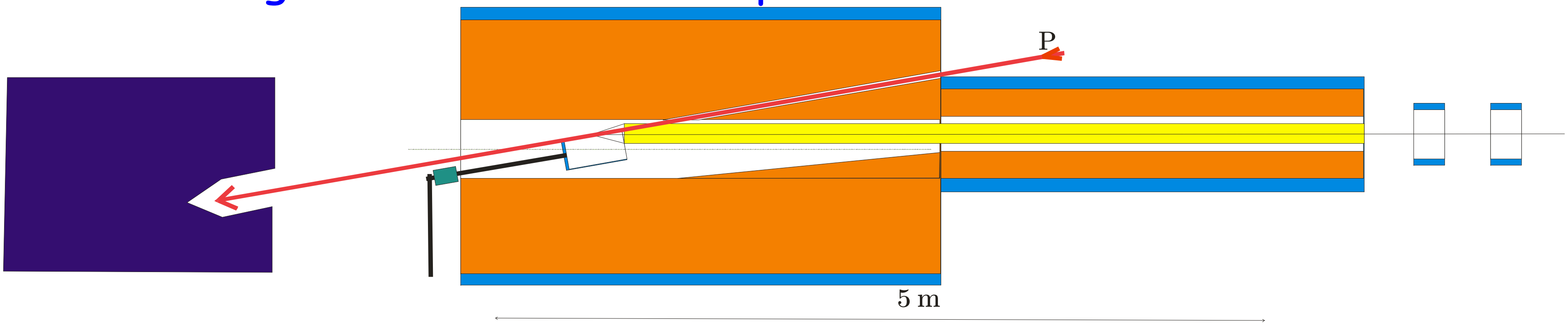


Dependence of muon yield on target angle relative to magnetic field for carbon target into the following phase space: $\varepsilon_x=\varepsilon_y=1$ cm, $\Delta p/p=\pm 15\%$,
Optimal momenta are: 100 MeV/c for backward and 200 MeV/c for forward muons
Triangles show results for tantalum target

- Capturing the beam in a beam line reduces the muon flux by about 2 orders of magnitude

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

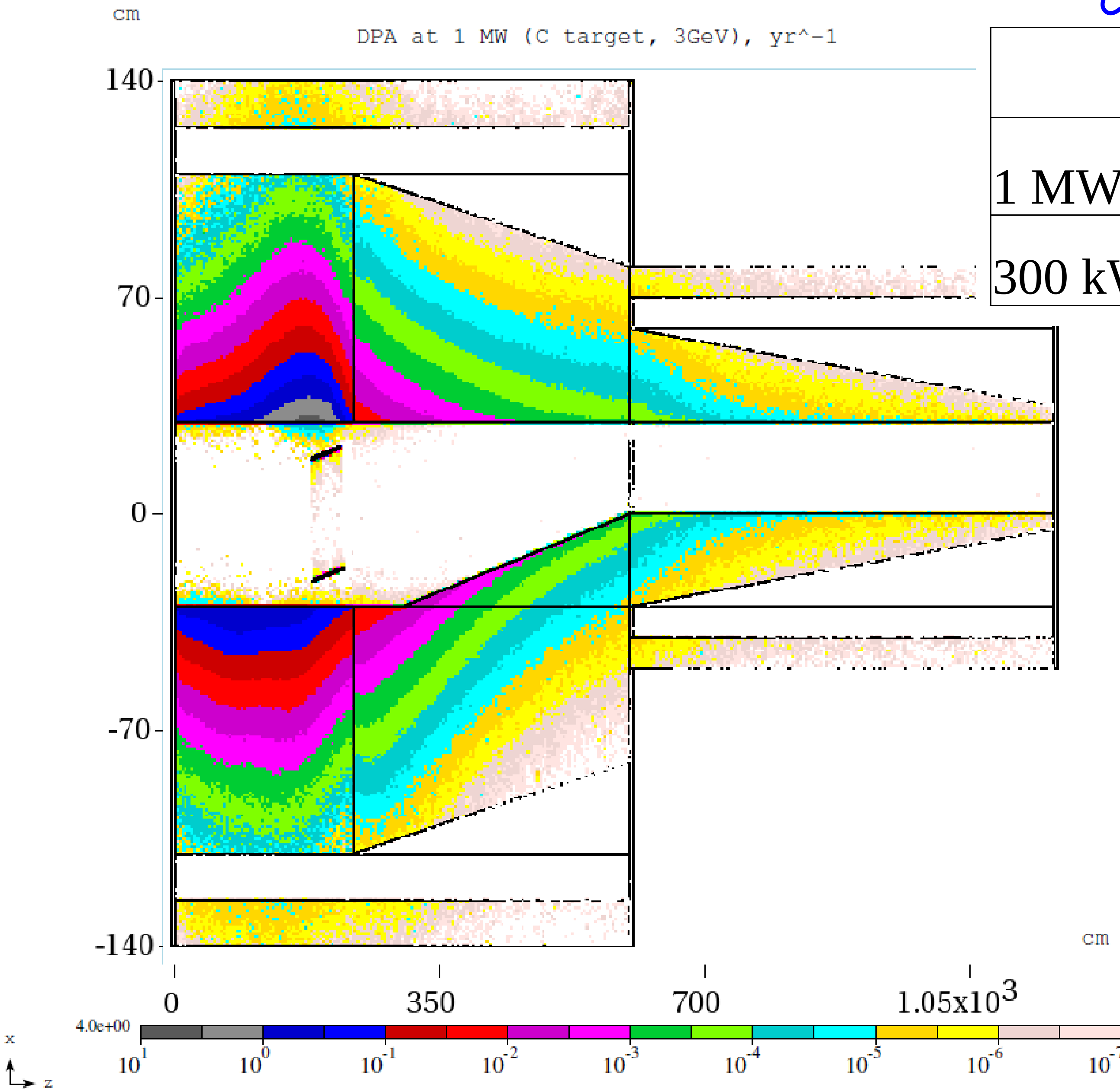
- For 1 MW beam power the power left in the target is ~ 100 kW
  - Heat cannot be removed from pencil target: dP/dS~2 kW/cm^2 for R~0.5cm
  - Relative to this an oxidation and repairs look as an easy problem
- Two possibilities
  - Liquid metal stream (muon collider)
    - Looks expensive
    - Reliability, 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

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

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

      ⇒ 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)

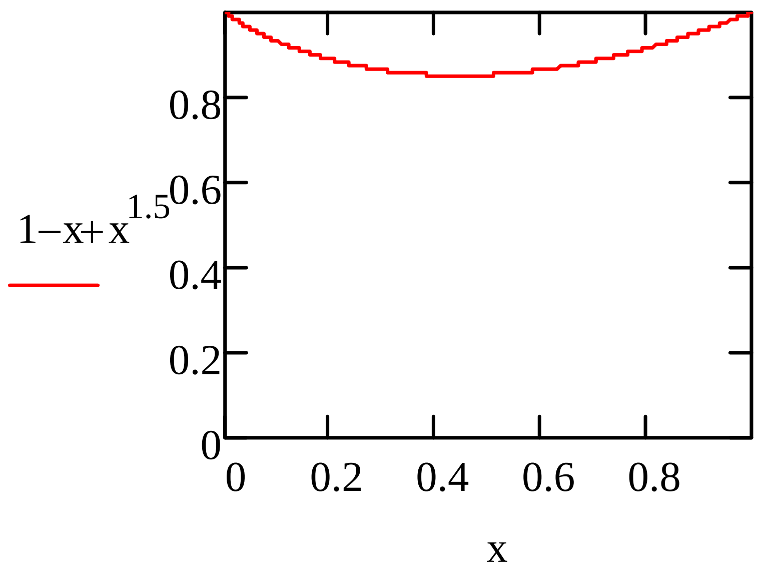
This preliminary absorber design satisfies typical requirements for SC coils

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

- Transition from 25 kW of μ-to-e to 1 MW increases the shield radius from ~80 cm 110 cm => B=5 T → 3 T for the same stored energy

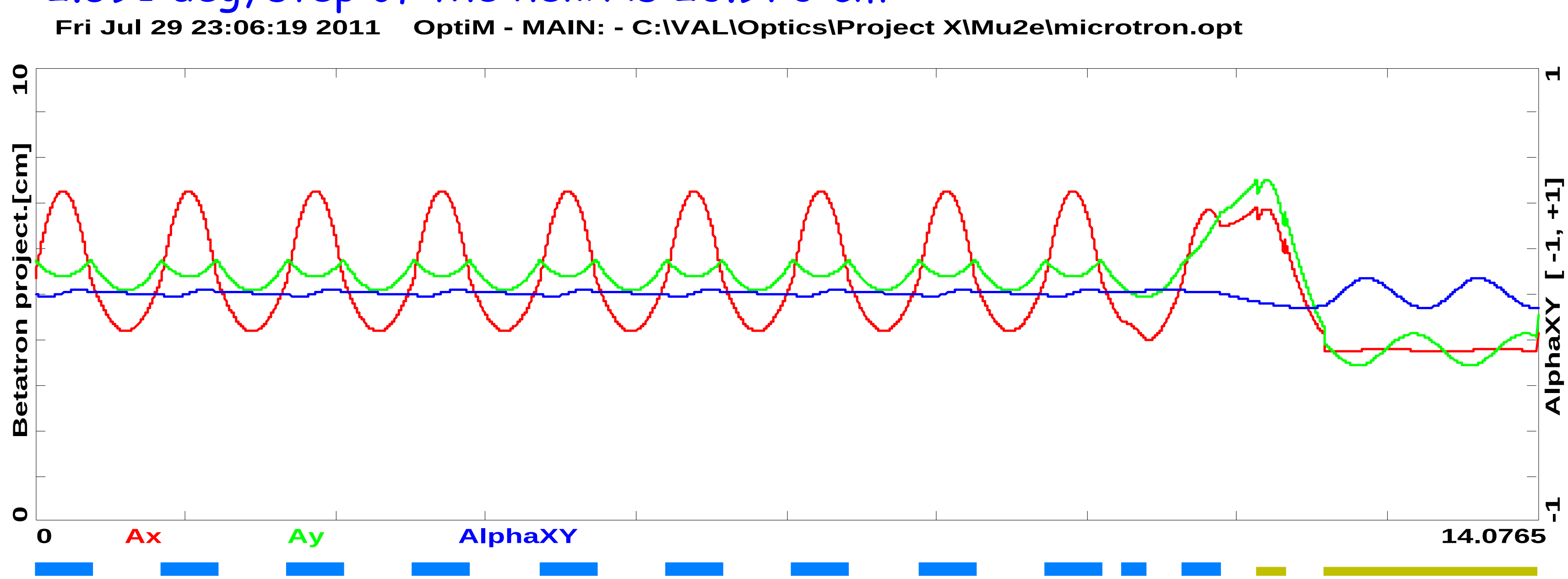
Multiple scattering of protons in the target

- Multiple scattering limits the thickness of cylindrical target to a few millimeters
- Optimal target thickness is weakly affected by its material
  - Heavy target has larger scattering but is shorter
    - It has approximately the same overall effect on the beam envelope growth due to multiple scattering
- Small proton beam emittance in Project X allows some reduction of multiple scattering effects
  - the beam is focused to the small spot at the target end

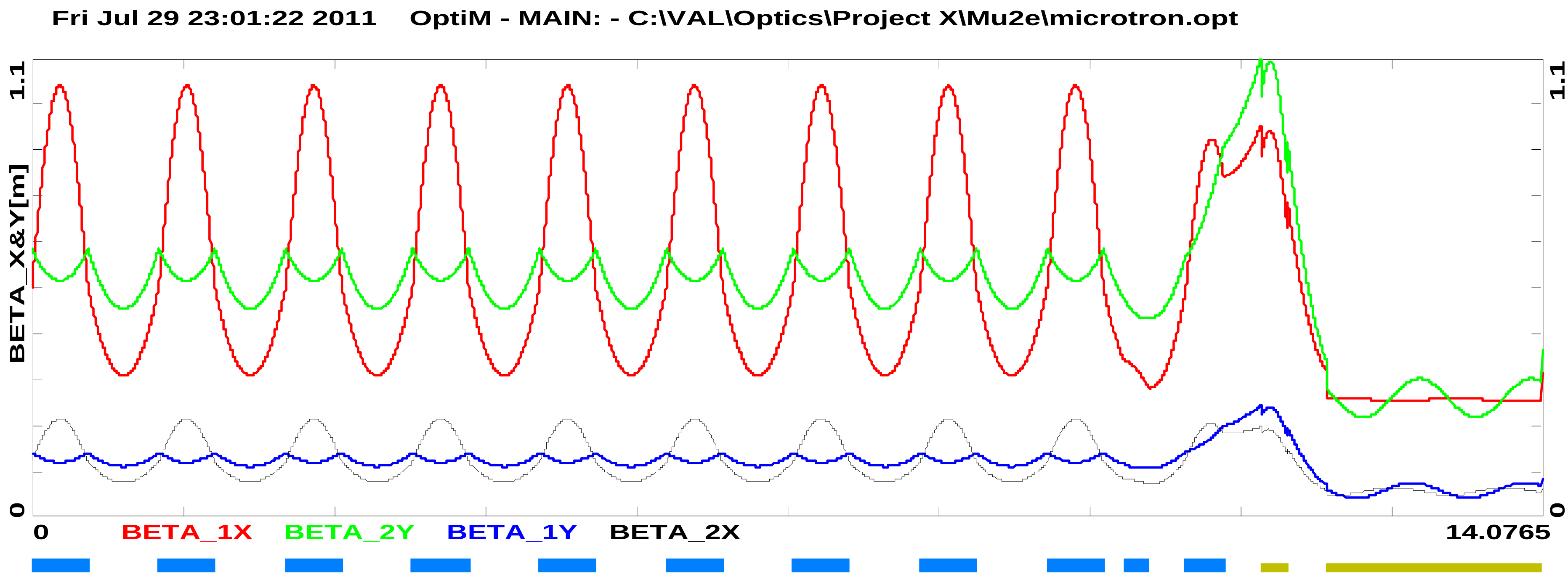


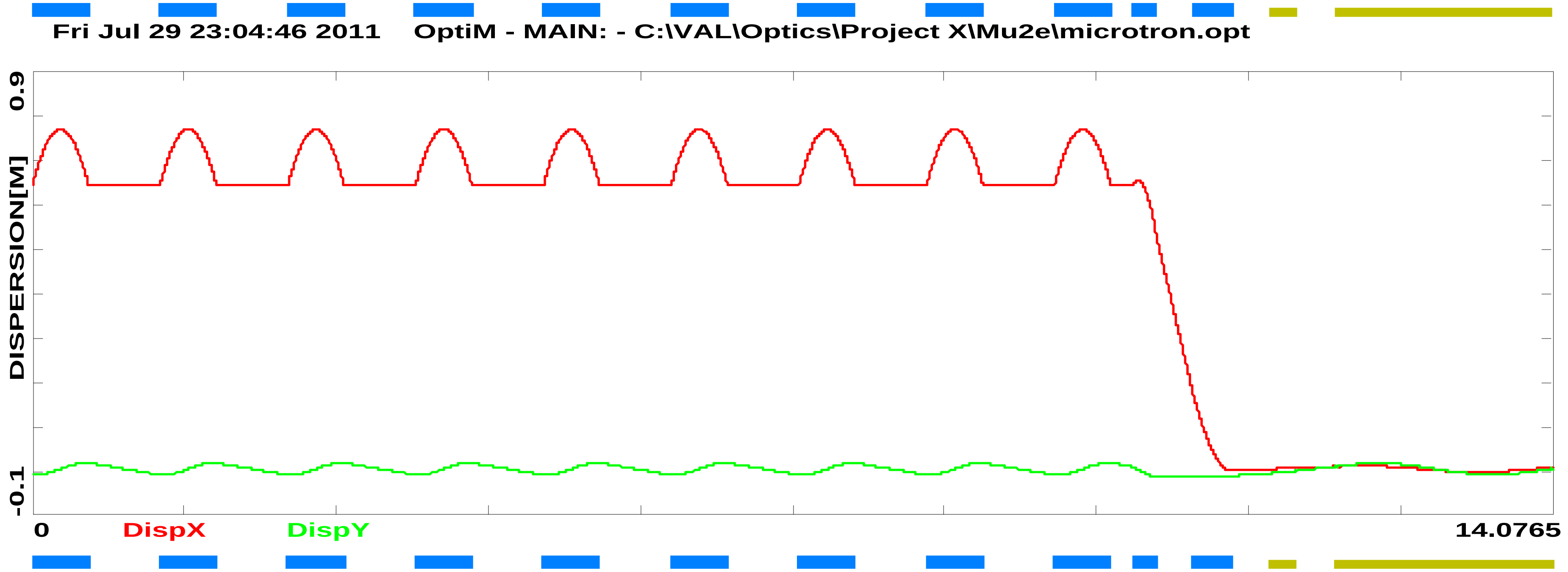
Beam transport in Helical Transport Line

- If isochronicity of beam transport is required then the beam transport in a "standard" line is the only choice
- The line may consist of downward spiral
  - It is matched to the production and detector solenoids with two dipoles and one or two solenoids at each end
- Toy example
  - 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





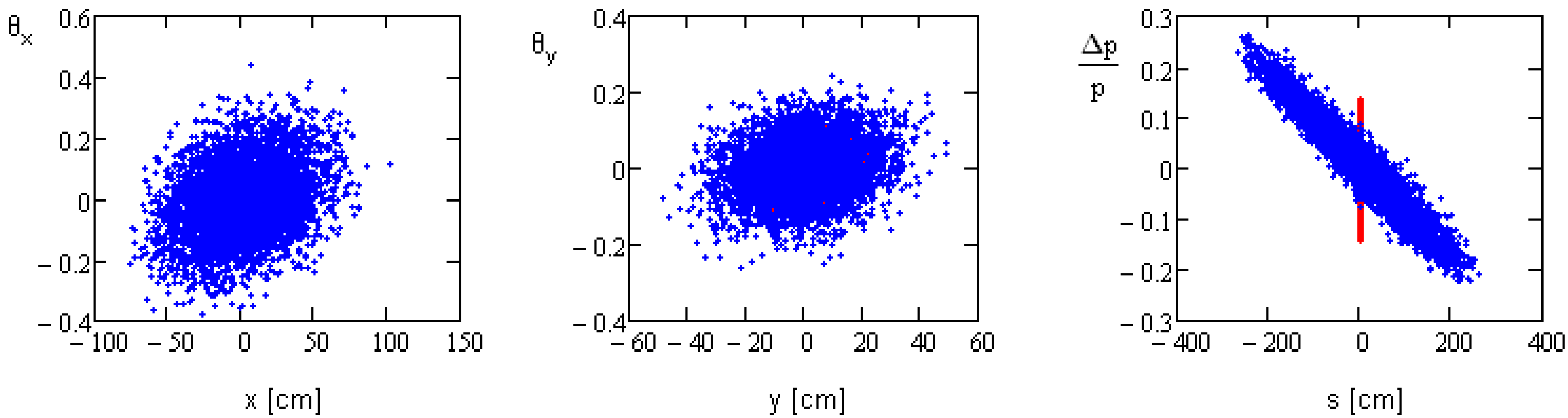
4D beta-functions (top) and dispersions (bottom) for helix and match to the detector solenoid

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: $\varepsilon \propto a \propto \beta_{x,y} \propto R_o$
  - Isochronicity requires soft focusing, $Q_x \sim 1$
  - Magnetic fields are reduced with increase of R_o 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



$g_L \equiv 1$

$\kappa_{scat} \equiv 1$

$\mu_x \equiv 2 \cdot \pi \cdot 0.25$

$\mu_y \equiv 2 \cdot \pi \cdot 0.25$

$D \equiv 150$ cm

$\varepsilon_x \equiv 3$ cm

$\beta_x \equiv 200$ cm

$\beta_y \equiv 200$ cm

$D_p \equiv 0.0$

$\varepsilon_y \equiv 3$ cm

$\alpha_x \equiv -0.3$

$\alpha_y \equiv -0.2$

$M_{56} \equiv 0$

$\sigma_p \equiv 0.15$

$\kappa_{eff} = 0.281$

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

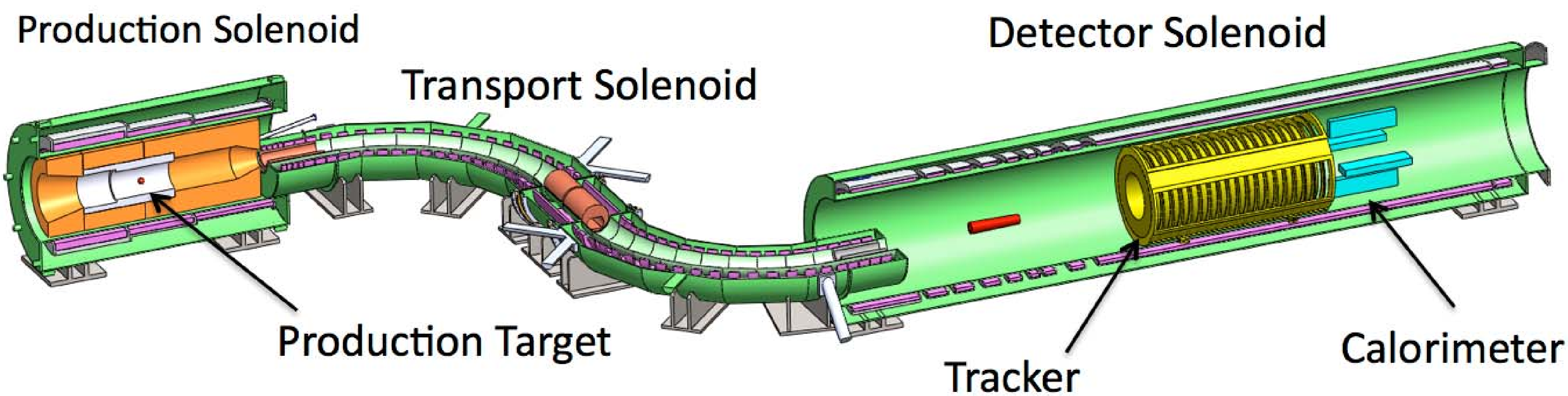
Conclusions

- μ-to-e in Project X
  - Using graphite rotating target we lose factor of ~2 in muon yield
  - Larger radius of radiation shield reduces magnetic field by ~2 times
  - That results in that to get the same yield ~100 kW is required
  - 1 MW available in the Project X can increase the muon flux by ~10 times
  - Its optimal use need to be investigated
- Beam line option
  - Sufficiently large muon flux accepted into a beam line can be achieved for muons with momenta ~100 MeV (E_{kin}=40 MeV)
  - If required the line can be done isochronous
  - Slow muons for stopping in a thin target
    - Phase density of muons at low energy is reducing fast
    - Deceleration results in about the same yield decrease as the direct capture would do
    - Beam ionization cooling with acceleration is expensive. Its usefulness requires additional study
  - Small emittance of Project X beam will be helpful
    - ⇒ Convergent beam
    - ⇒ Mitigation of multiple scattering for protons in the target

Backup Slides

Present μ-to-e

- Conversion – $2.1\cdot10^{-3}$ ($dN_p/dt=2.4\cdot10^{13}\ s^{-1}$, 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 $p_{||}$)

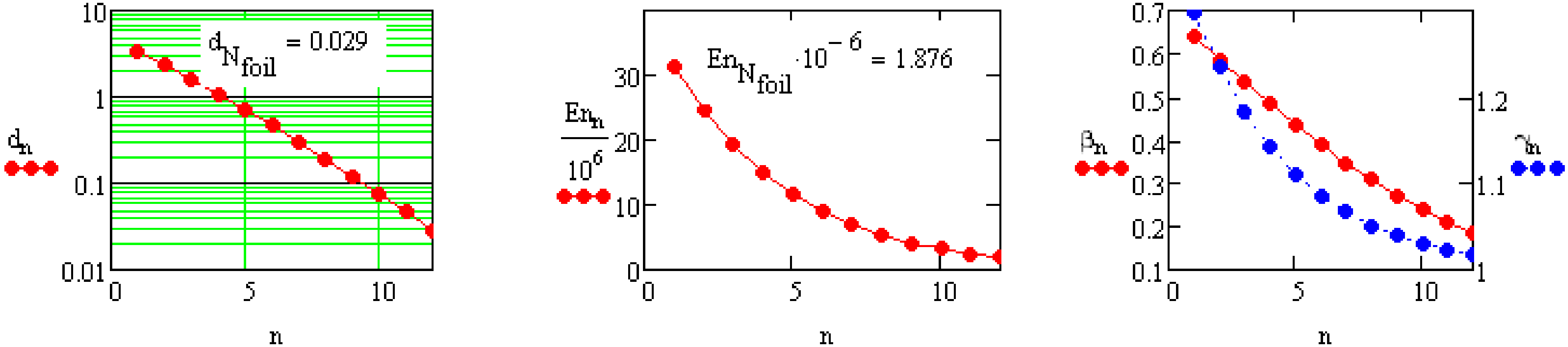


Major Requirements to a New Generation μ-to-e Experiment†

- ~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
    - ⇒ $5\cdot10^{12}$ muons/s
  - 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

† Bernstein & Prebys, July 26, 2011

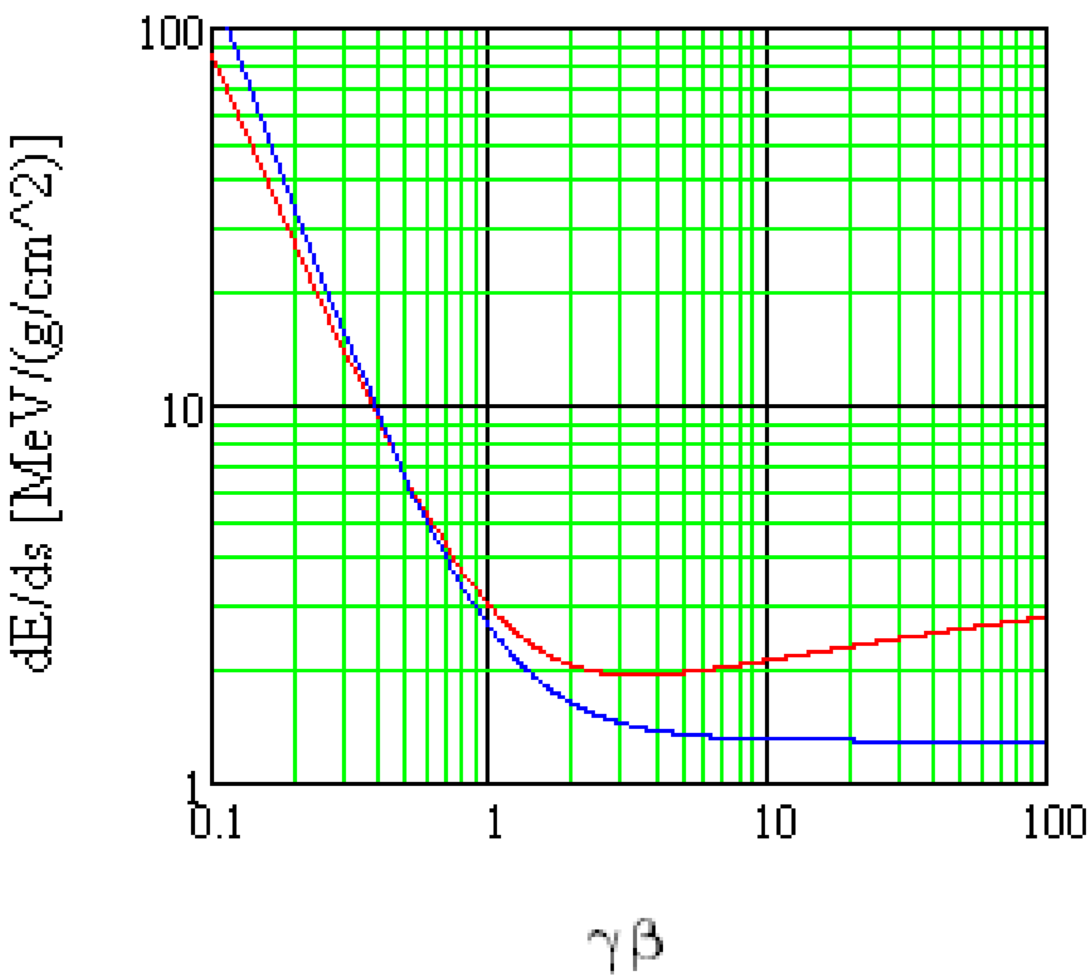
Deceleration from 100 to 20 MeV/c



Foil thickness [cm], energy [MeV] and β&γ as functions of foil number for Δp/p = 0.15 per foil

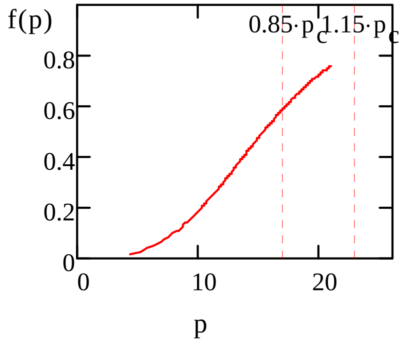
- Difficulty to control wedging at thickness below ~1-2 mm

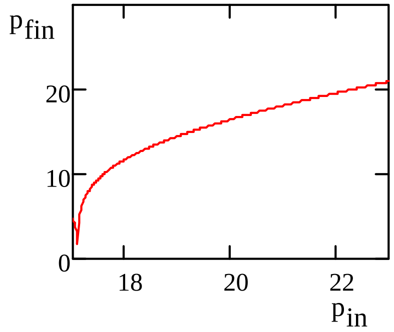
Deceleration in LiH



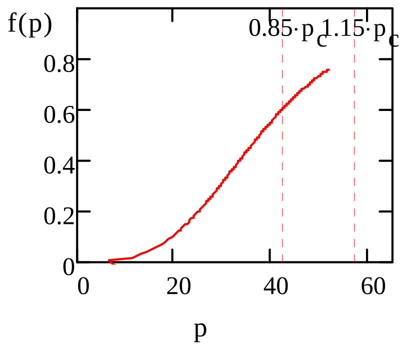
Deceleration of +-15% momentum bite

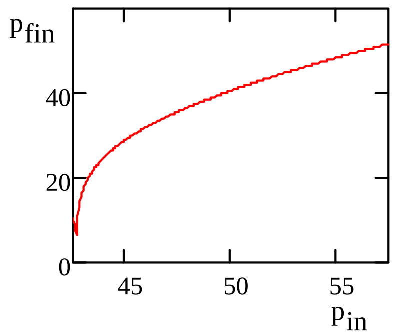
$p_c := 20$ $p_{in} := p_c\cdot 0.85, p_c\cdot 0.851 .. p_c\cdot 1.15$ $\Delta E_0 := 0.00775\cdot 10^6$





$p_c := 50$ $p_{in} := p_c\cdot 0.85, p_c\cdot 0.851 .. p_c\cdot 1.15$ $\Delta E_0 := 0.2792\cdot 10^6$





$p_c := 100$ $p_{in} := p_c\cdot 0.85, p_c\cdot 0.851 .. p_c\cdot 1.15$ $\Delta E_0 := 3.5\cdot 10^6$