Surface muon beam at PSI and Project X

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Outline

- General introduction to surface / cloud muons
- Muon beam facilities overview
- General considerations for muon beam
  - Experimental requirements
  - Proton target
  - Beam channel
  - Muon stopping target
- What could the future bring (PSI, Project X, ...)?

Surface mouns (p_μ = 29.8 MeV/c)

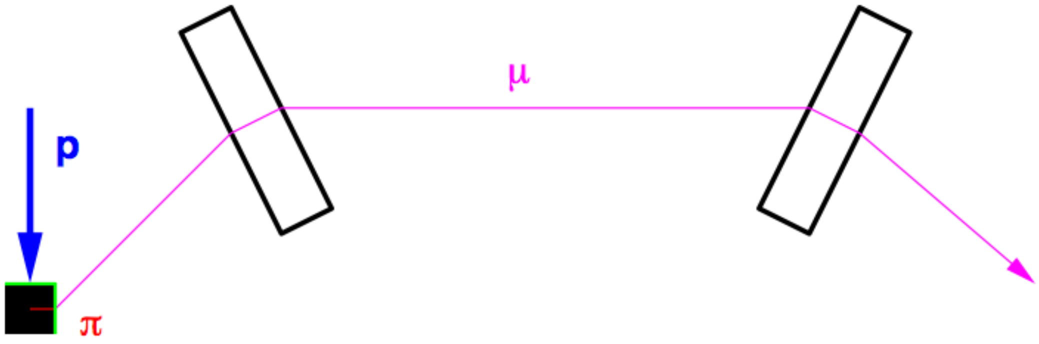


Figure 6: Surface muon production schematic. Pions decay in the green region.

- 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 ($R_\mu \sim 0.14\ \mathrm{g/cm}^{-2}$ 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.

Cloud mouns (p_{μ} > 30 MeV/c)

Muon production: cloud muons

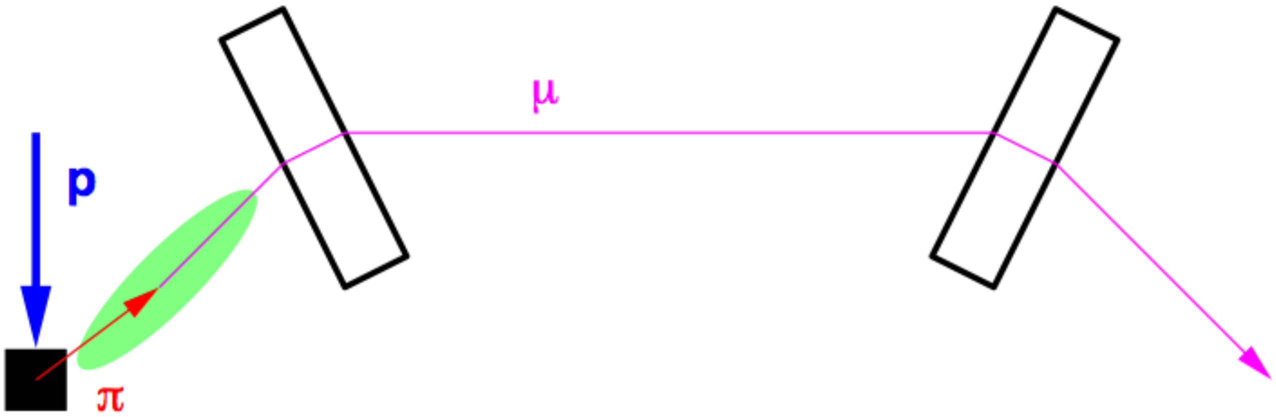
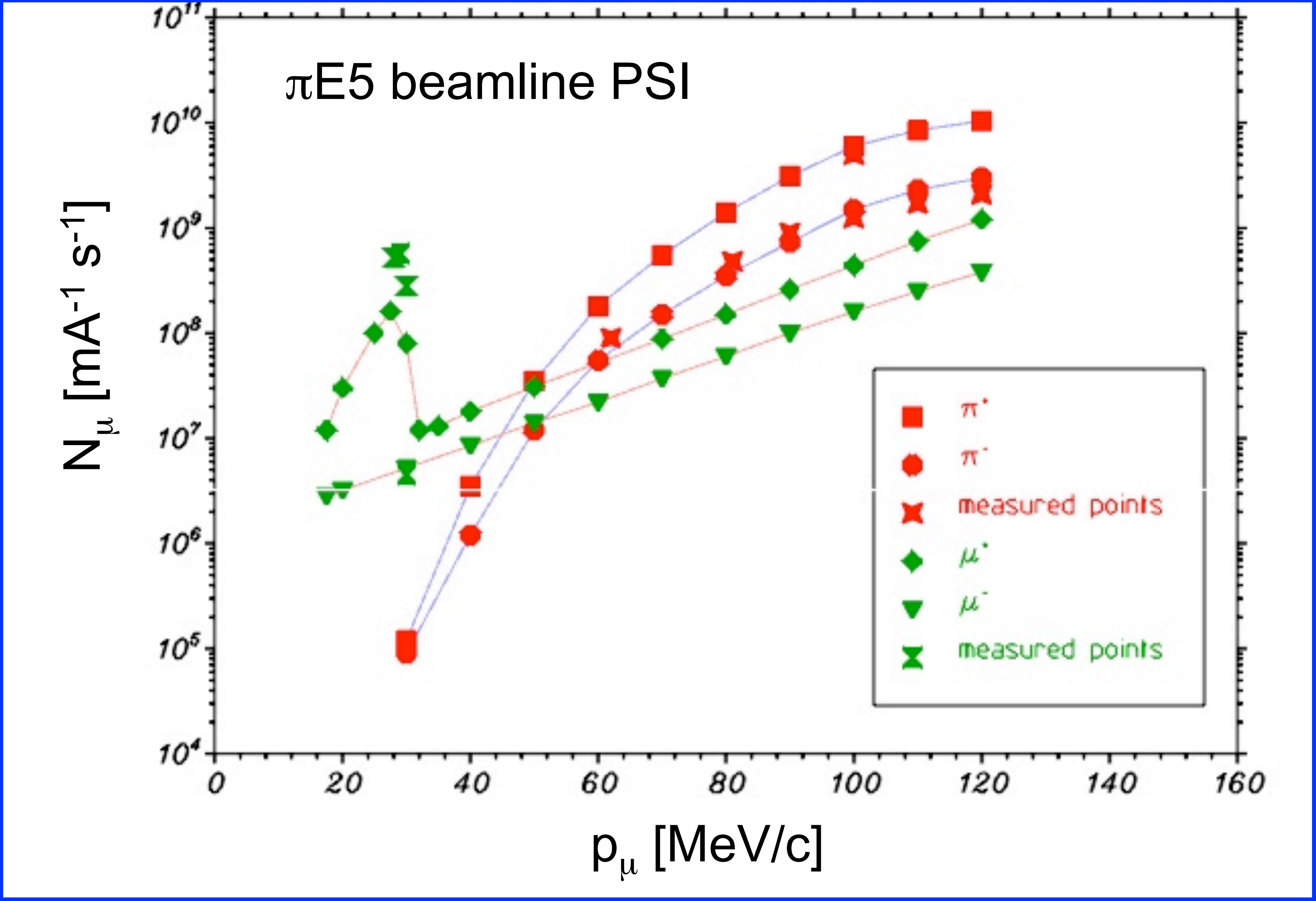


Figure 3: Cloud muon production schematic. Pions decay in the green region.

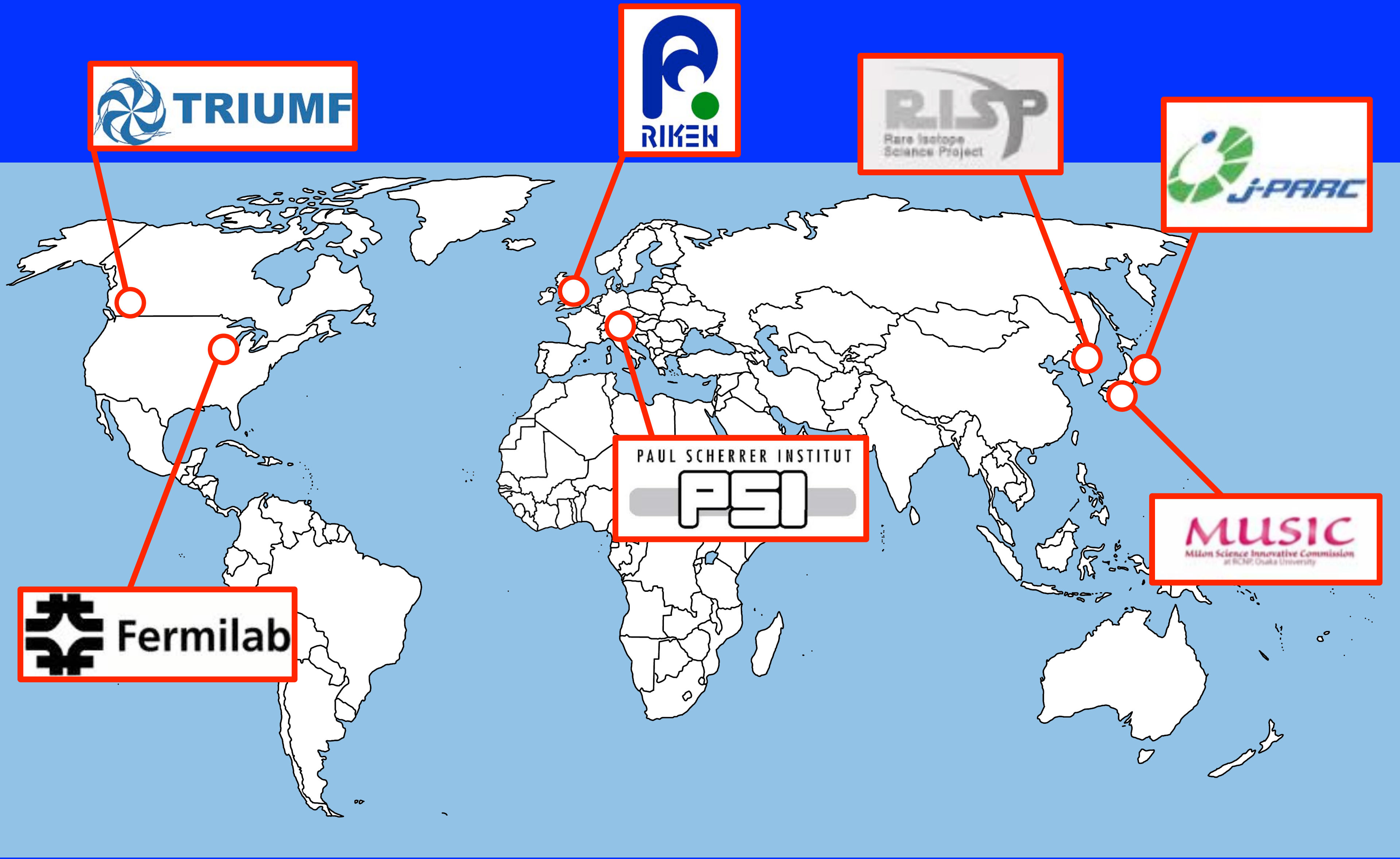
- Cloud muons:
  - ▷ From pion decay in flight, close to the production target.
  - ▷ Wide range of momentum available.
  - ▷ Source is larger than the production target.
  - ▷ Contaminated by $\pi^{\pm}$ and $e^{\pm}$.
  - ▷ Polarization is low, depending on momentum and geometry.

Muon beams



http://aea.web.psi.ch/beam2lines/

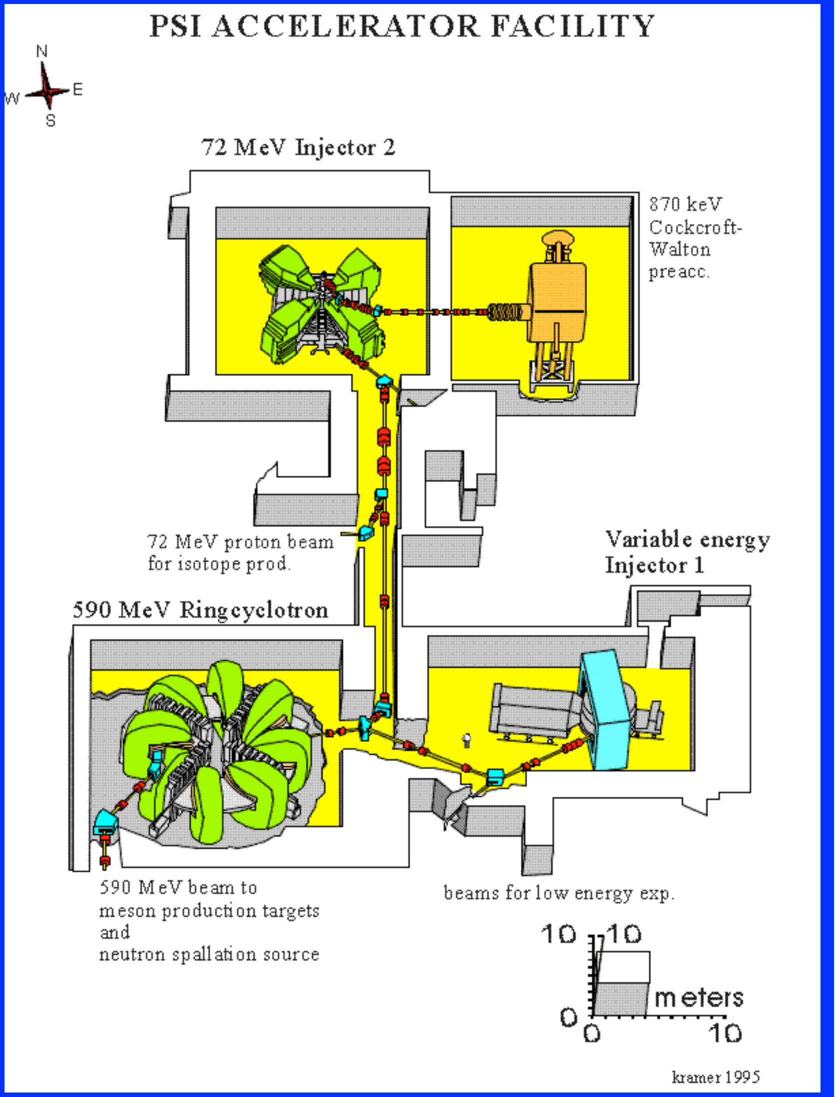
Facilities overview

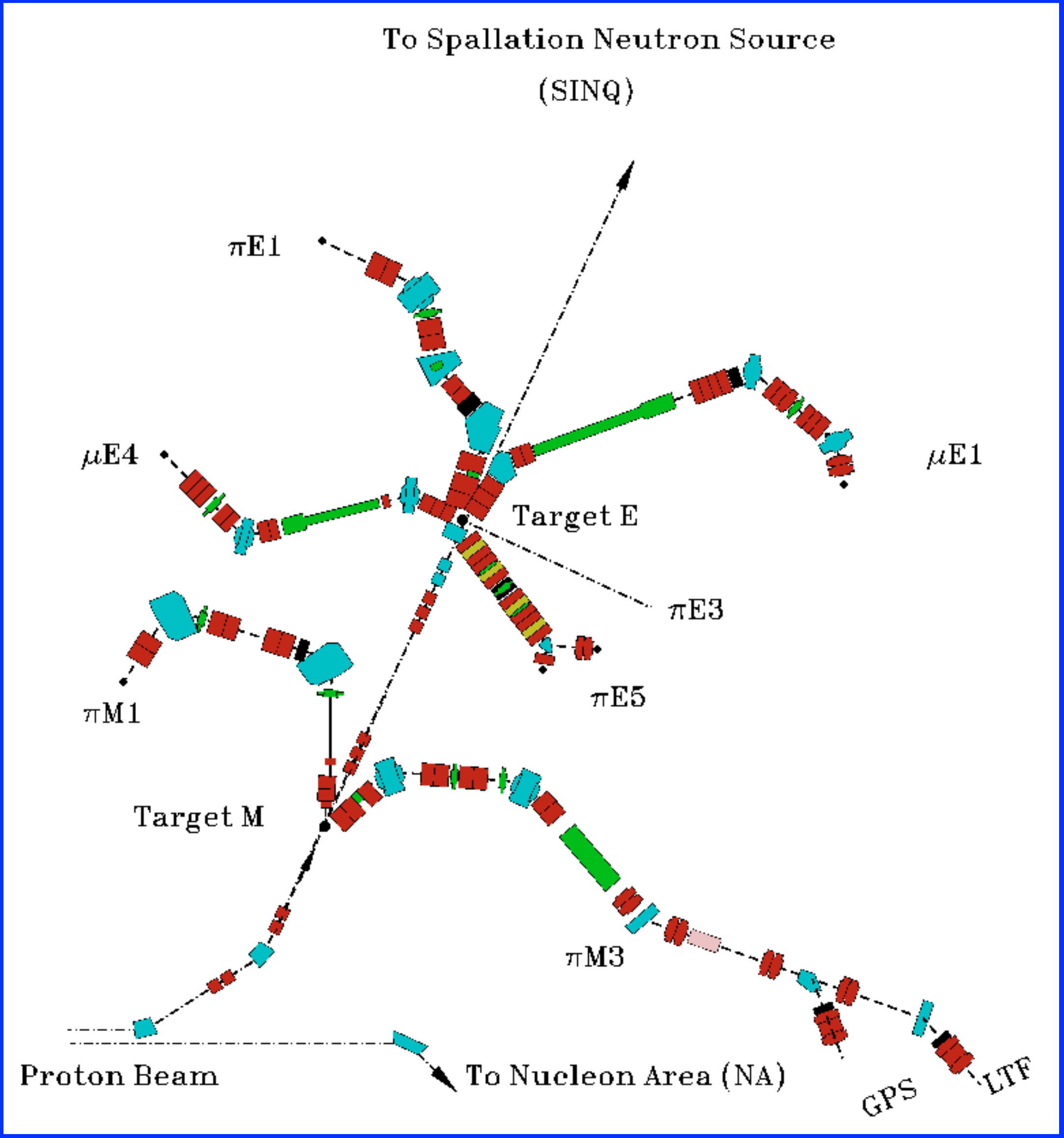


Muon beams

Laboratory/ Beam line	Energy/ Power	Present Surface μ^+ rate (Hz)	Future estimated μ^+/μ^- rate (Hz)
PSI (CH)	(590 MeV, 1.3 MW, DC)		
LEMS	"	$4 \cdot 10^8$	
$\pi E5$	"	$1.6 \cdot 10^8$	
HiMB	(590 MeV, 1 MW, DC)		$4 \cdot 10^{10} (\mu^+)$
J-PARC (JP)	(3 GeV, 1 MW, Pulsed) currently 210 KW		
MUSE D-line	"	$3 \cdot 10^7$	
MUSE U-line	"		$2 \cdot 10^8 (\mu^+)$ (2012)
COMET	(8 GeV, 56 kW, Pulsed)		$10^{11} (\mu^-)$ (2019/20)
PRIME/PRISM	(8 GeV, 300 kW, Pulsed)		$10^{11-12} (\mu^-)$ (> 2020)
FNAL (USA)			
Mu2e	(8 GeV, 25 kW, Pulsed)		$5 \cdot 10^{10} (\mu^-)$ (2019/20)
Project X Mu2e	(3 GeV, 750 kW, Pulsed)		$2 \cdot 10^{12} (\mu^-)$ (> 2022)
TRIUMF (CA)	(500 MeV, 75 kW, DC)		
M20	"	$2 \cdot 10^6$	
KEK (JP)	(500 MeV, 2.5 kW, Pulsed)		
Dai Omega	"	$4 \cdot 10^5$	
RAL -ISIS (UK)	(800 MeV, 160 kW, Pulsed)		
RIKEN-RAL		$1.5 \cdot 10^6$	
RCNP Osaka Univ. (JP)	(400 MeV, 400 W, Pulsed)		
MUSIC	currently max 4W		$10^8 (\mu^+)$ (2012) means $> 10^{11}$ per MW
DUBNA (RU)	(660 MeV, 1.65 kW, Pulsed)		
Phasatron Ch:I-III		$3 \cdot 10^4$	

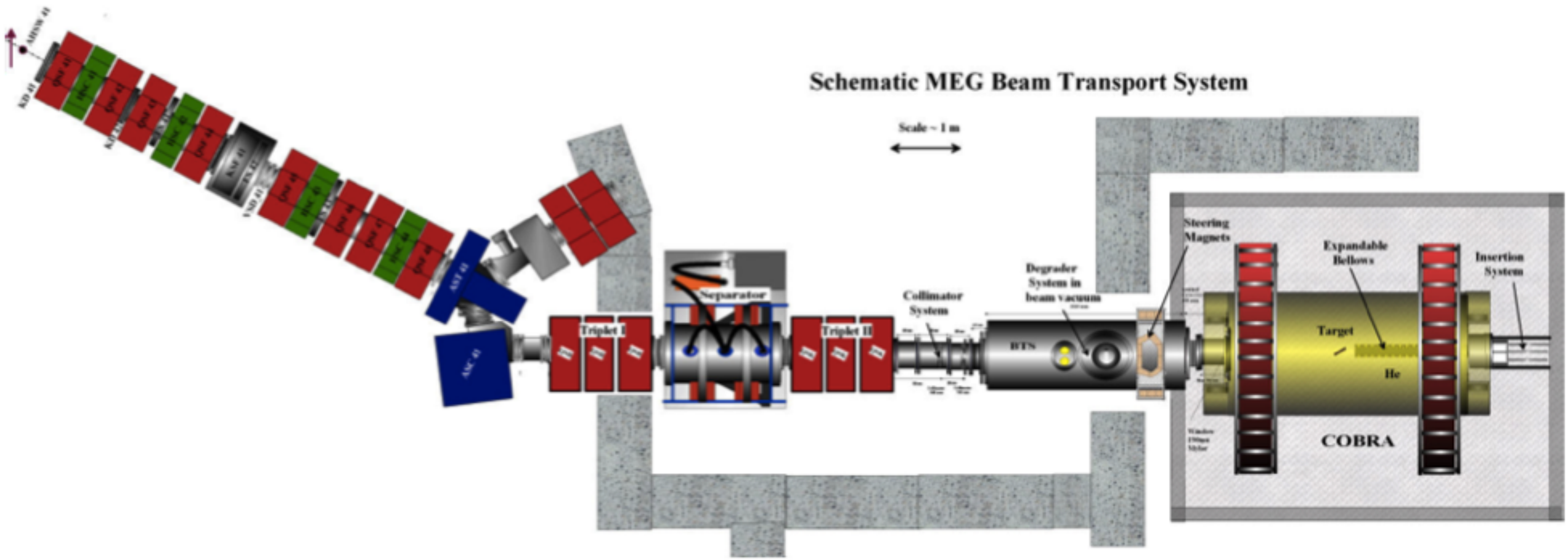
Muon beams at PSI





http://aea.web.psi.ch/beam2lines/

πE5 at PSI

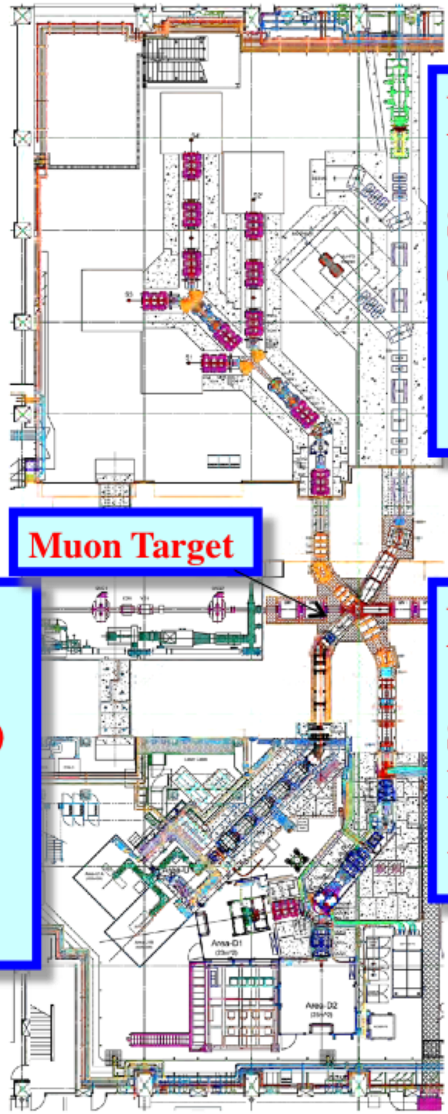


- 175° relative to proton beam
- dipole and focussing quadrupole channel
- Solid angle: 150 mSr
- $\Delta p / p$ = 10% (acceptance)
- Spot size: 15mm, 20mm
- 2 * 10^8 muons/s @ 2.4mA (590 MeV)

Muon beams: J-PARC

S-Line

Surface μ⁺(30 MeV/c)
For material sciences



H-Line

Surface μ⁺ For HF, g-2 exp.
e⁻ up to 120 MeV/c For DeeMe
μ⁻ up to 120 MeV/c For μCF

U-Line

Ultra Slow μ⁺(0.05-30keV)
For multi-layered thin foils, nano-materials, catalysis, etc

D-Line

Surface μ⁺(30 MeV/c)
Decay μ⁺/μ⁻(up to 120 MeV/c)

Users' RUN, in Operation

MUSE

Some muon experiments

Experiment	Beam	Momentum	Rates	Beamline
MEG	μ^+	29.8 MeV/c	3 * 10^7/s	πE5 @ PSI
MuLan	μ^+	29.8 MeV/c	8 * 10^6/s	πE3 @ PSI
TWIST	μ^+	29.8 MeV/c	<5 * 10^3/s	TRIUMF
MuCap / MuSun	μ^-	34 MeV/c	1 * 10^5/s	πE3 @ PSI
SINDRUM II	μ^-	88 MeV/c	1.2 * 10^7/s	μE1 @ PSI

Material science community (muSR) using surface muons as well!

Some muon experiments

Experiment	Beam	Momentum	Rates	Beamline
MEG	μ^+	29.8 MeV/c	$3 * 10^7$/s	πE5 @ PSI
MuLan	μ^+	29.8 MeV/c	$8 * 10^6$/s	πE3 @ PSI
TWIST	μ^+	29.8 MeV/c	$<5 * 10^3$/s	TRIUMF
MuCap / MuSun	μ^-	34 MeV/c	$1 * 10^5$/s	πE3 @ PSI
SINDRUM II	μ^-	88 MeV/c	$\sim 10^7$/s	μE1 @ PSI
Mu2e	μ^-	~40 MeV/c	$5 * 10^{10}$ /s	FNAL
MEG upgrade	μ^+	29.8 MeV/c	$7 * 10^7$/s	πE5 @ PSI
$\mu^+ \to e^+e^-e^+$ (Ph. I)	μ^+	29.8 MeV/c	$<1 * 10^8$/s	πE5 @ PSI
$\mu^+ \to e^+e^-e^+$ (Ph. II)	μ^+	29.8 MeV/c	$2 * 10^9$/s	HIMB @ PSI

MEG, μ3e:

- **DC μ^+ beam:** Accidental background ~ R_μ^2 (see pulsed mode comments at end of slides)

Mu2e:

- **Pulsed μ^- beam:** Wait until beam background gone (π, e, ...) are gone

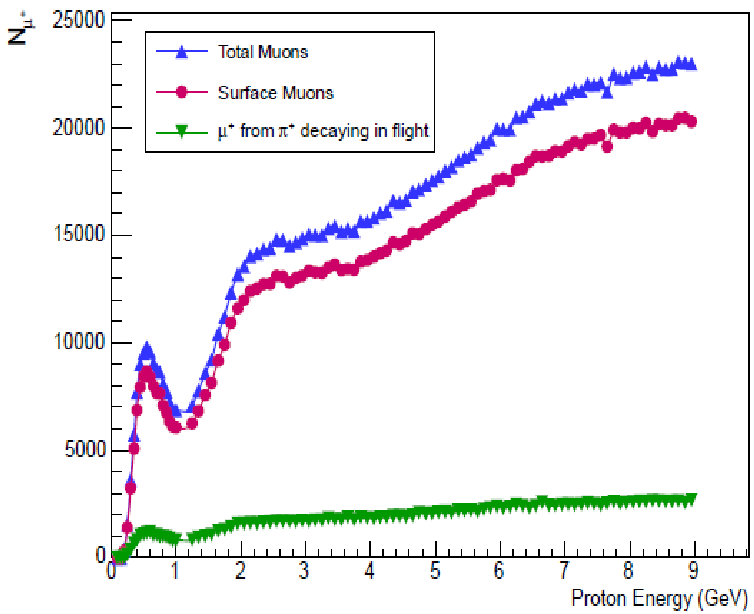
Muon beams: General considerations

① protons

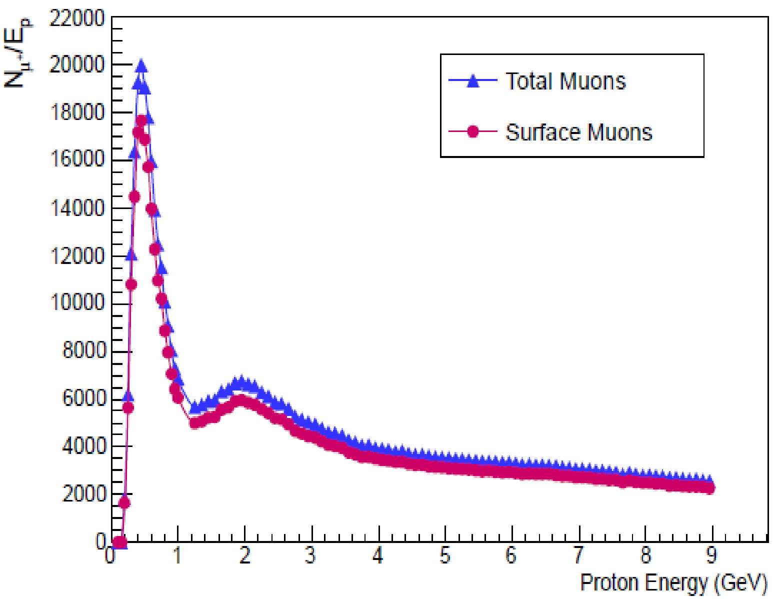
1. Proton beam: momentum, power and beam structure

Surface muons – ISIS study (2010) - II

No gain is achieved in going to higher energies for this particular target geometry and material

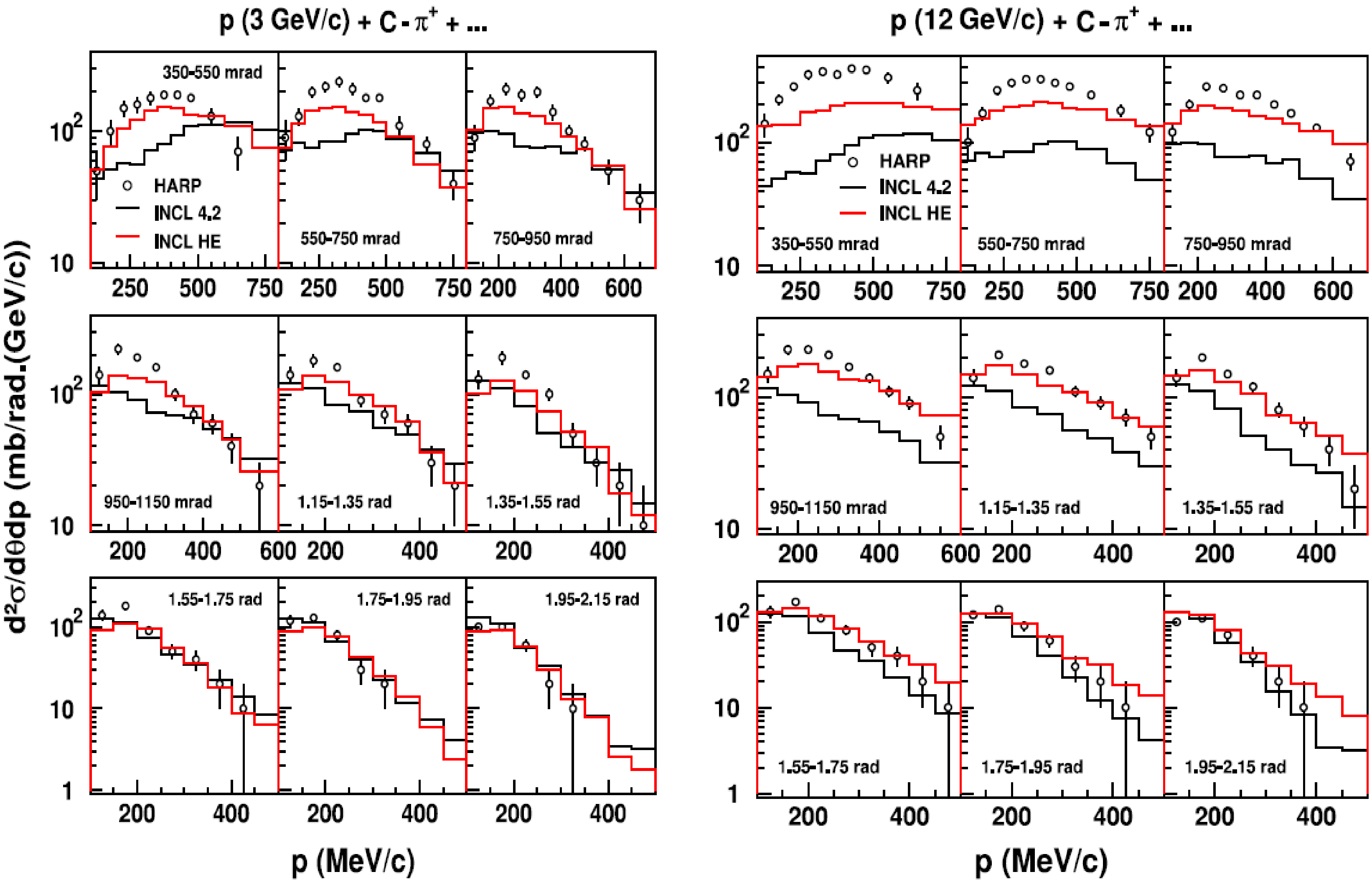


(a) Variation of muon yield with proton energy at higher energies.



(b) Normalisation of the muon yield to the proton energy.

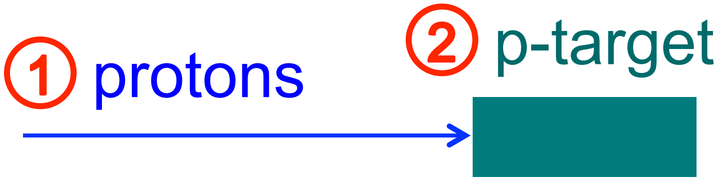
New Geant4 generator vs HARP data: INCL 4.2 already in Geant4, INCL HE coming soon?



Conclusion – surface muon beam

- ISIS study claims that intensity/watt of surface muon beam at Project X energies is about 3-7 times lower than at 500 MeV
- This result is based on GEANT4 model which underestimates measured cross section of positive pion production about few times at 2–8 GeV
- Our crude estimate predicts nearly same surface beam intensity/watt for 2 GeV and 590 MeV protons
- Direct simulation of surface muons based on developed approximation of low energy pion yield is need to make more solid conclusion
- Optimization study of target geometry and material should be performed in new energy range

Muon beams: General considerations



1. Proton beam: momentum, power and beam structure
2. Target: Material, cooling, size

Muon beams: General considerations

1. Proton beam: momentum, power and beam structure
2. Target: Material, cooling, size
3. Proton transmission: Neutron facility or last in chain

Proton target

- Target material and shape for high yields of pions (muons)
- Cooling: Low heat production and high dissipation
- Minimize secondary particles (e, π, γ, n)
- Target size influences channel acceptance and beam spot
- Low activation
- Long lifetime (mechanical stress, fatigue)

PSI target E

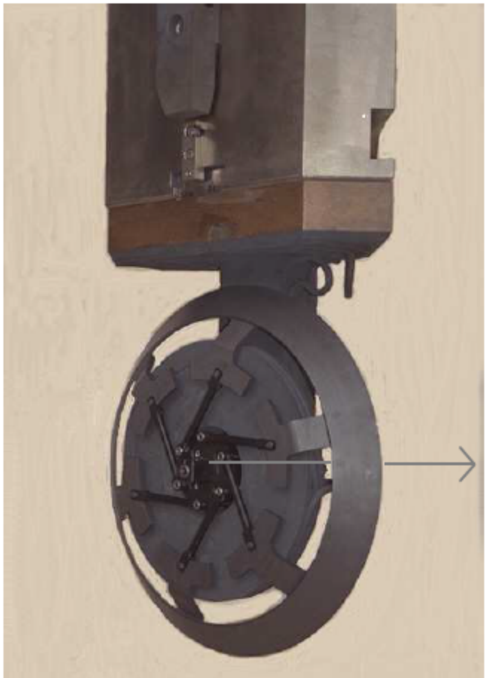
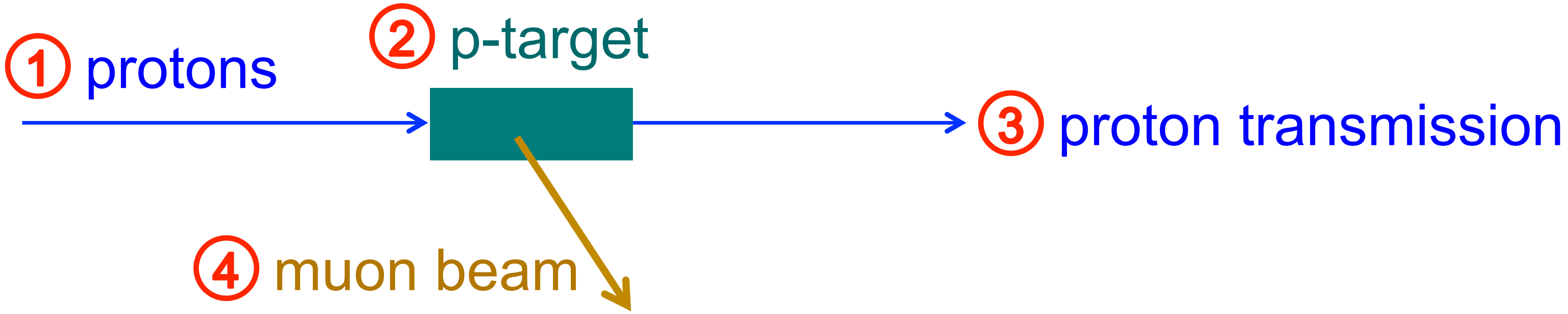


TABLE 1. Some Parameters For The Targets

Meson Production Target	M	E
Mean Diameter (mm)	320	450
Target Length (mm)	5.2	60
Target Width (mm)	20	6
Graphite Density (g/cm^3)	1.8	1.8
Proton Beam Losses (%)	1.6	18
Power Deposition (KW/mA)	2.4	30
Irradiation Damage Rate (dpa/Ah)	0.11	0.1
Operating Temperature (K)	1100	1700
Rotational Speed (Turns/s)	1	1

- 6 cm long rotating graphite ring, radiation cooled
- ~70 kW power deposited at 2.4mA (590 MeV protons)

Muon beams: General considerations



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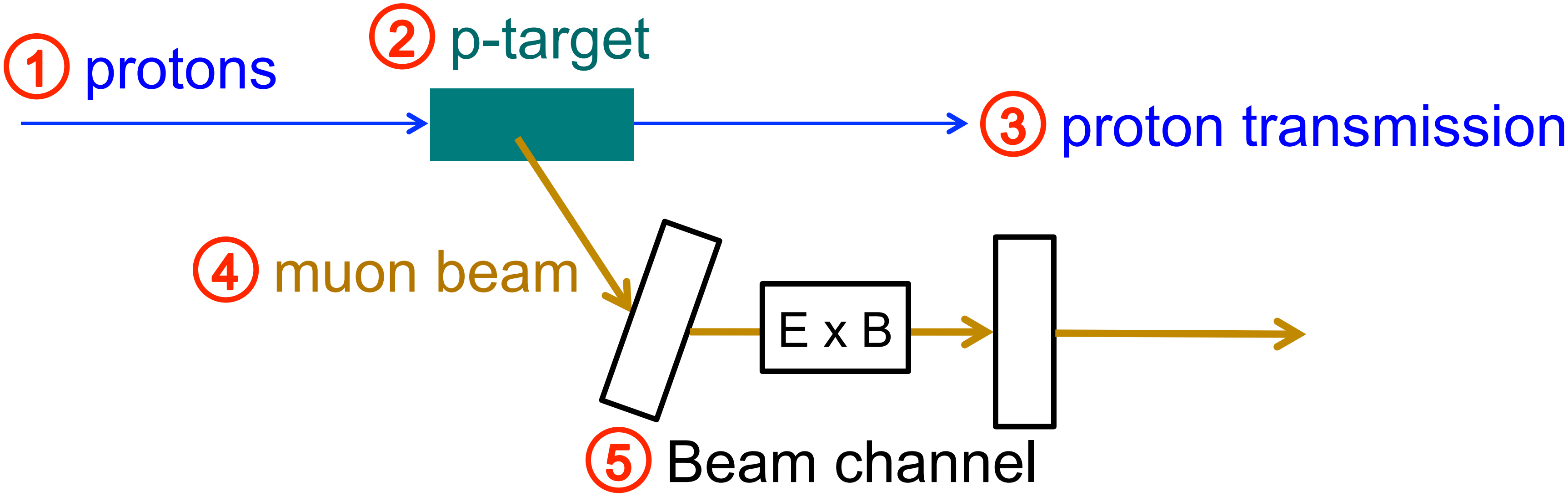
4. Muon beam: Momentum, rates, polarization

Muon beams: General considerations



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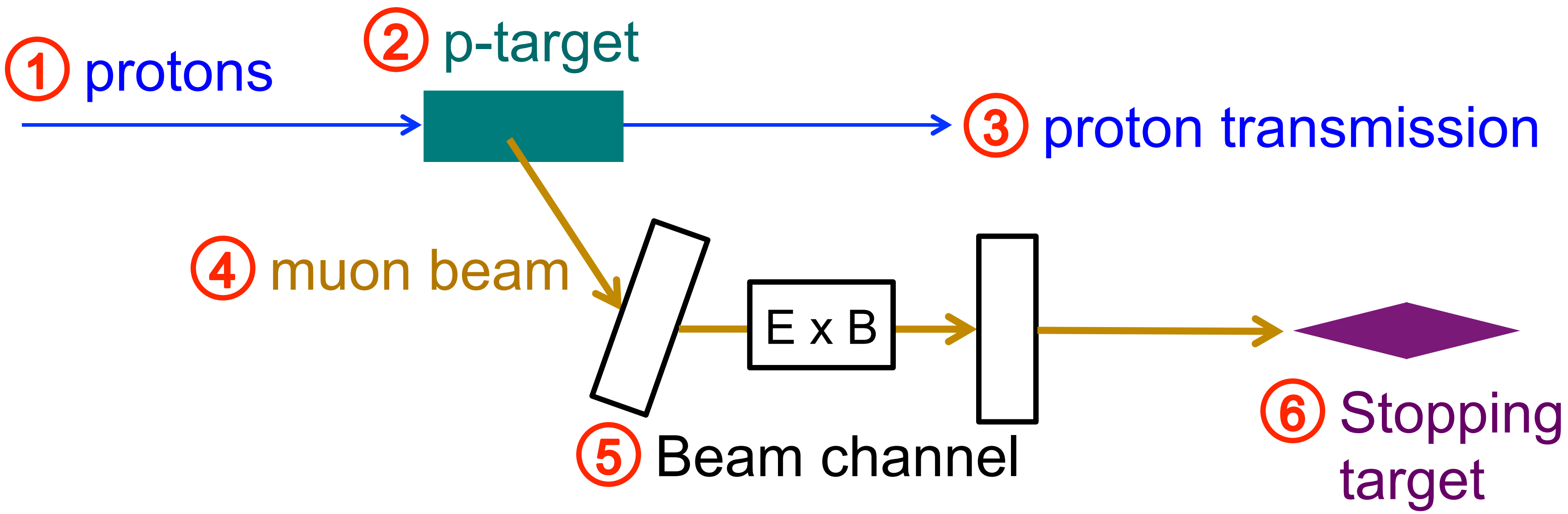

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5. Beam channel: Acceptance, transmission, momentum bite $\Delta p/p$, contamination (π, e)
6. Muon stopping target: Shape, beam spot

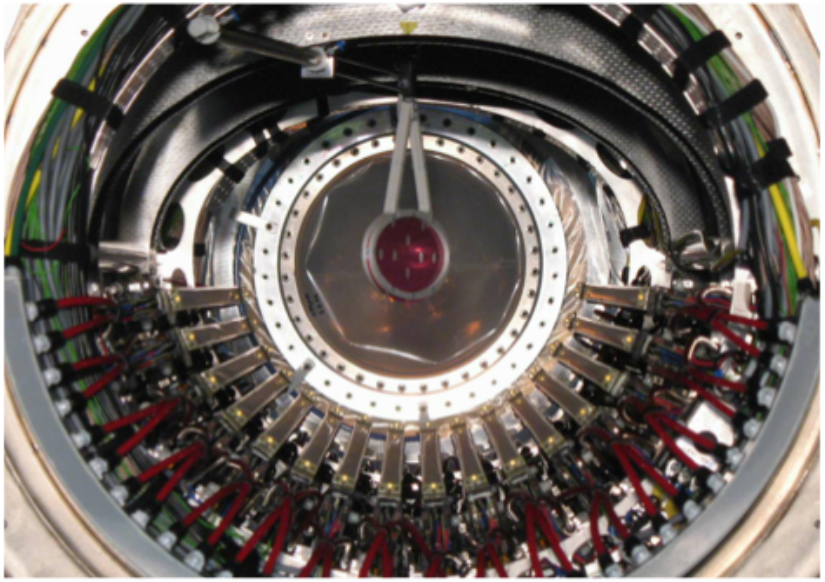
Current MEG target

requirements:

- depolarizing material (isotropic e^+)
- low-Z (γ-background, AIF)
- min. material traversed by decay e^+ and γ $\rightarrow$ slanted target
- 2-d flatness <$\pm$100 μm

realisation:

- 205 μm thick polyethylene / polyester foil density ρ = 0.895 g/cm^3
- freely suspended in Rohacell frame
- ellipse shape: major-axis 200.5 mm
  minor-axis 79.8 mm
- target angle: (20.5$\pm$0.3)°
- holes: 10 mm diameter
- pneumatic drive for „parking position“



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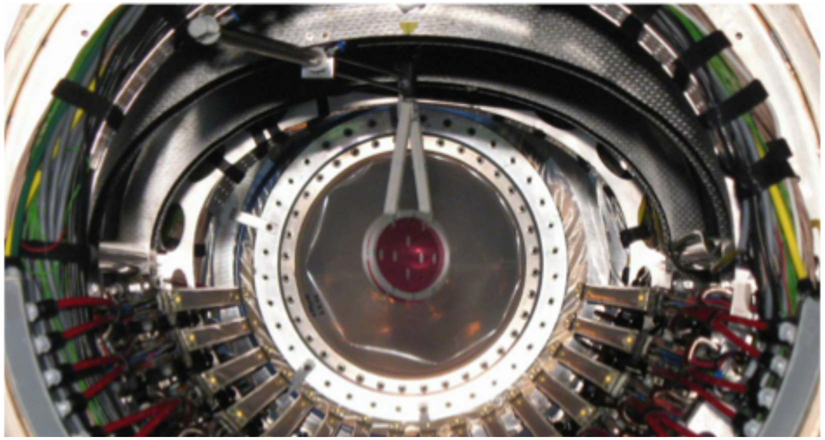


New target in MEG upgrade has two options:

- 160mm surface muons at 15°
- 140mm sub-surface muons at 15°

μ3e at πE5

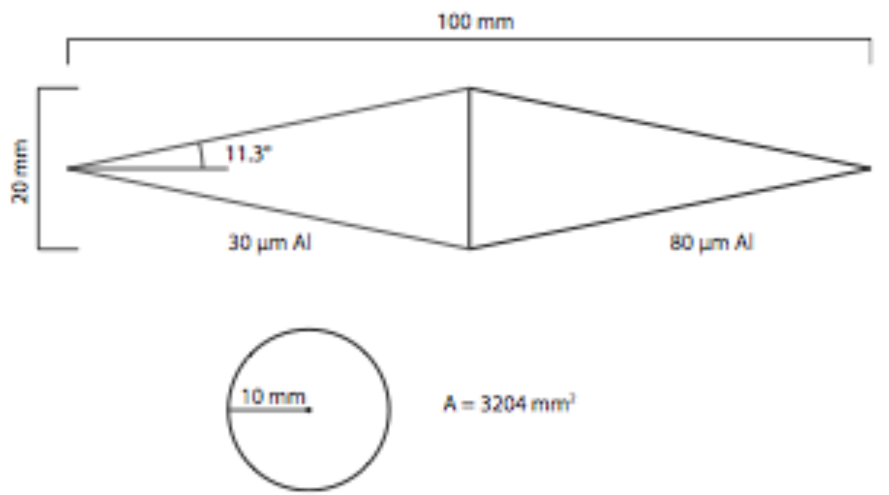


Figure 9.1: Dimensions of the baseline design target. Note that the material thickness is not to scale.

Double cone shaped to spread out vertices for suppression of accidental background

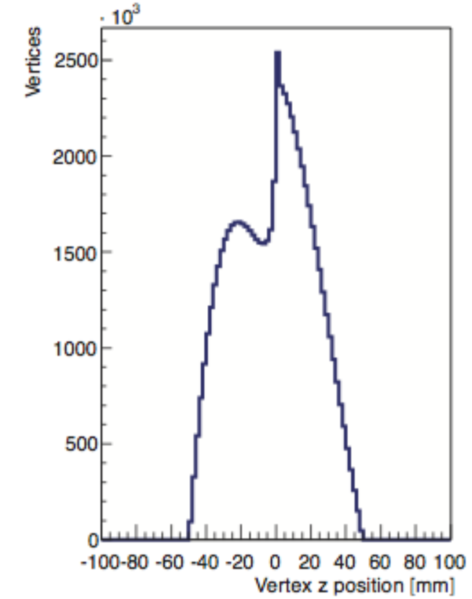


Figure 9.2: Vertex distribution along the beam direction.

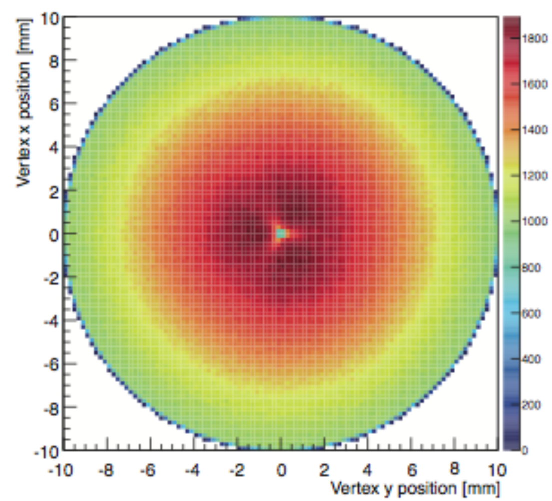
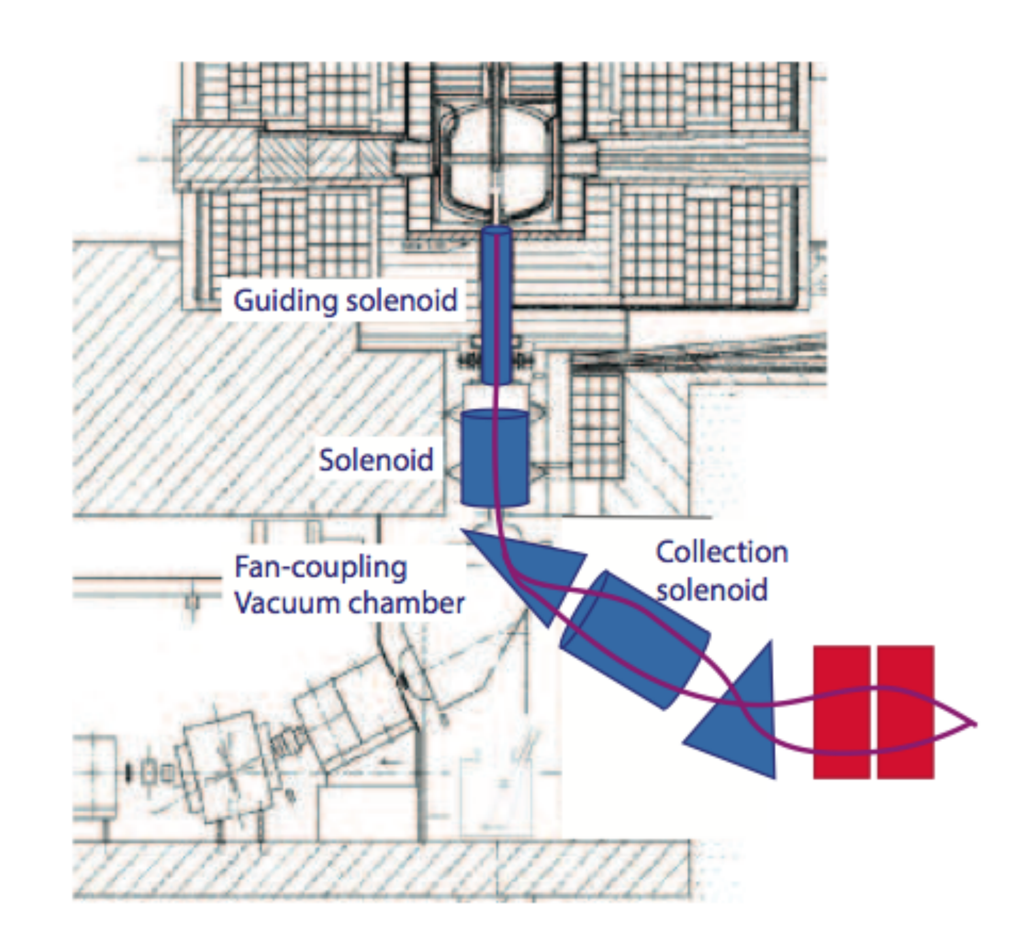


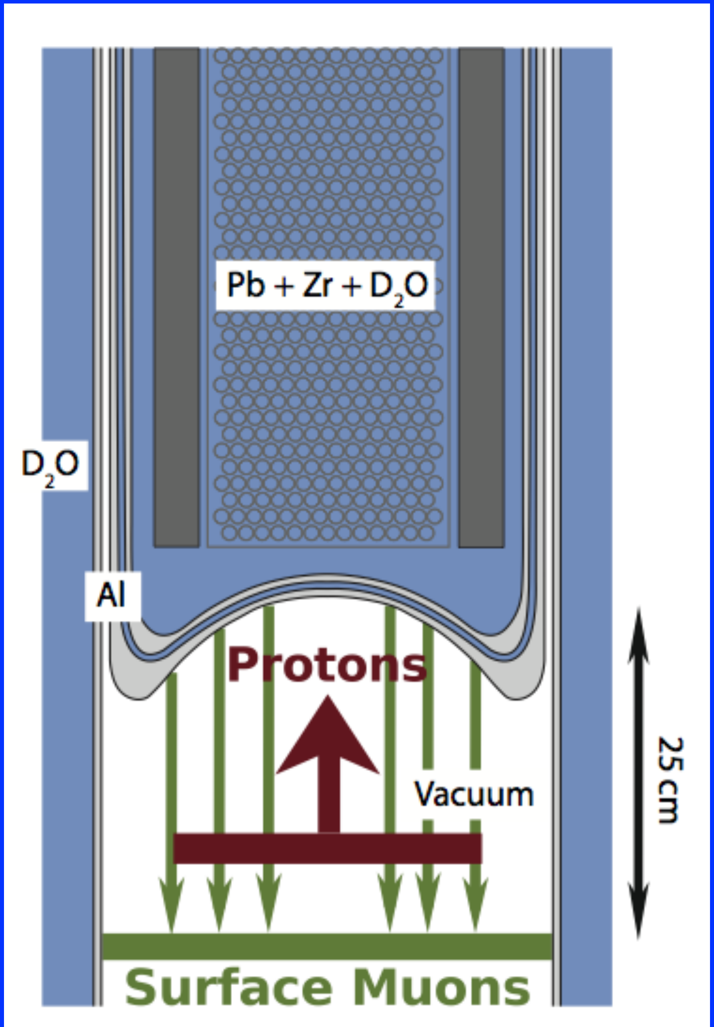
Figure 9.3: Vertex distribution transverse to the beam direction.

Surface muons in the future

- HIMB at PSI
- Mu2e beam channel with surface muons
- Muons in the Project X era

High intensity muon beam





Use spallation neutron source target

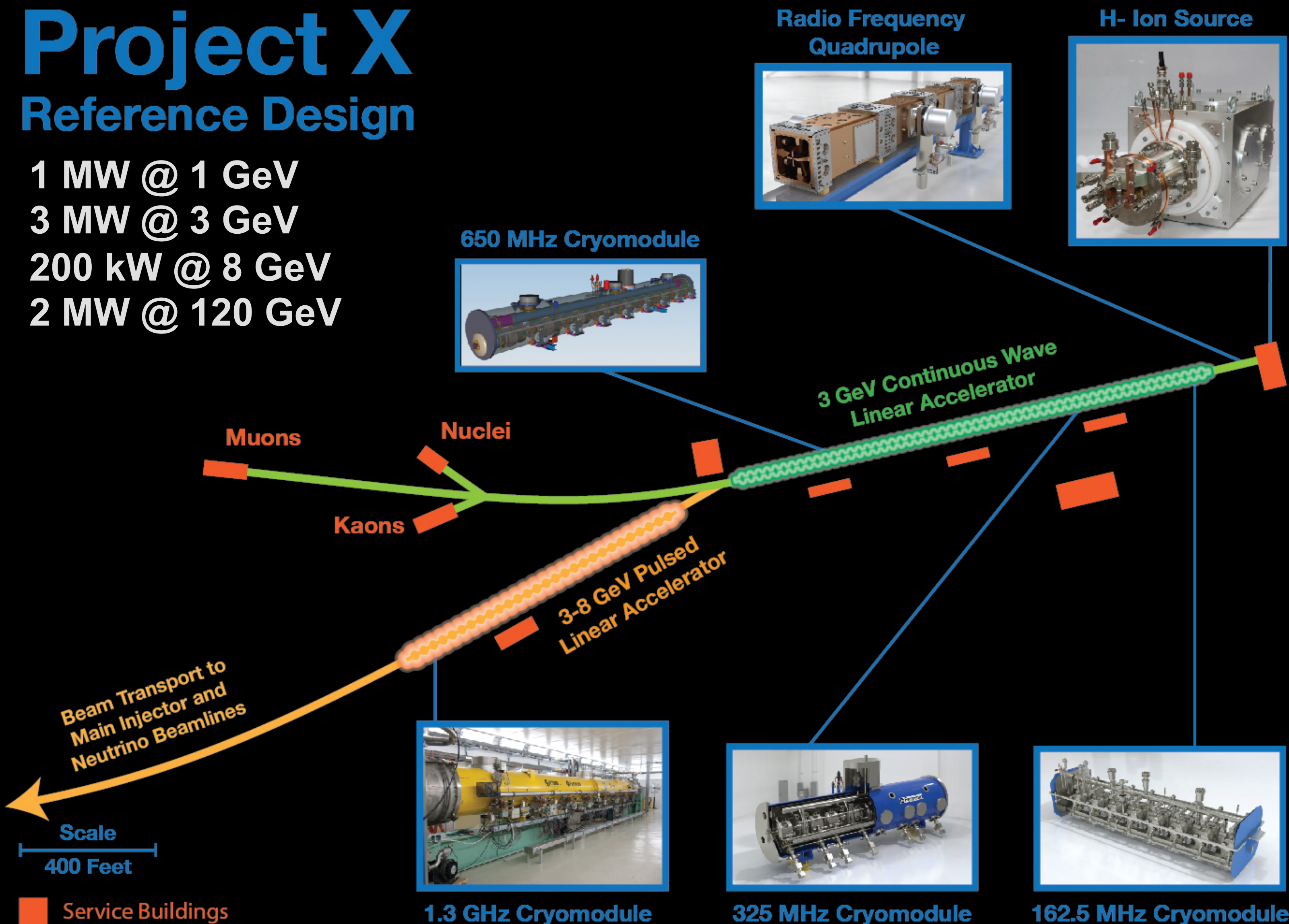
High intensity muon beam

P_0 MeV/c	$\Delta P/P$ % FWHM	Rate Hz
28	Full	$(7 \pm 1) \cdot 10^{10}$
28	10	$(3 \pm 1) \cdot 10^{10}$
26	10	$(3 \pm 1) \cdot 10^{10}$

Table 7.2: Estimated surface and sub-surface muon rates based on a proton current of 2.4 mA on Target E and full transmission efficiency.

Project X
Reference Design

1 MW @ 1 GeV
3 MW @ 3 GeV
200 kW @ 8 GeV
2 MW @ 120 GeV



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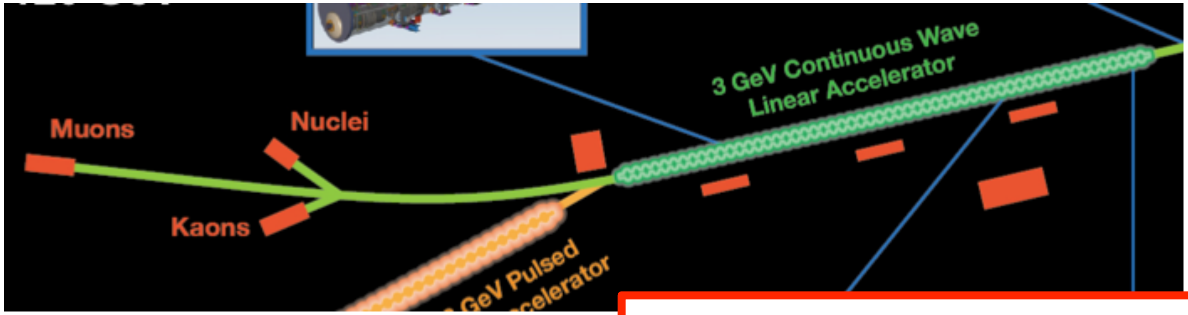
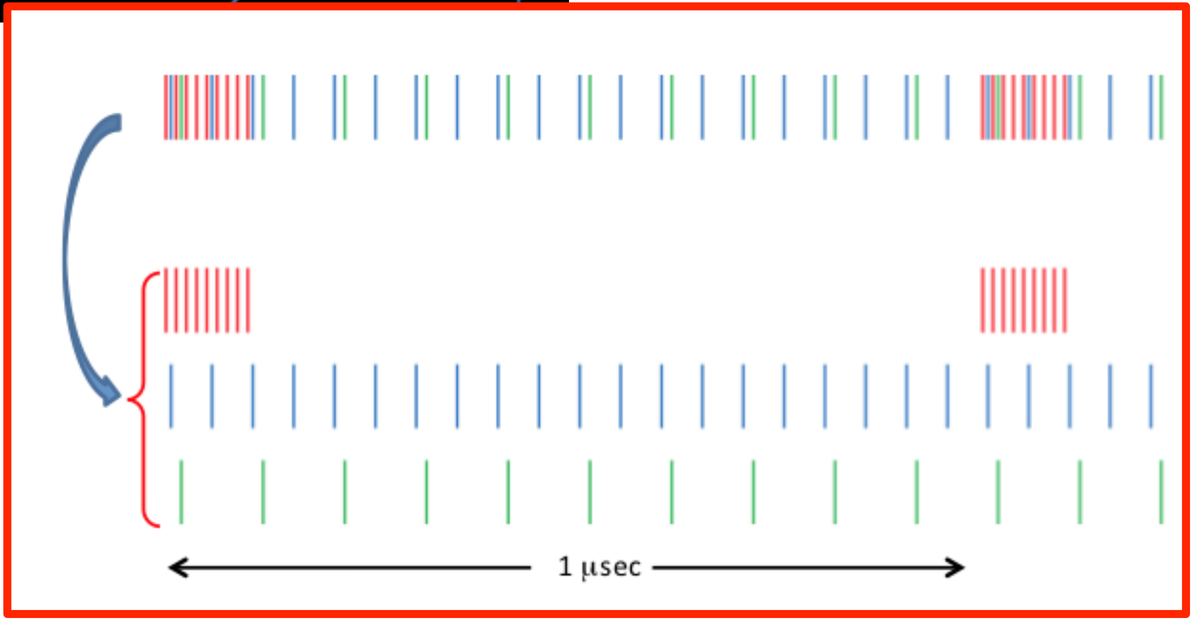
Pacific Northwest National Laboratory • Oak Ridge National Laboratory / SNS • SLAC National Accelerator Laboratory
Thomas Jefferson National Accelerator Facility • Cornell University • Michigan State University • ILC/Americas Regional Team
Bhabha Atomic Research Center • Raja Ramanna Center of Advanced Technology • Variable Energy Cyclotron Center • Inter University Accelerator Center

An example: Bunch structure



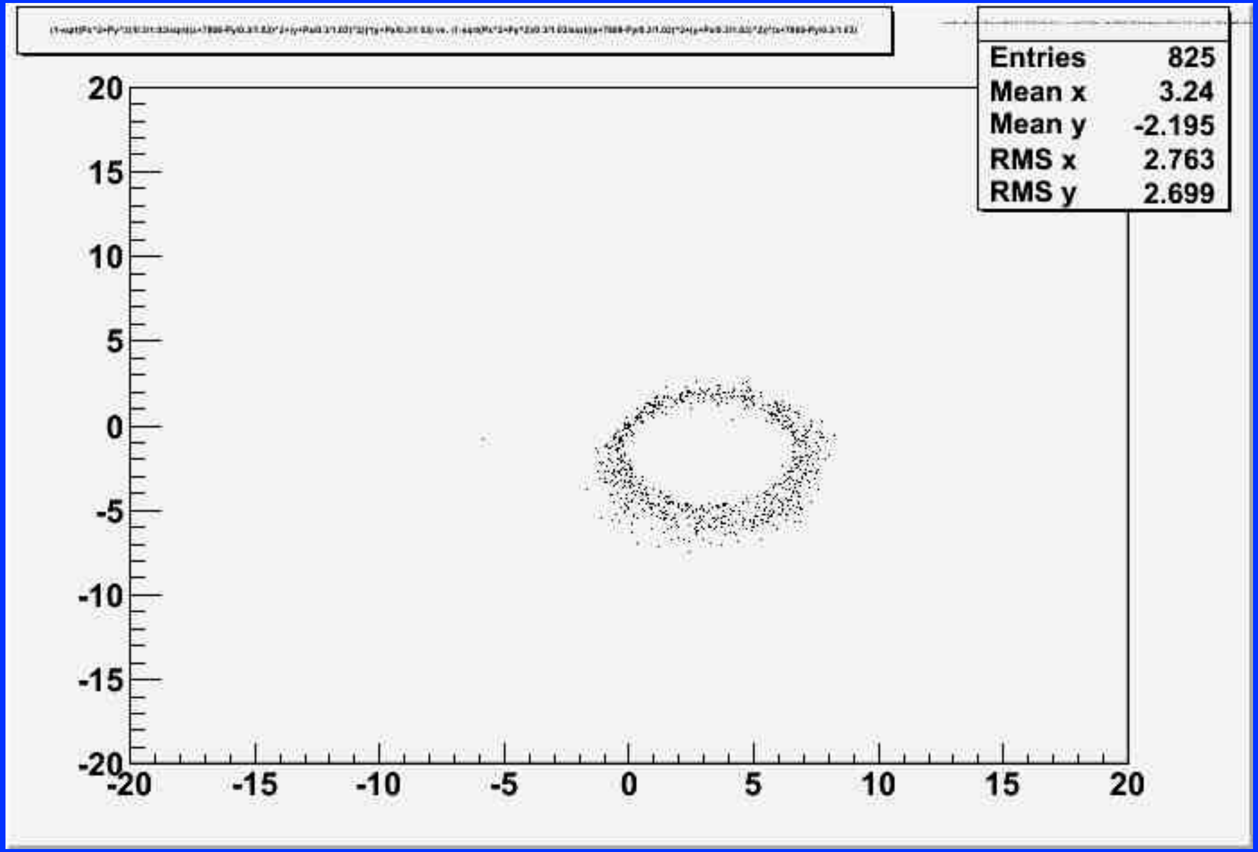


Area 1: 700 kW at 1MHz and 80 MHz substructure
Area 2: 1540 kW at 20 MHz
Area 3: 770 kW at 10 MHz

Mu2e with pulsed surface muons

Jim Miller's quick simulation:

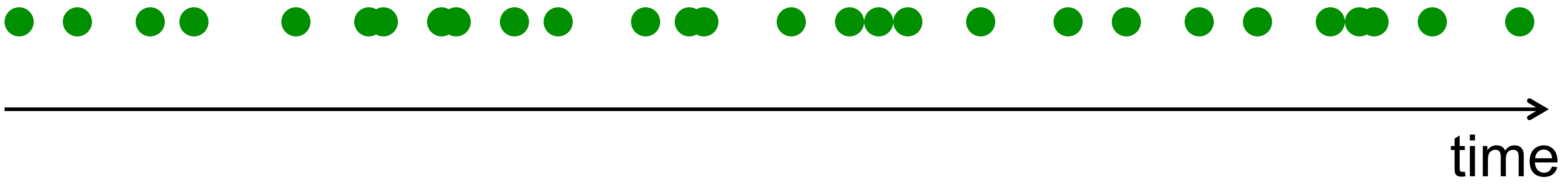
- Start with surface muon point source at Mu2e production target
- Plot point of closest approach along z-axis of detector solenoid



- Study stopping efficiency in thin cylindrical target in more realistic setup
- Need sparator for beam background or pulsed mode
- But what about the pulsed mode for accidental background (~ rate^2)?

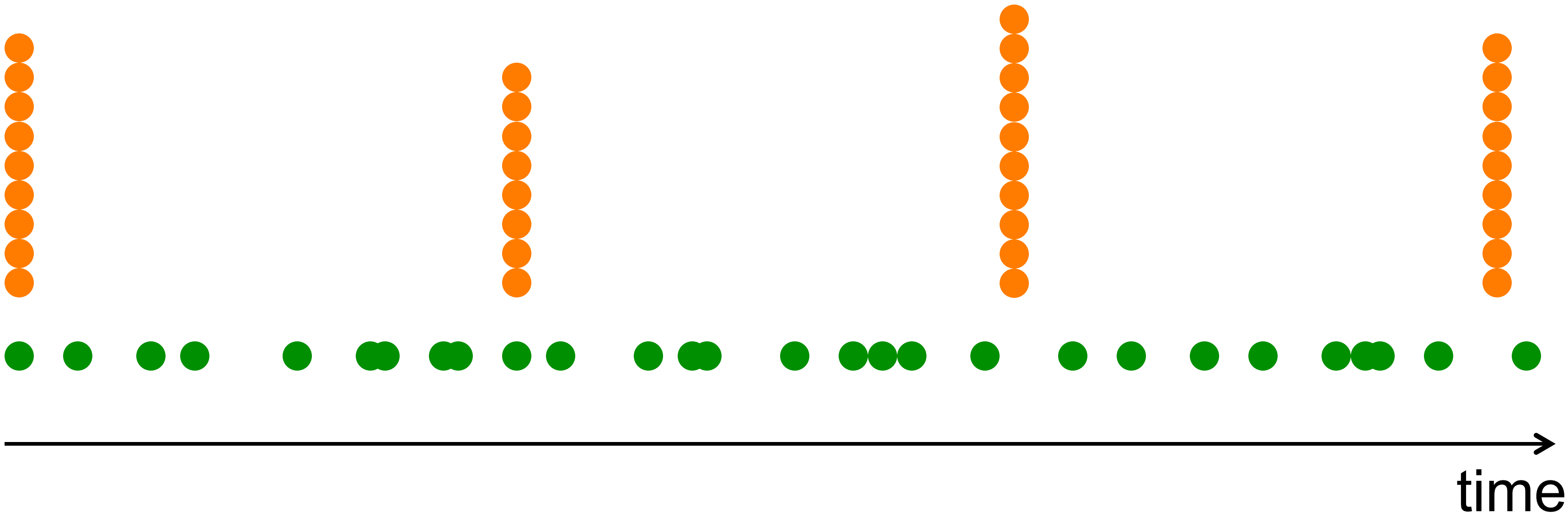
DC versus pulsed: Electron pileup

- DC beam with rate R



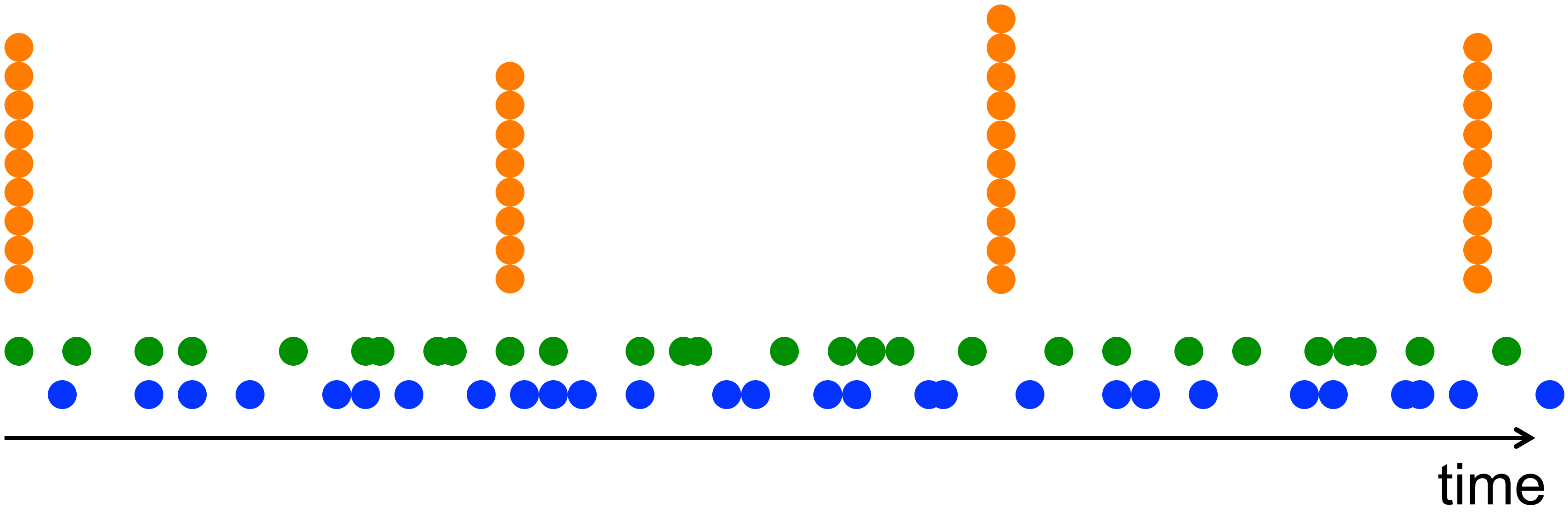
DC versus pulsed: Electron pileup

- DC beam with rate R
- Pulsed beam with averaged rate R



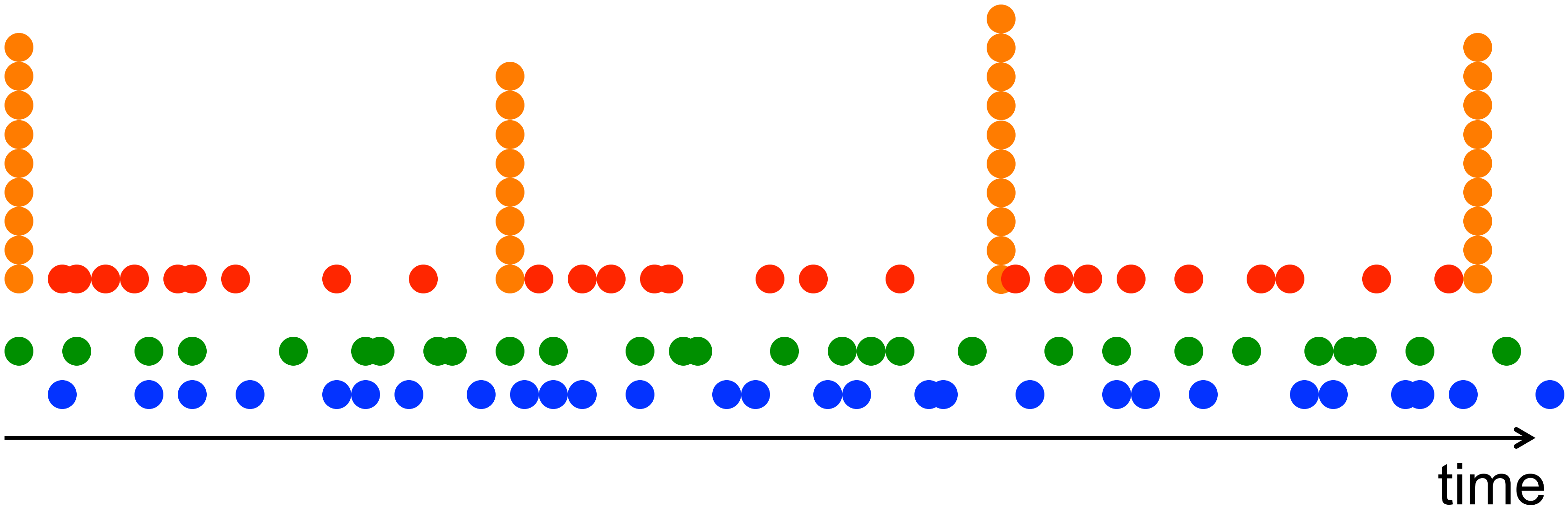
DC versus pulsed: Electron pileup

- DC beam with rate R
- Pulsed beam with averaged rate R
- Electrons from DC beam



DC versus pulsed: Electron pileup

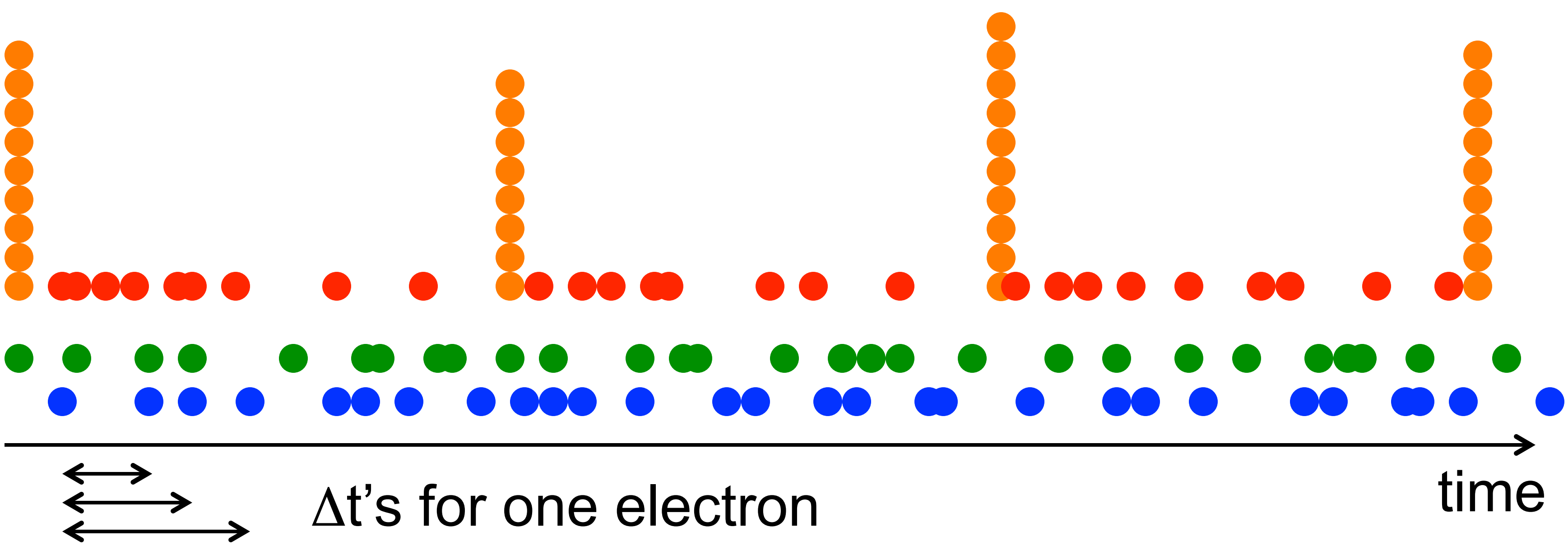
- DC beam with rate R
- Pulsed beam with averaged rate R
- Electrons from DC beam
- Electrons from pulsed beam



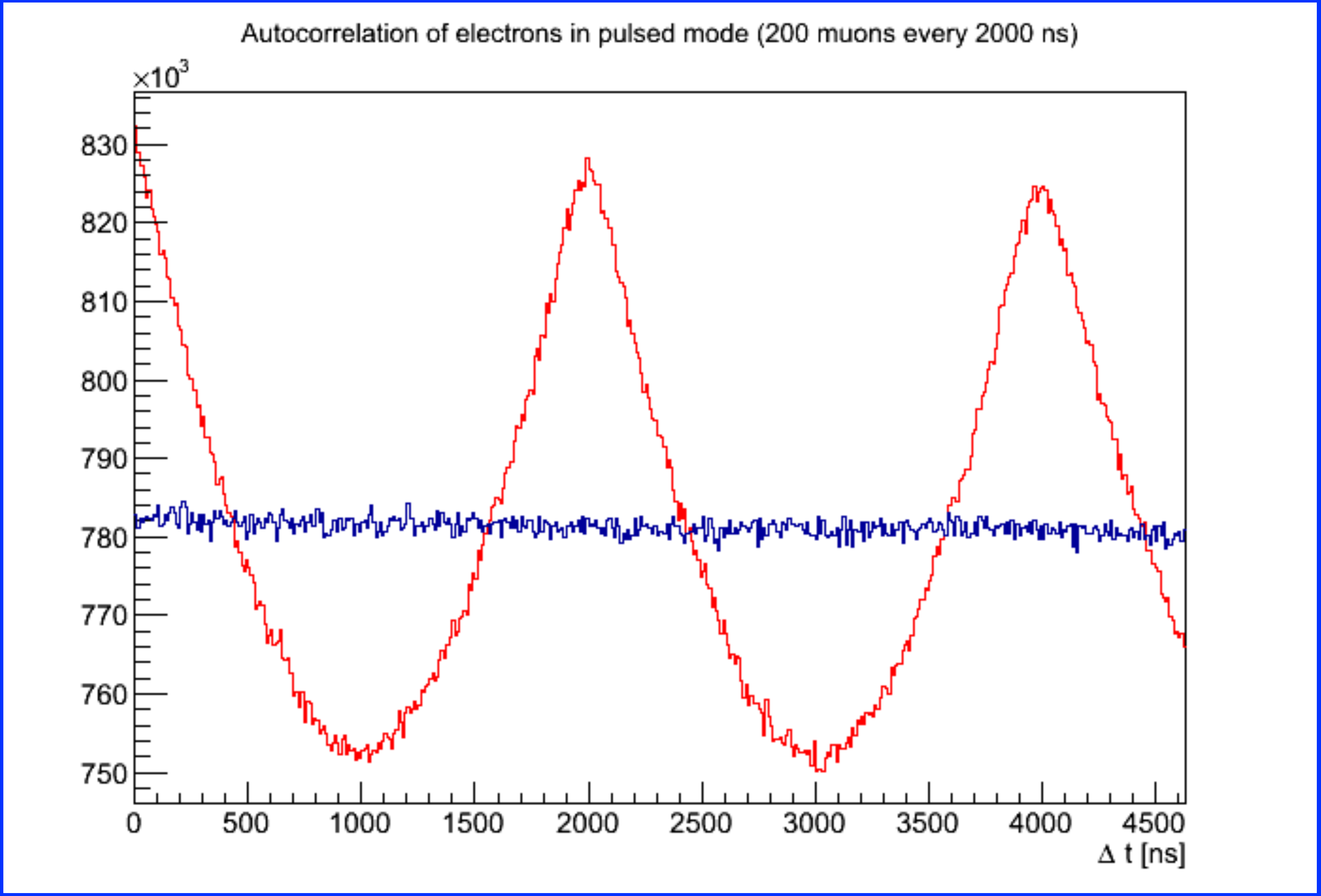
DC versus pulsed: Electron pileup

- DC beam with rate R
- Pulsed beam with averaged rate R
- Electrons from DC beam
- Electrons from pulsed beam

Histogram Δt between every electron and all others

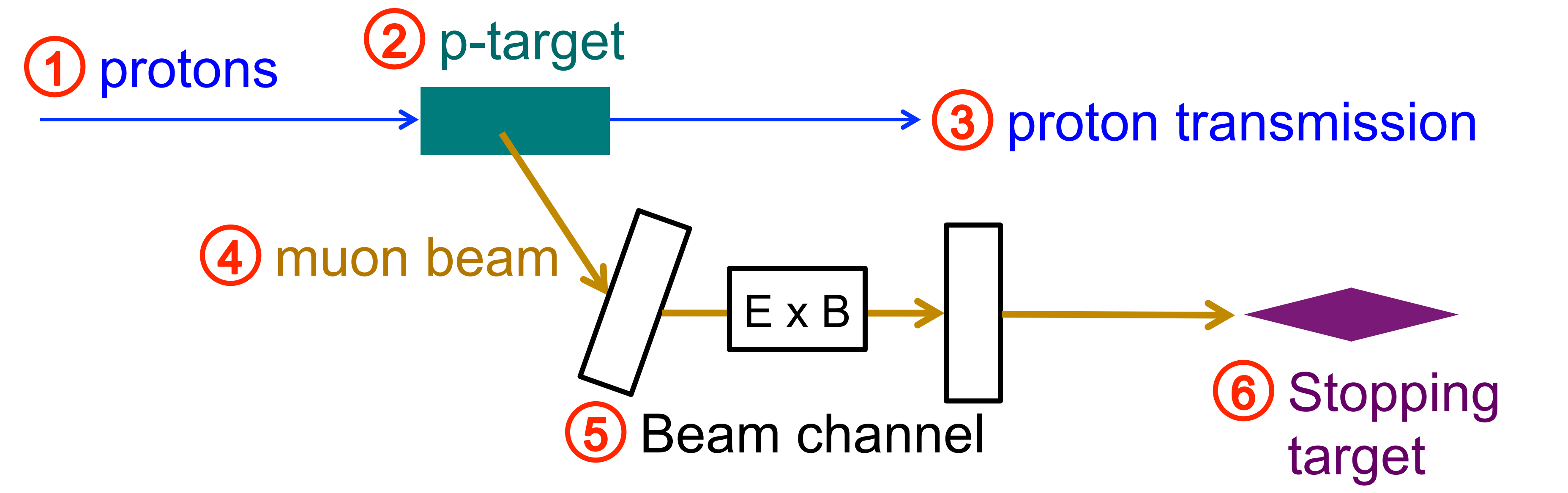


DC versus pulsed: Electron pileup



Ratio at Dt = 0 is only 1.06, i.e. accidental rate would increase by ~13%

Summary



- Optimization of muon beamline has many knobs
- Should look more into existing studies and continue from there
- Study Mu2e beamline in more details for μ^+ surface beam
- Future experimental requirements play important role in finding best strategy (cost, resources, physics, time, ...)
- It's hard to get the "Egg-laying-wool-milk-sow" but one shoud study which compromises might be feasible (multi-purpose or many beamlines)