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Beam energy optimization for Mu2e @ PIP-II

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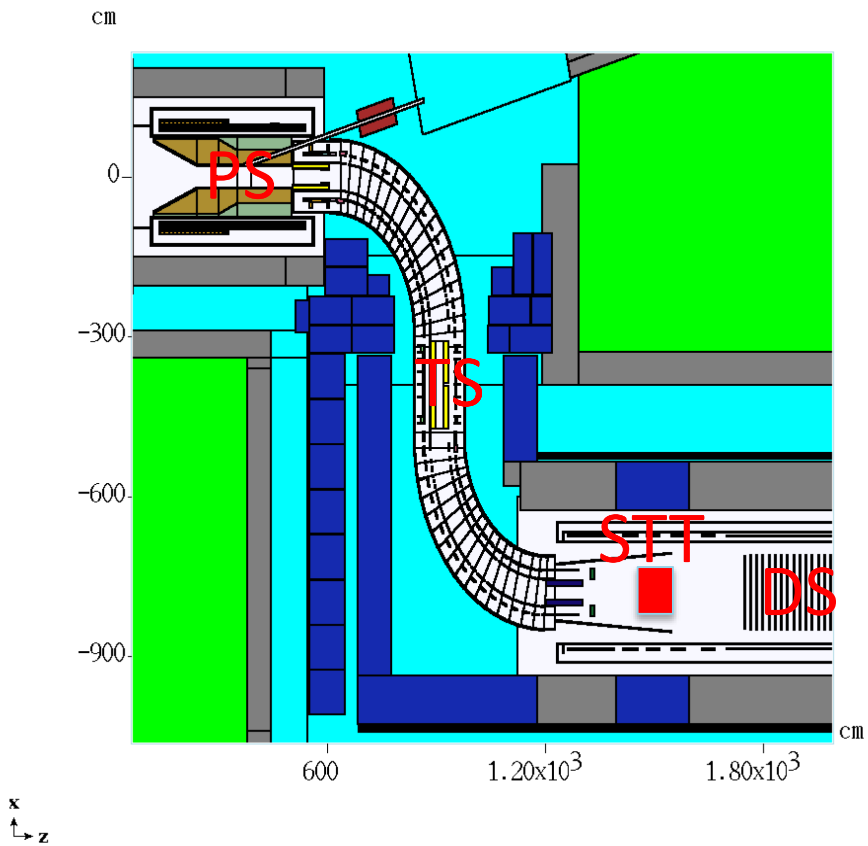
Introduction

- An improved proton source will be required for a next generation Mu2e
- Necessary to understand:
  - Expected muon yield and muon stopping rates as a function of proton energy
  - Potential performance constraints as a function of proton beam energy
- MARS15 is used because the energy-deposition-related quantities are well modeled as well as DPA damage (displacement-per-atom)
- PIP-II : Mu2e upgrade potential (@800 MeV) > 100 kW (linac), 120 kW (@8 GeV) (Booster), energies within the range were also considered
- The energy range studied: 0.5 GeV – 8 GeV.

Baseline Mu2e and MARS15 simulations

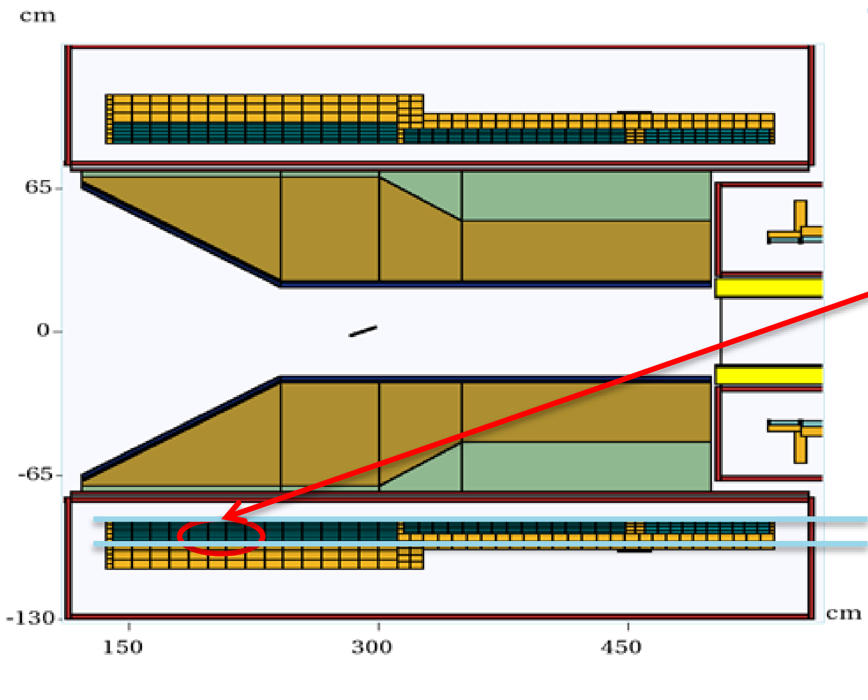


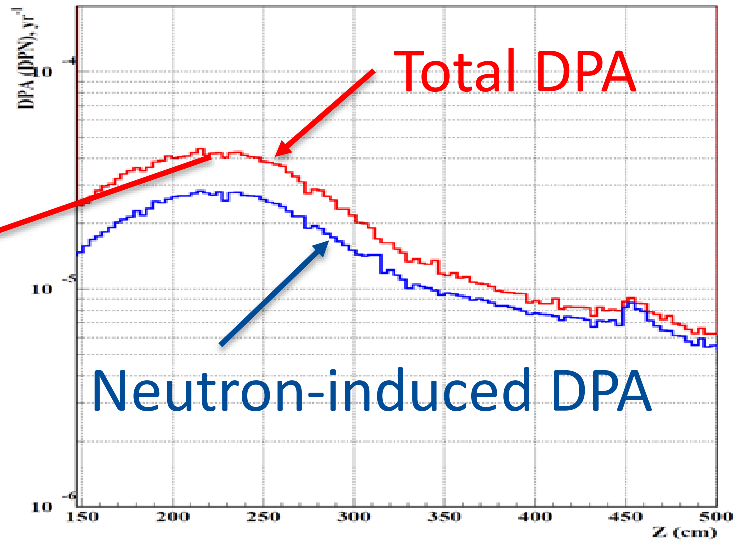
DPA and power density vs beam energy
vs HRS material
Muon yield/stopping rate vs beam energy
Figure of merit (stopping rate per DPA)

- 8 GeV 8 kW proton beam
- W target L=16 cm D=0.6 cm (beam σ=0.1 cm)
- Bronze HRS (tungsten considered for upgrade), CDR design is used for the study
- PS, TS, DS (17-foil Al stopping target (STT))

- In MARS15 simulations: LAQGSM, thresholds: 1E-12 GeV for neutrons, 100 keV for charged h., muons, photons

DPA limit and model



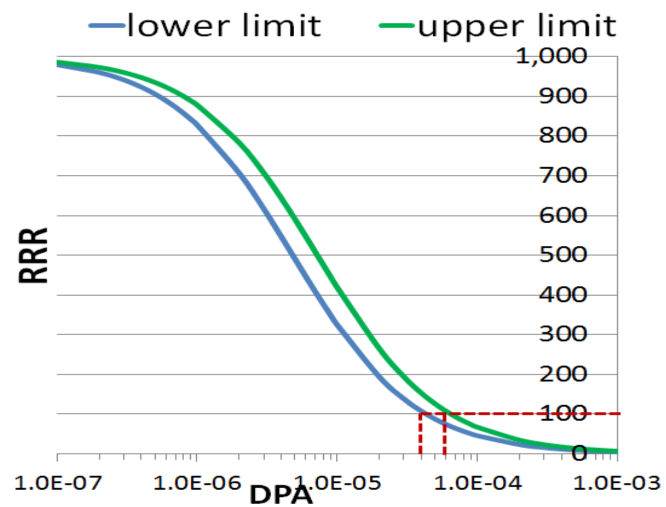


HRS: Bronze, Tungsten

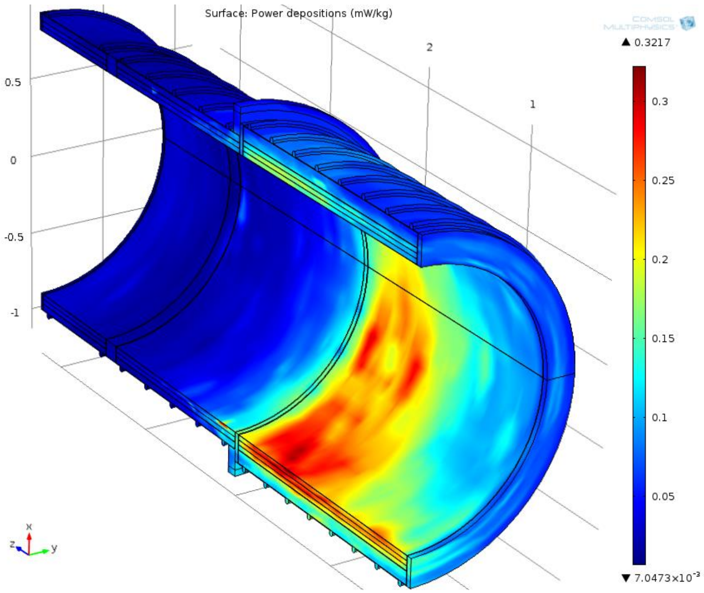
DPA model: NRT (below 20 (150) MeV ENDFB-VII/NJOY based cross section library FermiDPA 1.0) is used. NbTi coils

DPA limits incorporate KUR measured data

4-6E-5 DPA



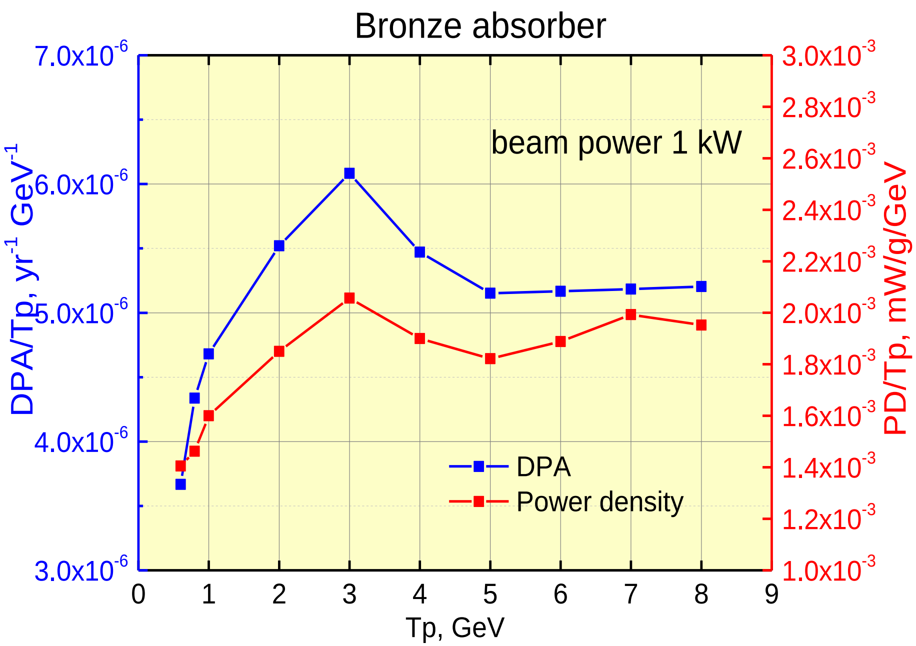
Power density (PD) and other limits

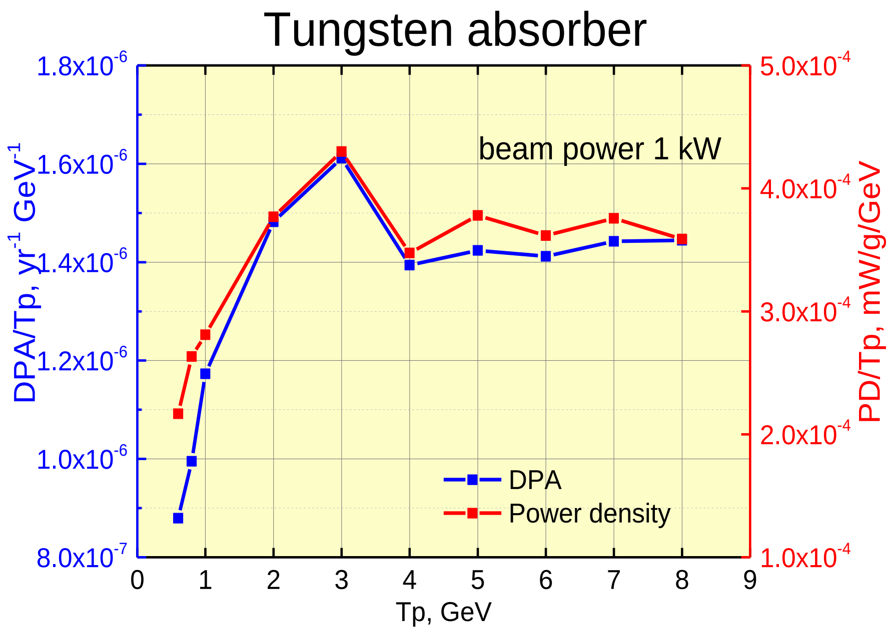


Power density limit:
-depends on the cooling scheme
-involves many other assumptions
Dynamic heat load limit:
-scales with the number of cooling stations
Absorbed dose limit: usually high

Quantity	DPA, 10^{-5}	Power density, μW/g	Absorbed dose, MGy/yr	Dynamic heat load, W
Specs	4-6	30	0.35	100

DPA as a function of beam energy



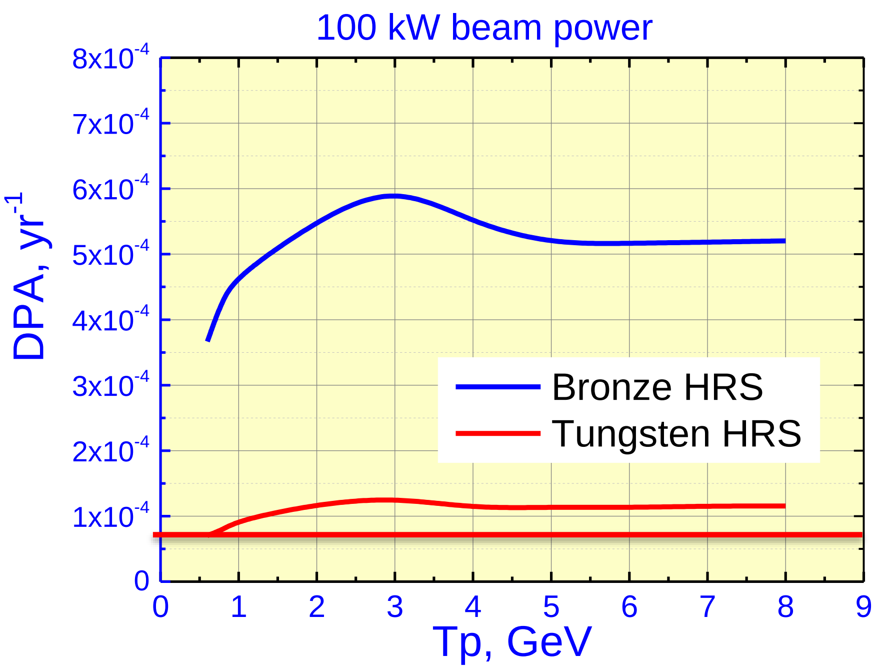


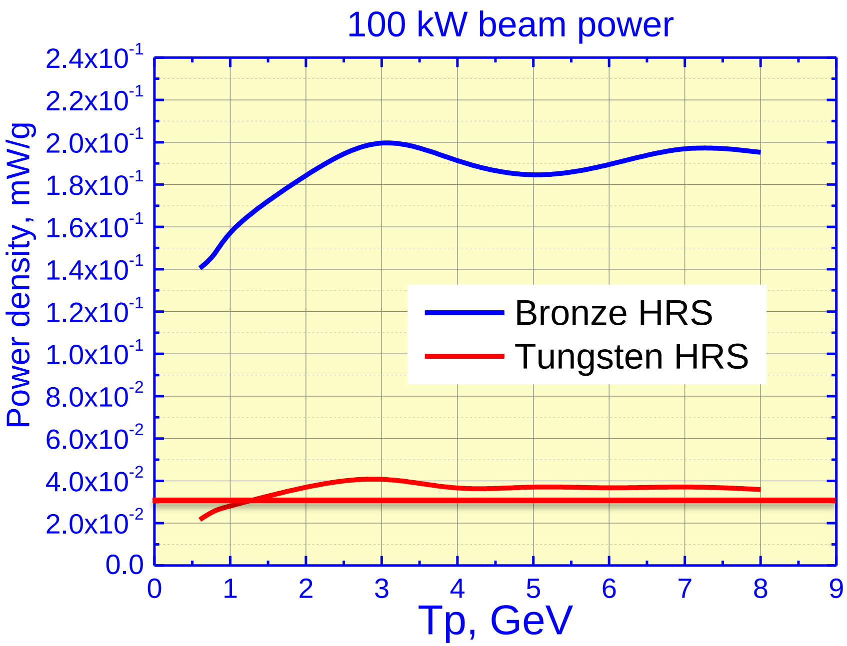
DPA damage and peak power density are:

Largest at ~3 GeV and drops with energy below that energy

Larger for bronze than for tungsten by a factor of ~3-4

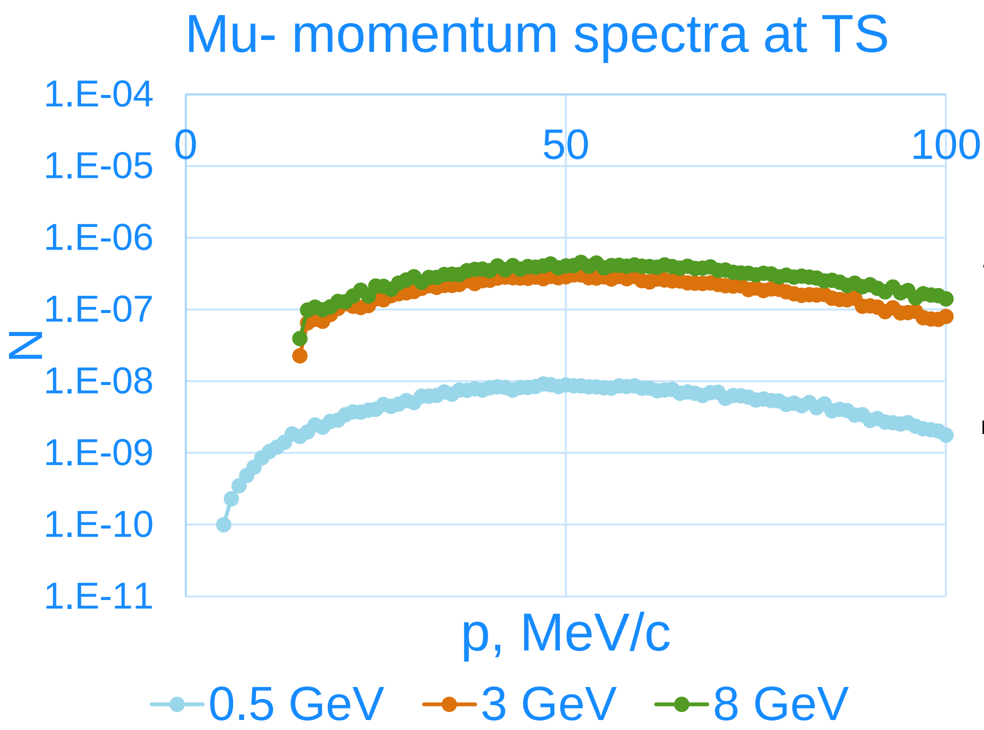
DPA and power density @ 100 kW

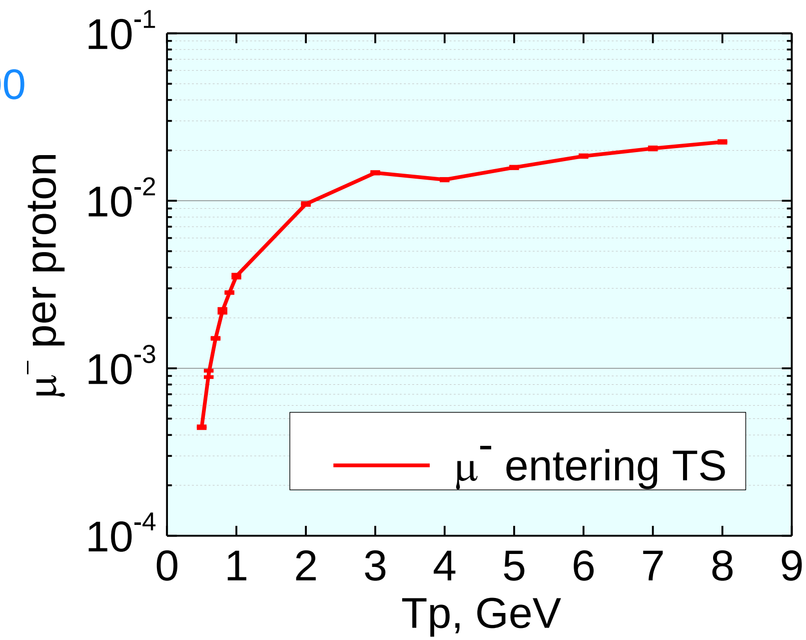




- DPA: Current coil design can likely tolerate 100 kW at proton energies < 1 GeV (if HRS thickness is increased).
- Power density: current coil design/cooling scheme can tolerate 100 kW at Ep = 0.8 GeV and lower. For higher energies another cooling scheme may be required.
- Above 1 GeV (DPA) or 2 GeV almost flat with energy.

Mu- spectra and yields at TS



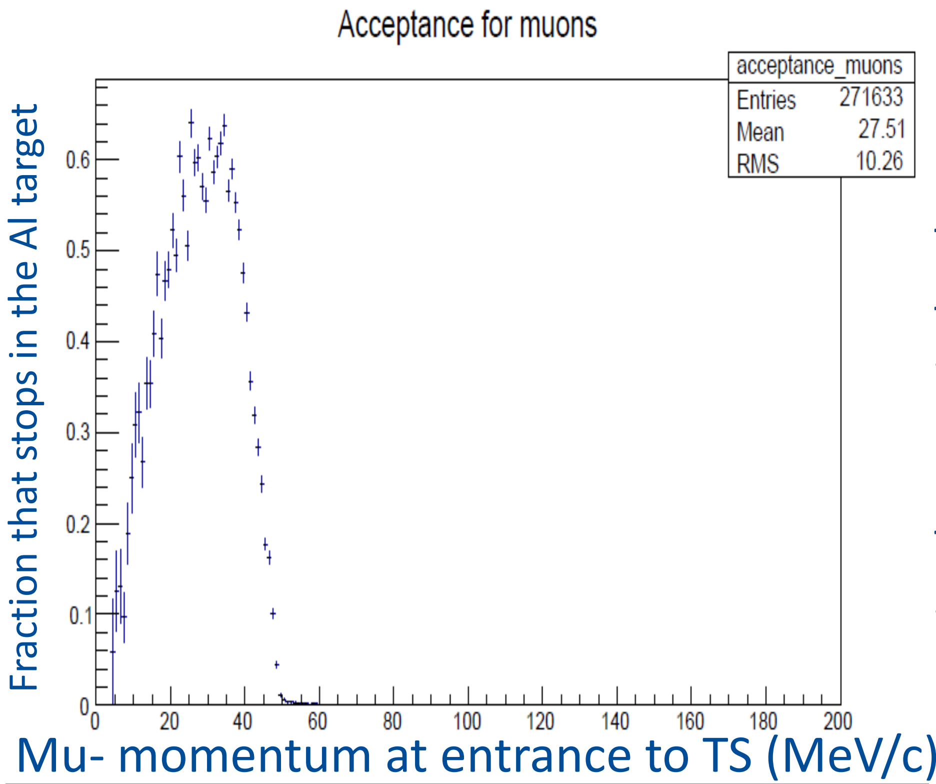


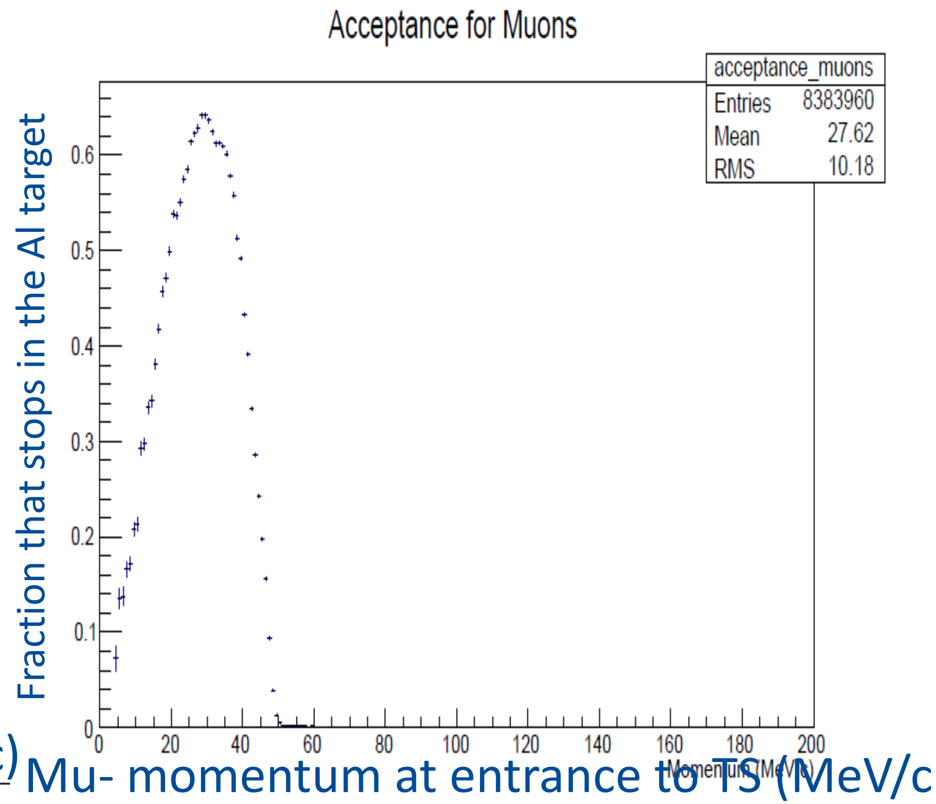
Constant beam intensity (not power) = $6 \cdot 10^{12}$ p/s

Steepest rise in μ^- yields is between 0.5 and 2 GeV.

Effective flux-based approach was used for counting muons

Acceptance

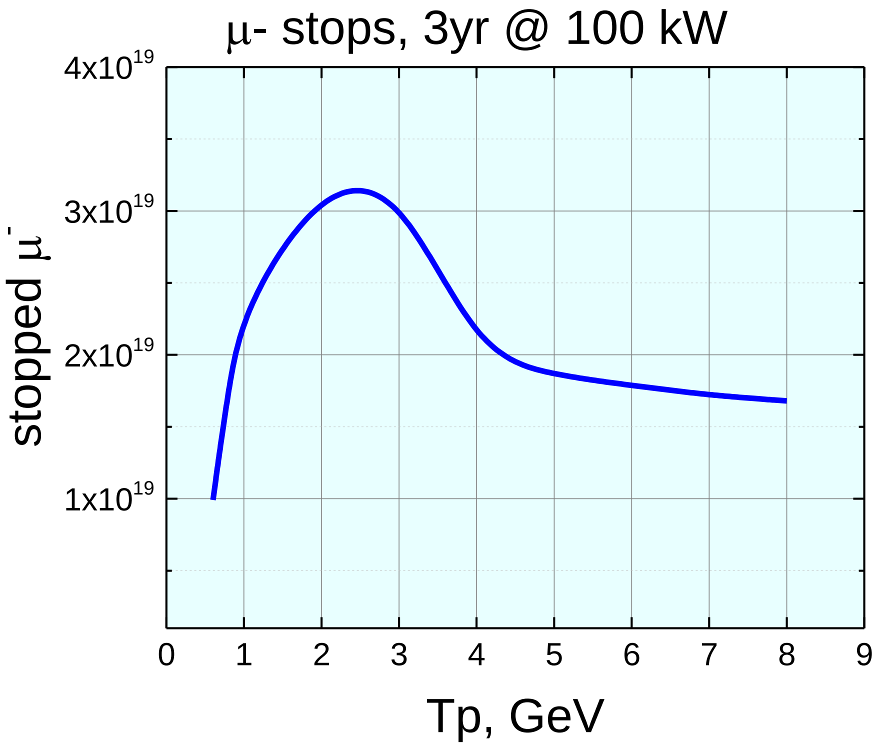


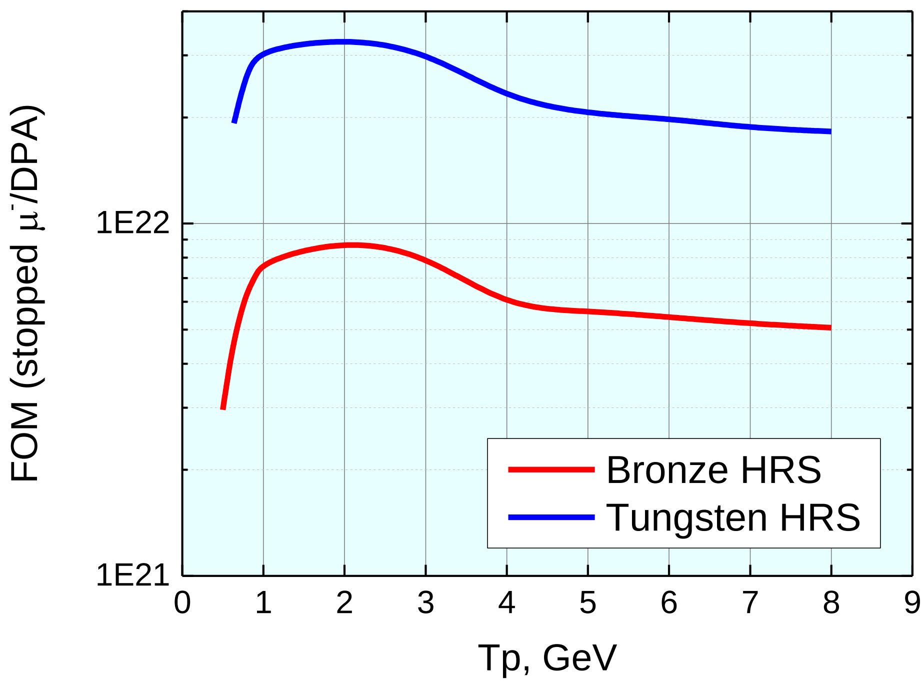


At 0.8 GeV Average 1-8 GeV

Calculated using G4beamline, used with MARS15 calculated muon spectra at TS

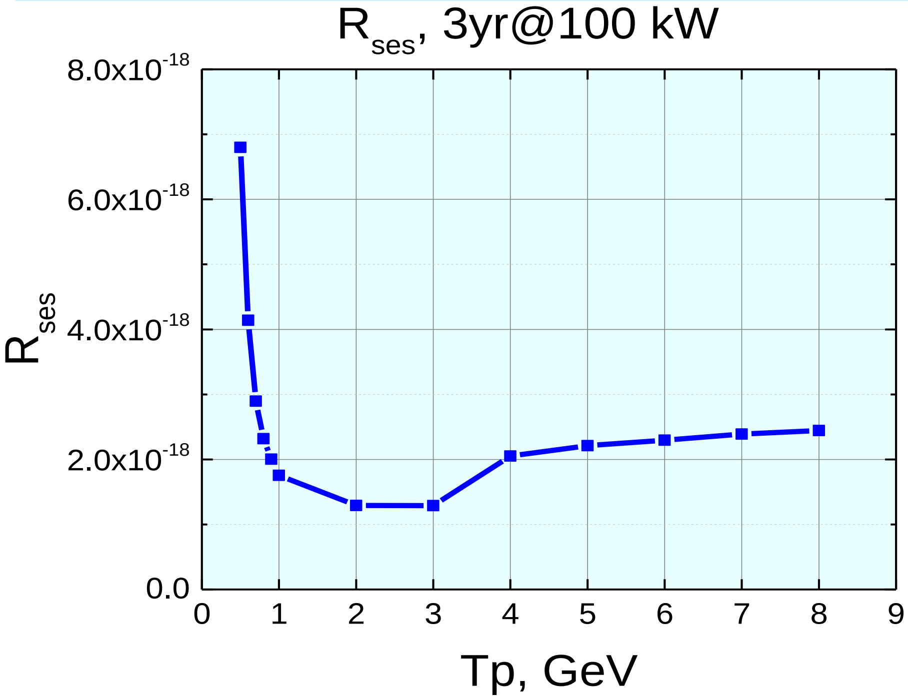
Mu- stopping rates and Figure of Merit





- 3 years = 4.7E21 protons on target @ 8 GeV (4.7E22 @ 0.8 GeV)
- If only stopped muons are considered: 2-3 GeV
- If DPA is also considered: 1-3 GeV
- The FOM for 0.8 GeV is about the same as it is for 8 GeV

Single-event sensitivity and limiting beam power



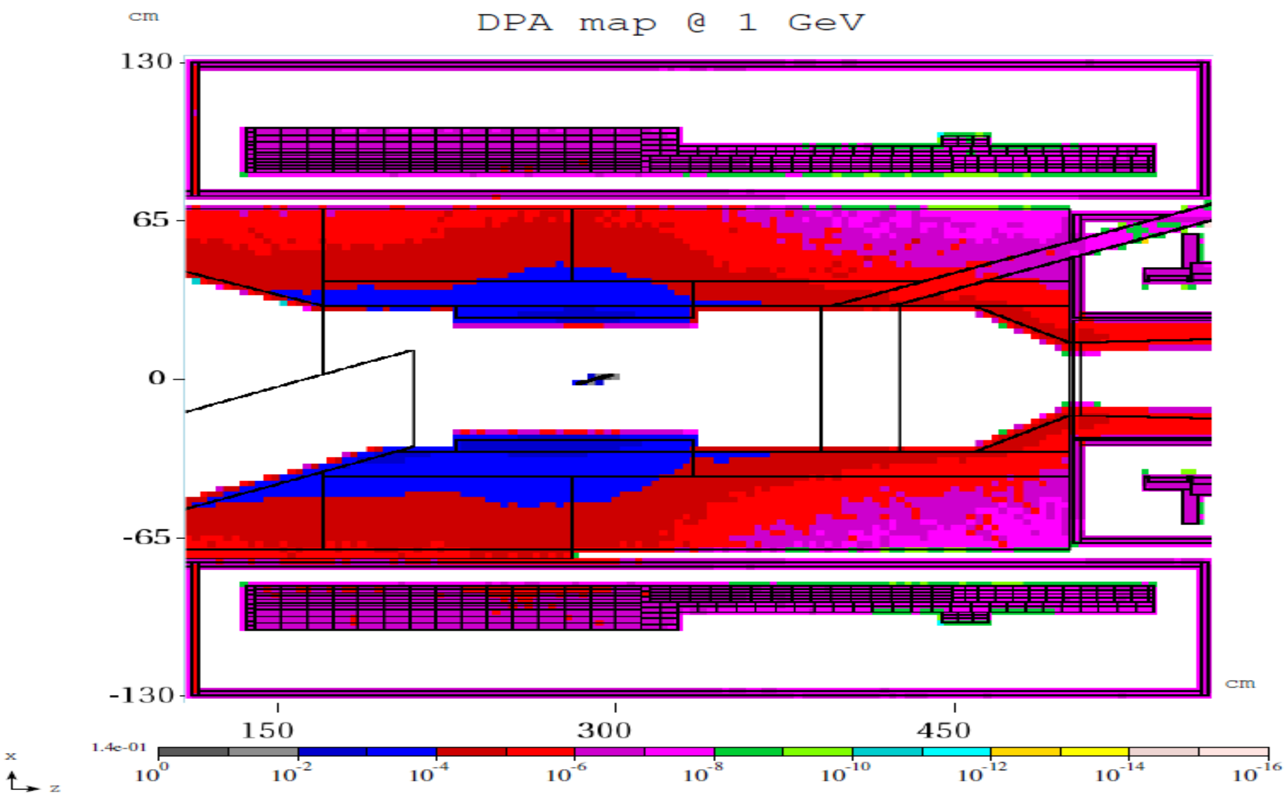
- The single-event-sensitivity (SES) corresponds to the rate of μ-to-e conversion at which the experiment would observe 1 event

  Current Mu2e $R_{ses}=3\cdot10^{-17}$

- Estimated SES as a function of proton beam energy

- Estimate is made assuming
  - 3y run at 100 kW (same timing structure, but increased duty factor)
  - Aluminum stopping target (ie. unchanged)
  - Total number of stopped muons as on page 10
  - Detectors can be made to handle increased rates so that acceptance and resolution comparable to current estimates
- Could achieve >x10 improvement for Tp in 0.8 – 5 GeV range

Future plans



Inner bore radius=20 cm

No yield drop for R>17 cm

Investigate the DPA and Power density deposition for a tungsten HRS with a reduced inner bore

Conclusions

- Energy dependence of DPA damage, power density, muon yield and muon stopping rate is studied.
- A Figure of Merit is proposed: the ratio of stopped muon rate to DPA
  - FOM is largest in the 1-3 GeV range
  - FOM for 0.8 GeV is comparable to 8 GeV
- Assuming detectors can be made to handle increased rates, can plausibly achieve x10 improvement in sensitivity for 100 kW at Tp = 0.8-5 GeV
- Additional work required to understand whether current coil + tungsten HRS design can likely tolerate 100 kW

Spare slides

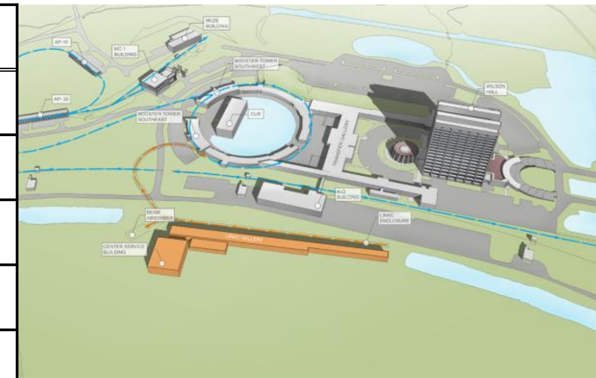
Mu- entering TS

Ep, GeV	Mu-/proton	Stat. uncertainty	Stat. uncertainty, %
0.5	4.45E-04	5.17E-06	1.2
0.6	9.26E-04	3.96E-05	4.3
0.7	1.51E-03	9.53E-06	0.6
0.8	2.20E-03	5.51E-05	2.5
0.9	2.83E-03	1.31E-05	0.5
1	3.55E-03	7.06E-05	2.0
2	9.57E-03	1.16E-04	1.2
3	1.47E-02	1.44E-04	1.0
4	1.34E-02	1.38E-04	1.0
5	1.58E-02	1.50E-04	0.9
6	1.85E-02	1.93E-04	1.0
7	2.06E-02	2.83E-04	1.4
8	2.25E-02	2.51E-04	1.1

Mu2e@PIP-II upgrade plans

Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.5	msec
Linac Pulse Repetition Rate	15	15	Hz
Linac Beam Power to Booster	4	13	kW
Linac Beam Power Capability (@>10% Duty Factor)	4	~200	kW
Mu2e Upgrade Potential (800 MeV)	NA	>100	kW
Booster Protons per Pulse	4.2×10^{12}	6.4×10^{12}	
Booster Pulse Repetition Rate	15	15	Hz
Booster Beam Power @ 8 GeV	80	120	kW
Beam Power to 8 GeV Program (max)	32	40	kW
Main Injector Cycle Time @ 120 GeV	1.33	1.2	sec
LBNF Beam Power @ 120 GeV*	0.7	1.2	MW
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

Table from S.Holmes, Neutrino Summit, 2014



- Early next decade
- 250 meter linac (20 Hz)?
- 800 MeV proton beam (2 mA)
- -> Booster -> 8 GeV (120 kW)
- -> Main Injector/Recycler
- ->120 GeV (1.2 MW)