New Booster Collimation Unit MARS Optimization

Igor Tropin, Target Systems Department Topical Meeting

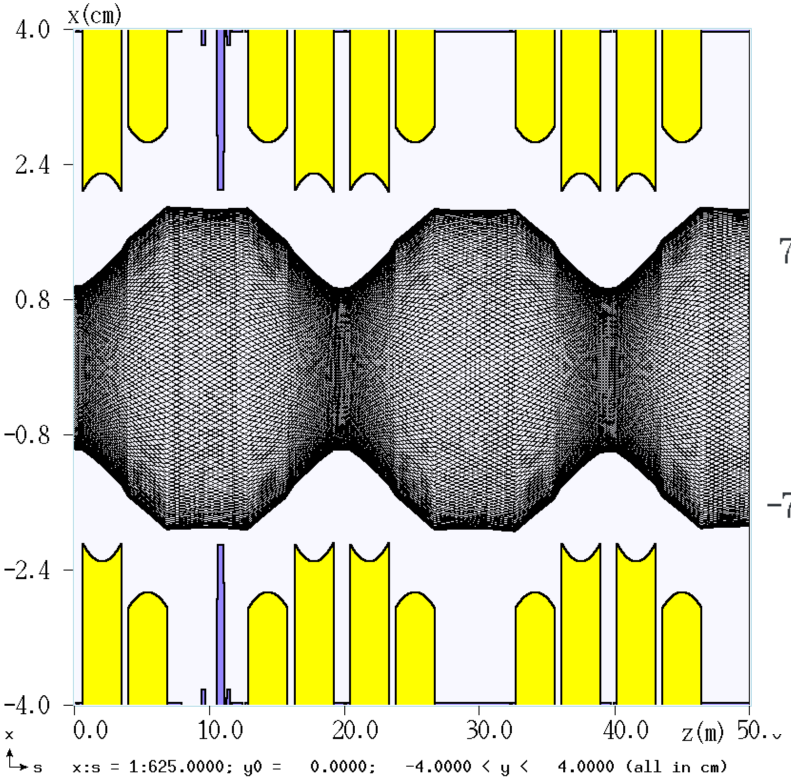
Initial Data and Task Formulation

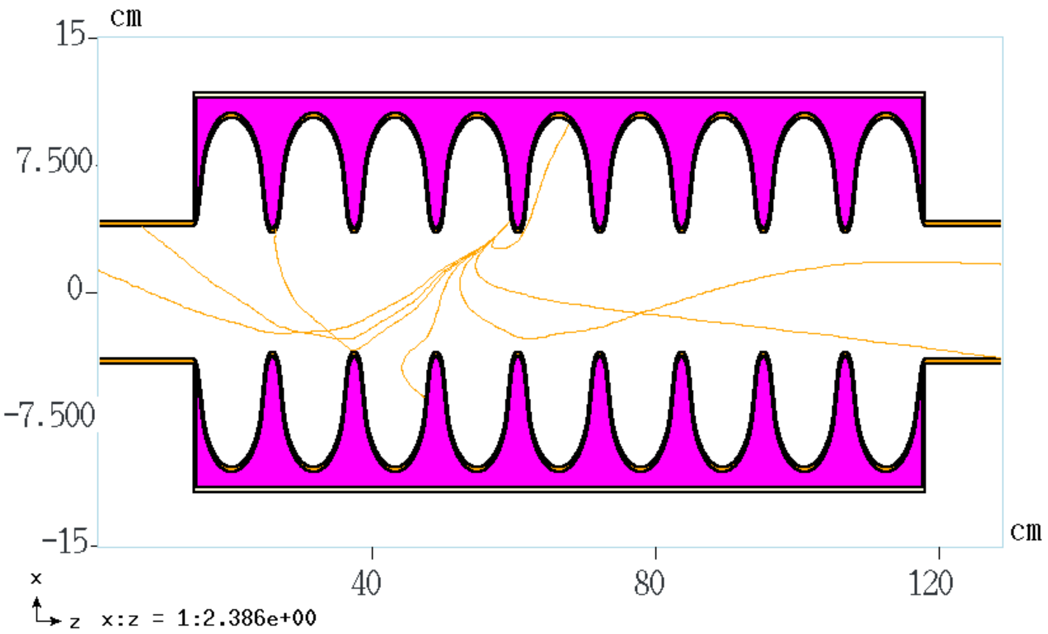
Simple Halo Model : A single jaw of horizontal primary collimator in the assembly is irradiated by protons with a kinetic energy 400 MeV. A number of primary protons hitting the jaw per second – scraping rate – suggested by Chandra Bhat is N_a=3.89·10^{12} (p/s). Vertical coordinates y_{mad} , $v=\alpha_y y_{mad}+\beta_y p_y$ are sampled from restricted Gauss distribution with zero mean value and standard deviation $\sigma=0.635$ in such a way that $|y_{mad}|<h$, h – half-height of the horizontal jaw. Horizontal coordinates are sampled from uniform distribution $w(x_{mad})=(b-a)^{-1}$, where $a=3\sigma_x=1.126\,cm$ is jaw opening, $b=a+1\,mm$

Jaw positioning: Opening of the irradiated jaw of primary collimator is 3σ, which is 1.126 cm for horizontal jaw. Remaining 3 jaws of primary collimators are in a garage position. All jaws of secondary collimators are aligned with the 3σ+2mm beam envelope: 1.326 cm for the horizontal collimator, 2.105 cm for the vertical collimator. Thickness of of the copper primary collimator jaws as defined to the provided CAD model is $T_0=1.016\,cm$

Goal: Collimator optimization.

ROOT and MAD-X based MARS extensions in action:

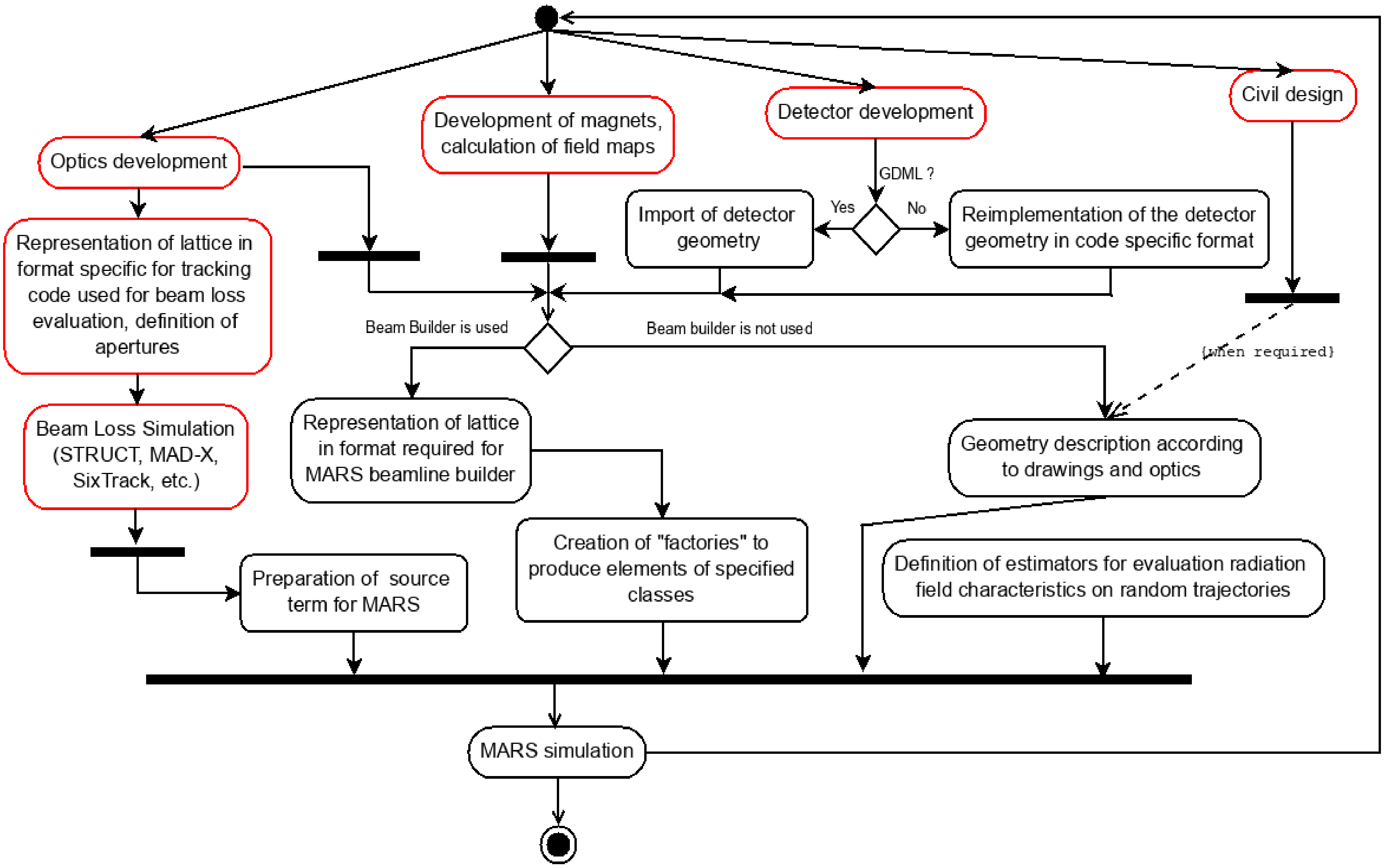




3-sigma proton beam envelope (vertical plane) in the Fermilab Booster, E=400MeV, 500 trajectories tracked by MAD-X PTC module.

Trajectories of a field-emitted electrons, E ~ 5 eV in ILC (LCLS) RF Cavities – CavityStepper

General Workflow for Beam Loss simulation



Optics development

Development of magnets, calculation of field maps

Detector development

Civil design

Representation of lattice in format specific for tracking code used for beam loss evaluation, definition of apertures

Import of detector geometry

Reimplementation of the detector geometry in code specific format

Beam Loss Simulation (STRUCT, MAD-X, SixTrack, etc.)

Representation of lattice in format required for MARS beamline builder

Geometry description according to drawings and optics

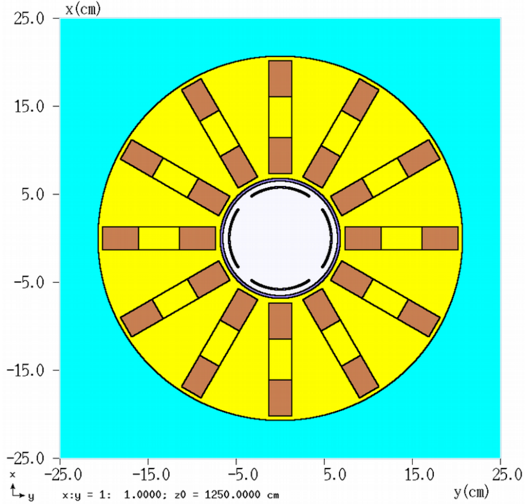
Preparation of source term for MARS

Creation of "factories" to produce elements of specified classes

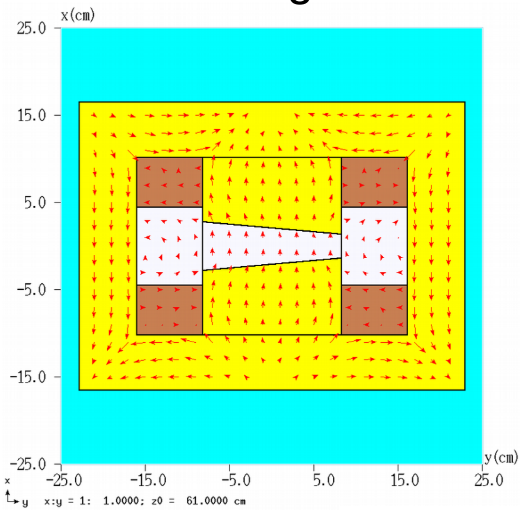
Definition of estimators for evaluation radiation field characteristics on random trajectories

MARS simulation

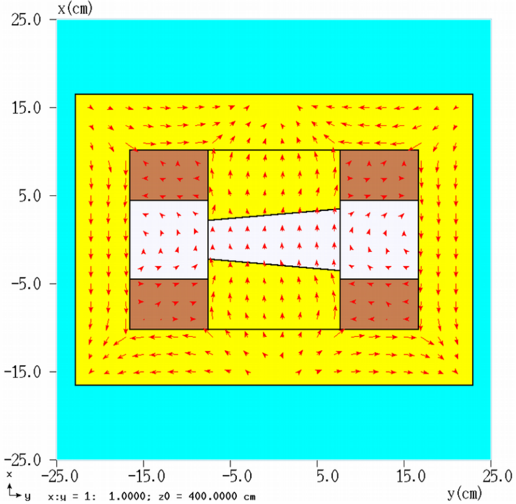
MAD-X classes in MARS15 Model for collimation region



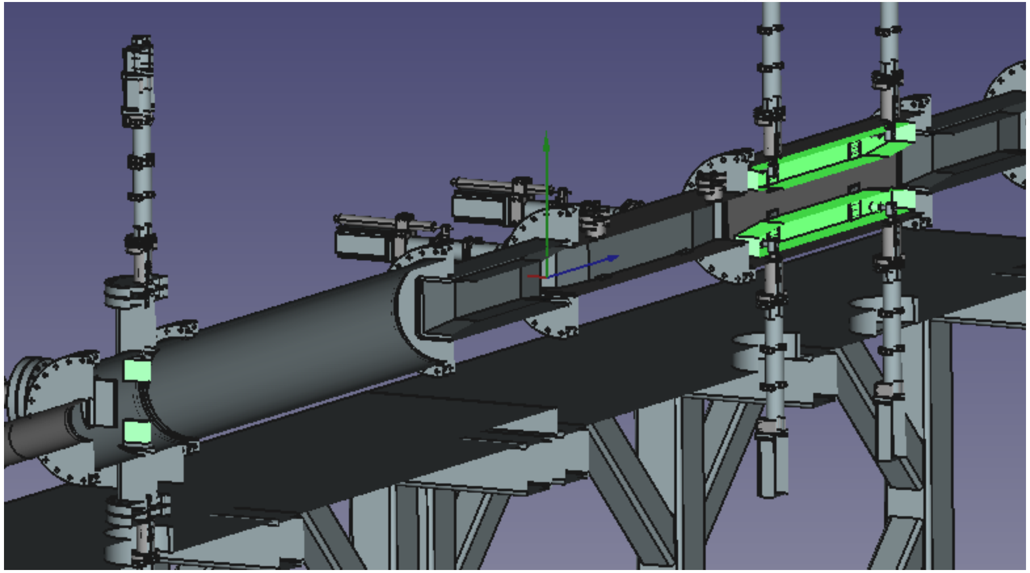
dhz, dvt, nquad, nsext, ssext

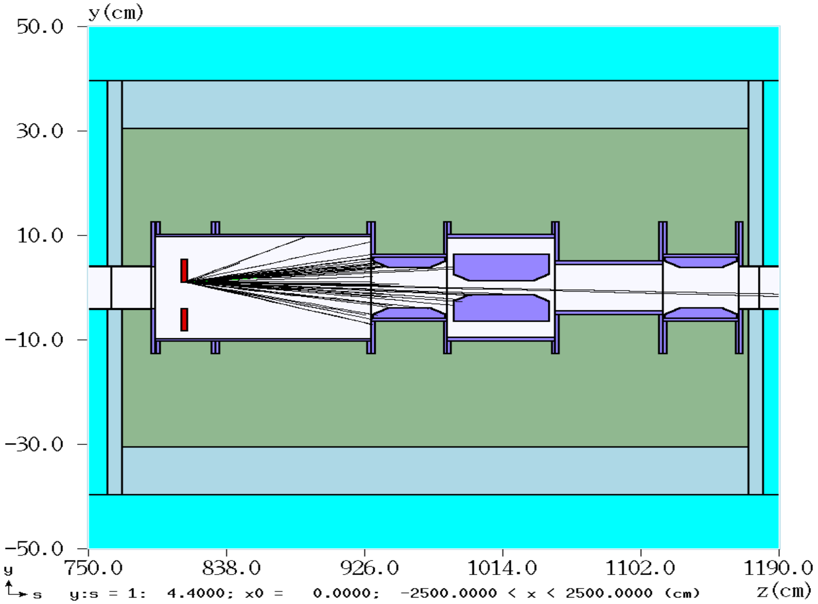


fmag

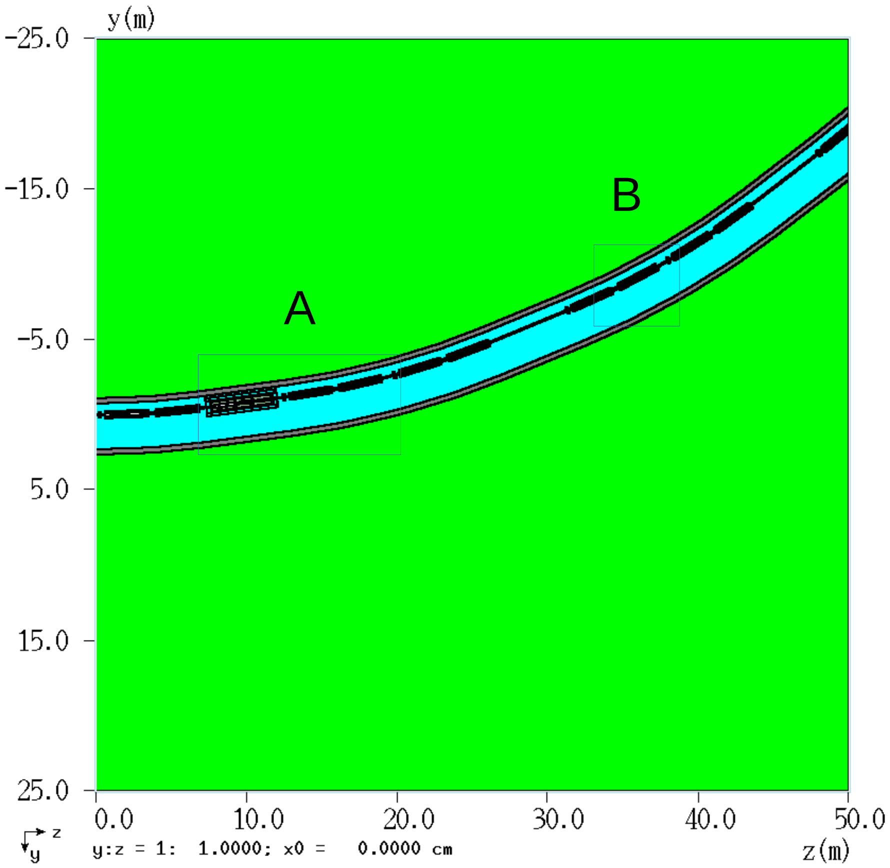


dmag

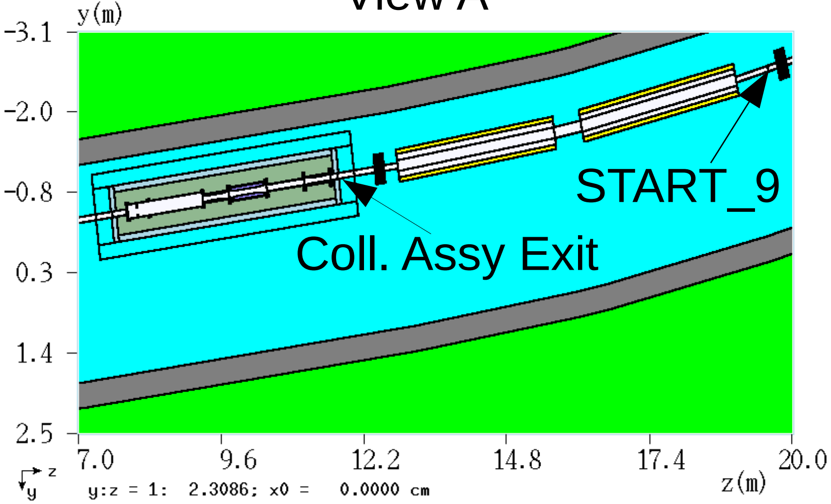




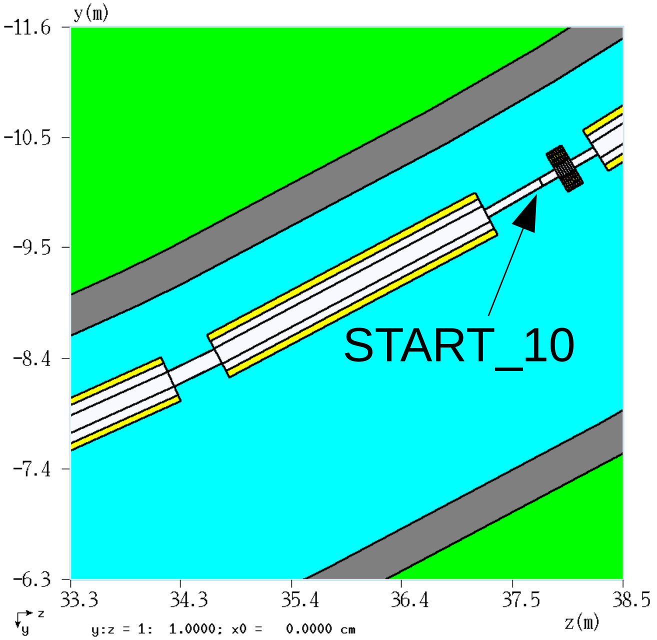
Scoring Positions (MAD-X Markers)



View A



View B



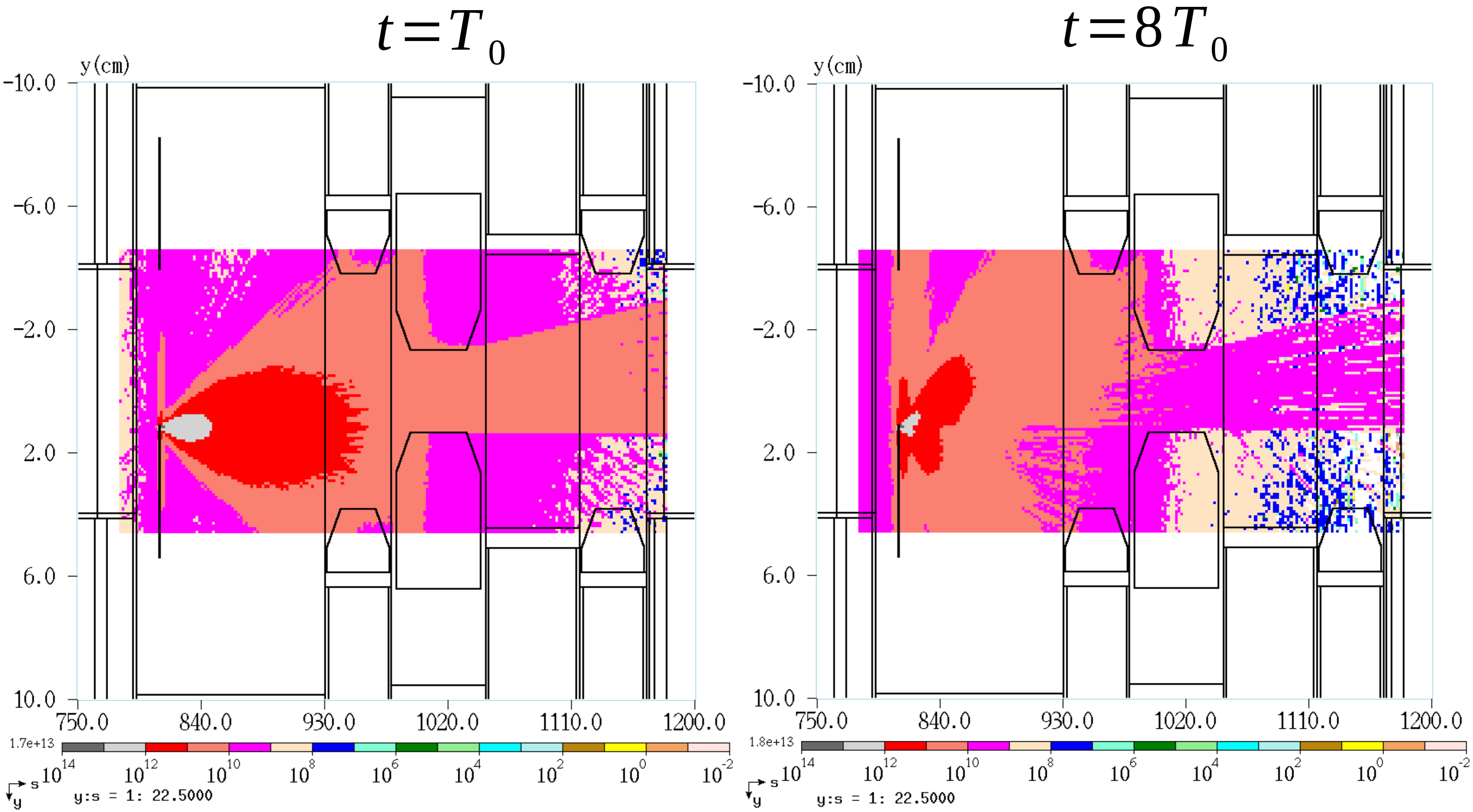
Number of Protons Inside Aperture (N_{pa}) at Marker Positions

Results normalized per single proton hitting the collimator jaw

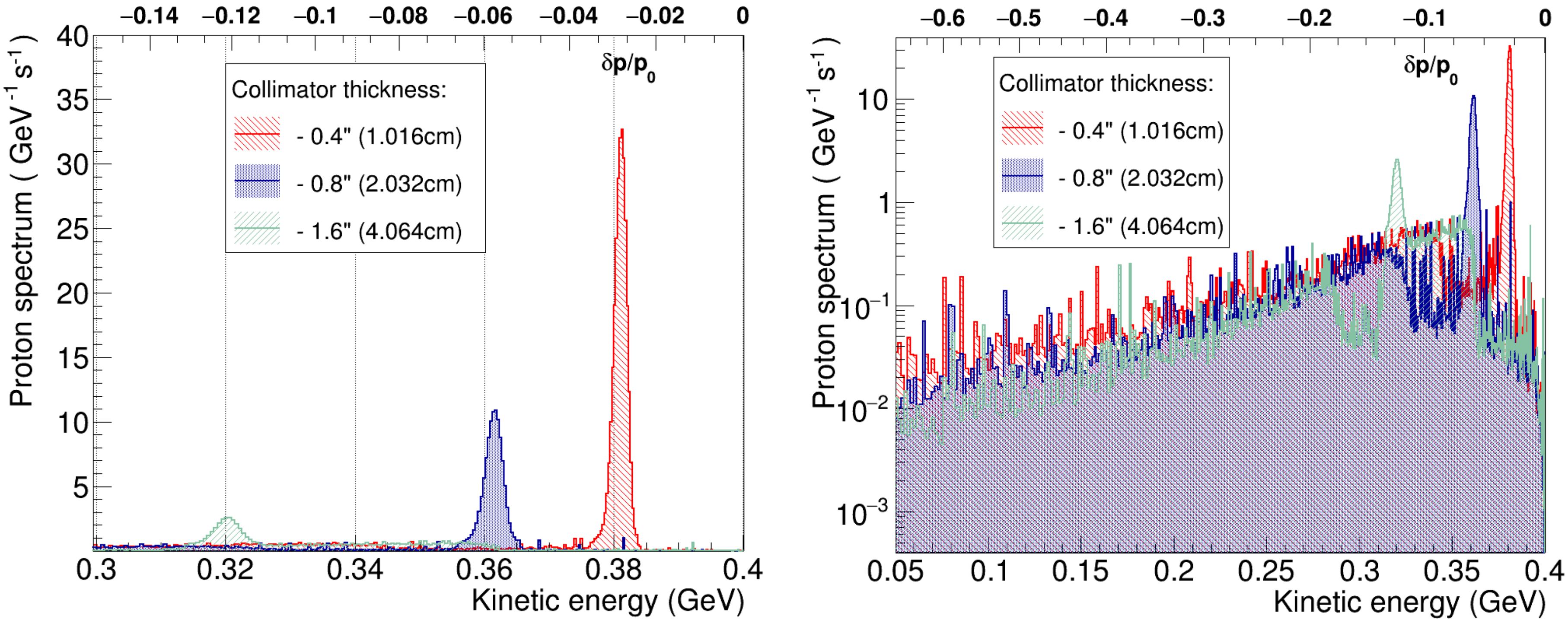
Collimator type	Jaw thickness, T_0 = 1.016 cm of Cu		
	T_0	$2 \cdot T_0$	$4 \cdot T_0$
	Coll. Assy Exit		
Horizontal	0.132	0.0742	0.051
Vertical	0.133	0.0745	0.054
	START_9		
Horizontal	0.0336	0.019	0.016
Vertical	0.0314	0.018	0.012
	START_10		
Horizontal	$2.89 \cdot 10^{-4}$	$2.27 \cdot 10^{-5}$	$4.32 \cdot 10^{-5}$
Vertical	$1.54 \cdot 10^{-4}$	$1.50 \cdot 10^{-5}$	$7.04 \cdot 10^{-6}$

Charged hadron cutoff energy is 1MeV

Hadron flux density above E_{th} = 1 MeV in the collimation unit for two thicknesses of the primary collimator



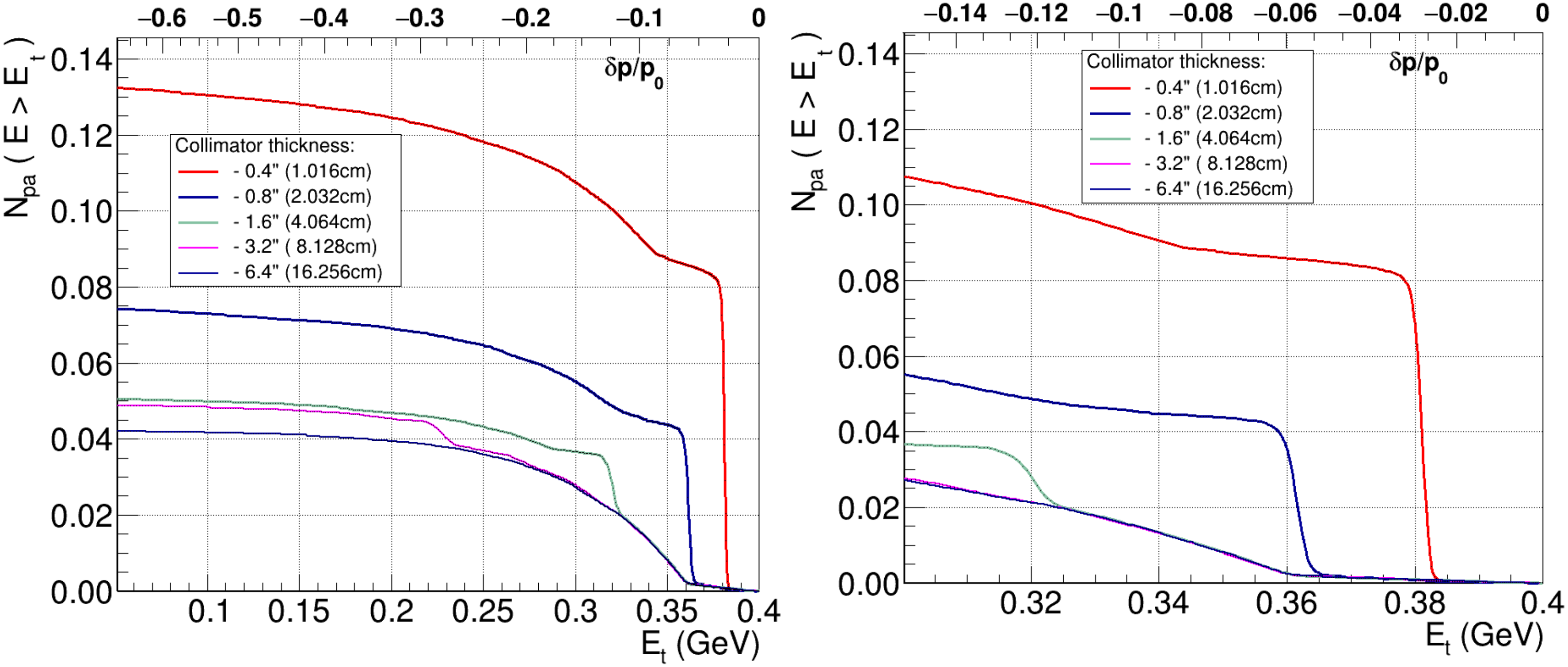
Proton Spectra Inside Aperture at Exit of Collimator Unit: Horizontal Collimator



Number of the beam-type particles in aperture with energy above E_t per beam proton hitting the jaw :

$$N_{pa}(E>E_t)=\frac{1}{N_a}\int_{E_t}^{E_0=400\ MeV} dE\,\frac{dN_{pa}}{dE}$$ – collimation inefficiency

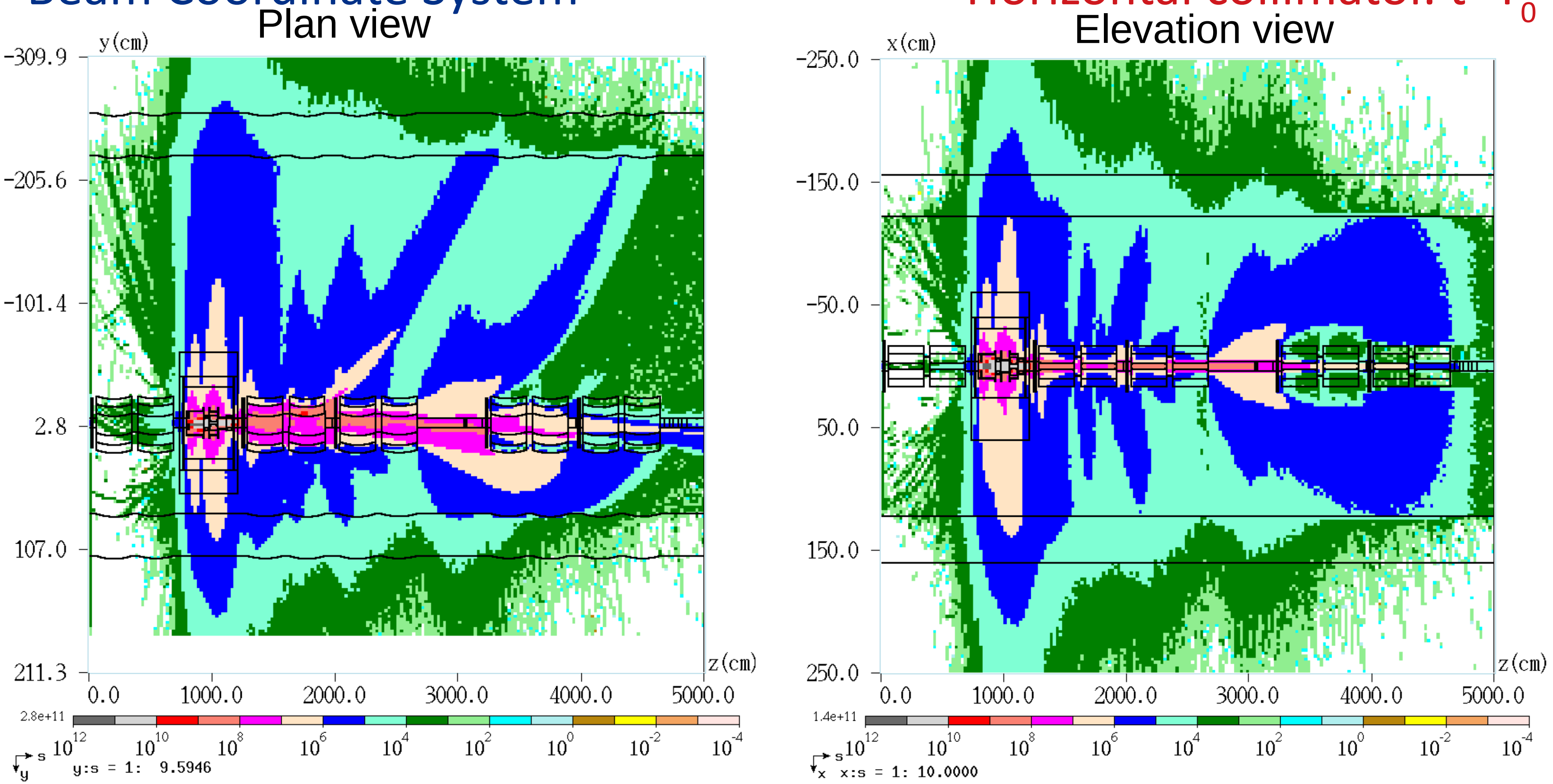
Collimation inefficiency as function of energy threshold for several thicknesses of the primary collimator jaws



Total Hadron Flux $\Phi(E>30MeV)$ $(cm^{-2}s^{-1})$ for Scraping Rate $N_a=3.89\cdot10^{12}$ p/s

Beam Coordinate System

Horizontal collimator. $t=T_0$


Plan view

Elevation view

Maximum flux in soil: $\Phi_{max} = 5.45\cdot10^{5}\ cm^{-2}\,s^{-1}$ at s=1040 cm

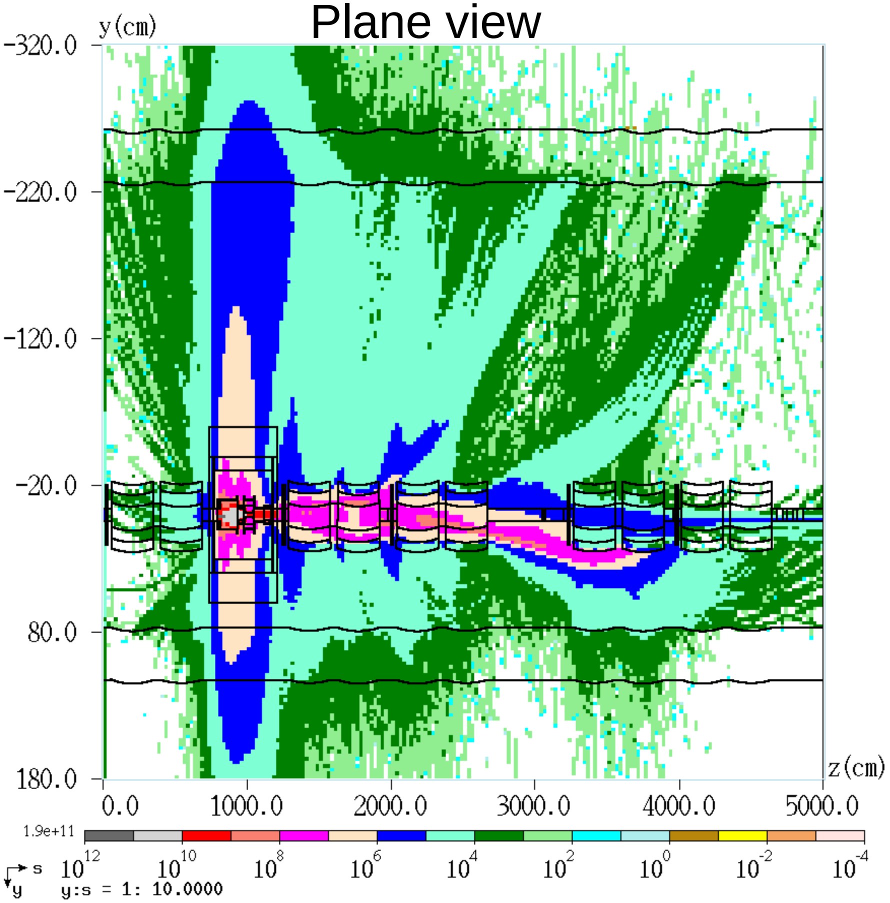
For sump water limit $\Phi_s(E>30MeV)< 3\cdot10^{4}\ cm^{-2}\ s^{-1}$ outside tunnel walls, the acceptable scraping rate for the given source and shielding configuration has to be $\leq 2.14\cdot10^{11}$ p/s $= N_a\cdot(\Phi_s/\Phi_{max})$

Total Hadron Flux $\Phi(E>30\mathrm{MeV})$ ($cm^{-2}s^{-1}$) for Scraping Rate $N_a=3.89\cdot10^{12}$ p/s

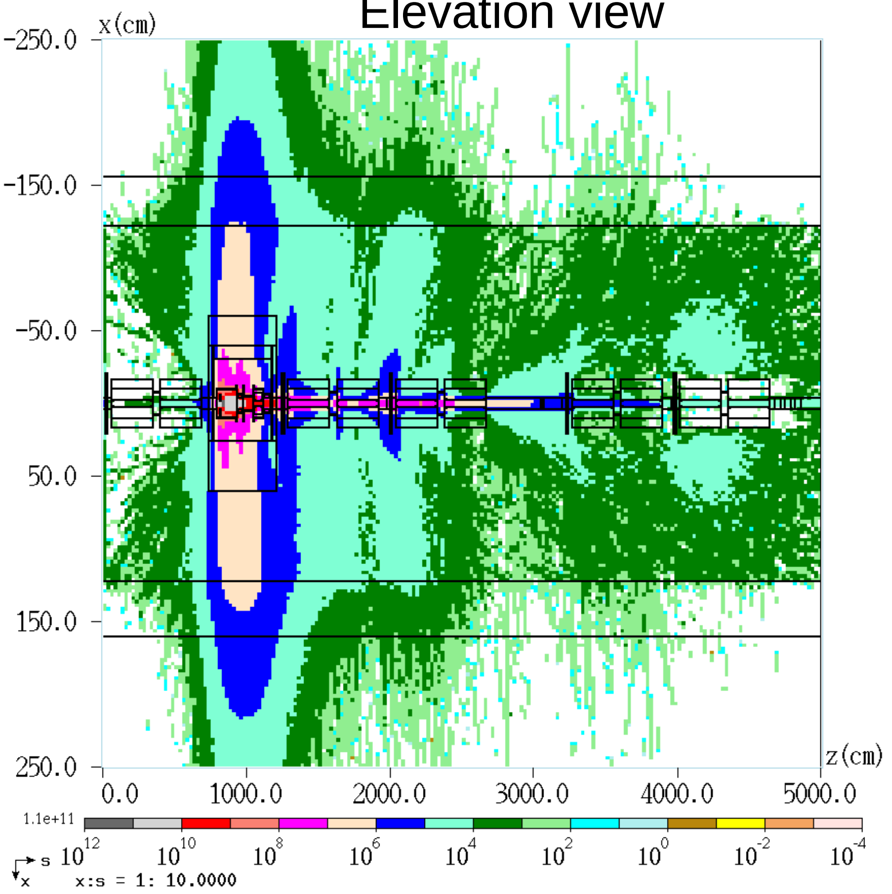
Beam Coordinate System

Horizontal collimator. $t=4\cdot T_0$

Plane view



Elevation view

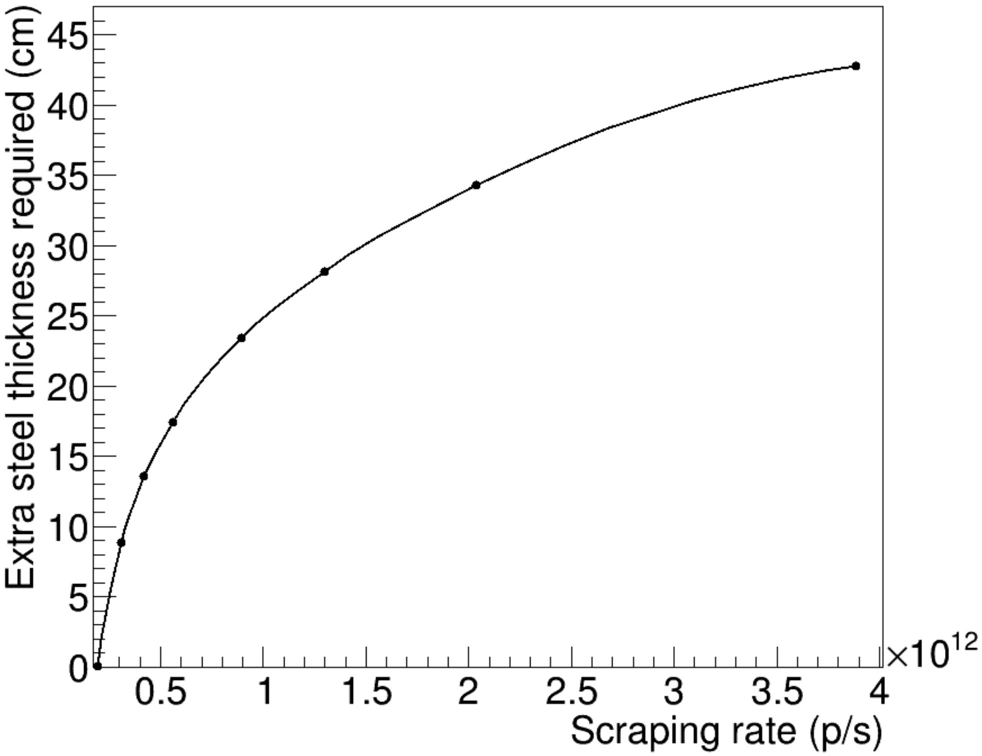


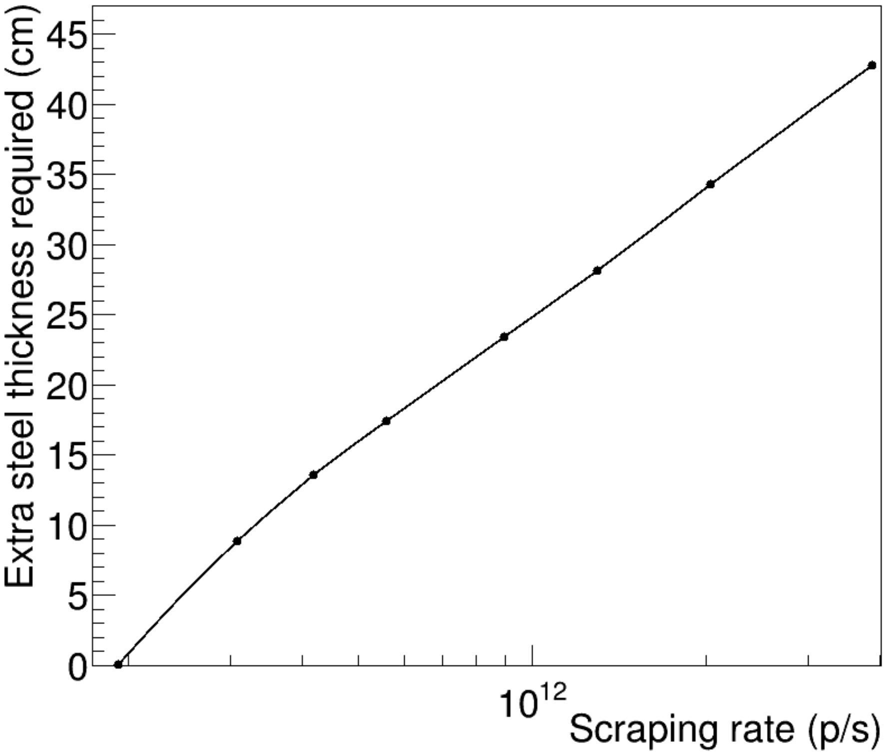
Maximum flux in soil: $\Phi_{max} = 6.22\cdot10^5$ cm^{-2} s^{-1} at s = 880 cm

For sump water limit $\Phi_s(E>30\mathrm{MeV}) < 3\cdot10^4$ cm^{-2} s^{-1} outside tunnel walls, the acceptable scraping rate for the given source and shielding configuration has to be ≤ $1.98\cdot10^{11}$ p/s $= N_a\cdot(\Phi_s/\Phi_{max})$

Fermilab

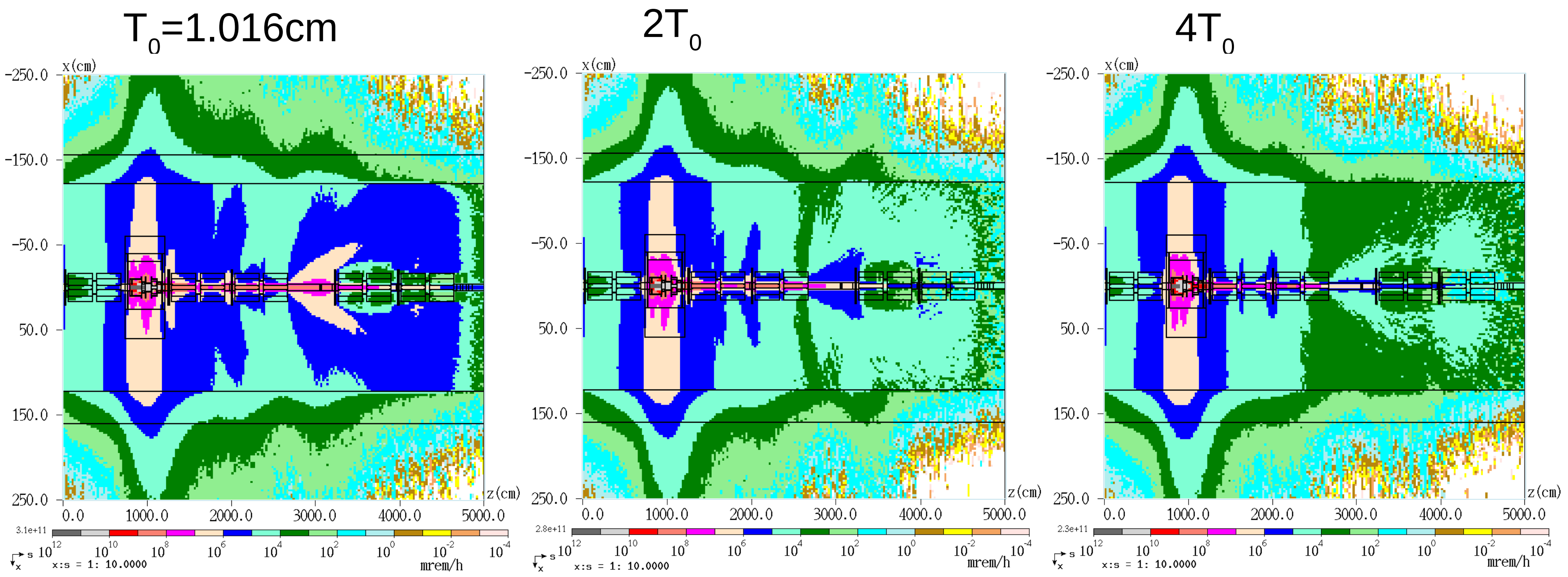
Required Increase in Steel Shielding Thickness as a Function of the Scraping Rate





Zero thickness increment corresponds to scraping rate of $1.98 \cdot 10^{11}$ p/s (slide 13). The slope corresponds to 35 cm of steel for 1/10 attenuation. This perfectly agrees with well known attenuation law. The curve moves left or right if initial scraping rate differs from $1.98 \cdot 10^{11}$ p/s.

Elevation view of Prompt Dose for 3 Thicknesses of Horizontal Primary Collimator



T_0=1.016cm

$2T_0$

$4T_0$

Dose at interface concrete/soil → dose on the berm (376 cm of the dirt)

$1.63 \cdot 10^5$ mrem/hr → 28 mrem/h $1.67 \cdot 10^5$ mrem/hr → 29 mrem/h $1.83 \cdot 10^5$ mrem/hr → 32 mrem/h

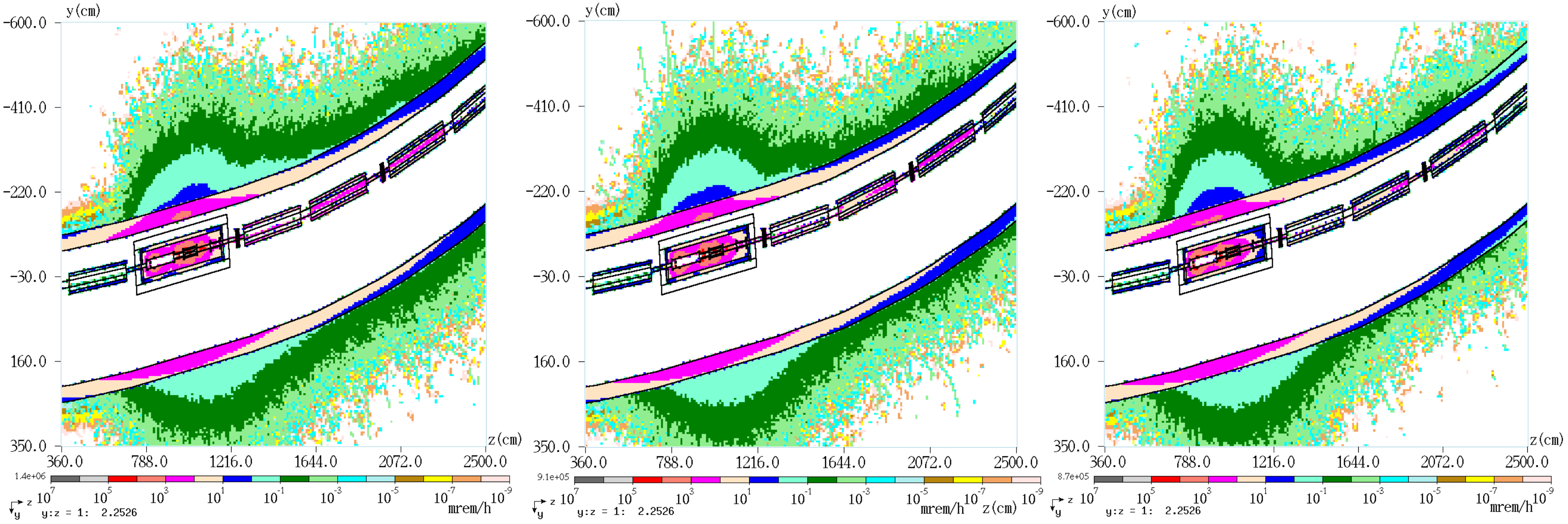
Assuming the safe level of 5 mrem/h, reduction factor for scraping rate has to be:

28/5 = 5.6 29/5 = 5.8 32/5 = 6.4

The maximum allowed scraping rate to keep dose on the berm below 5mrem/h :

$3.89 \cdot 10^{12}/5.6 = 6.95 \cdot 10^{11}$ p/s $3.89 \cdot 10^{12}/5.8 = 6.71 \cdot 10^{11}$ p/s $3.89 \cdot 10^{12}/6.4 = 6.07 \cdot 10^{11}$ p/s

Residual Dose on contact (100d/4h) for 3 Thicknesses of Horizontal Primary Collimator



T_0=1.016cm

$2\cdot T_0$

$4\cdot T_0$

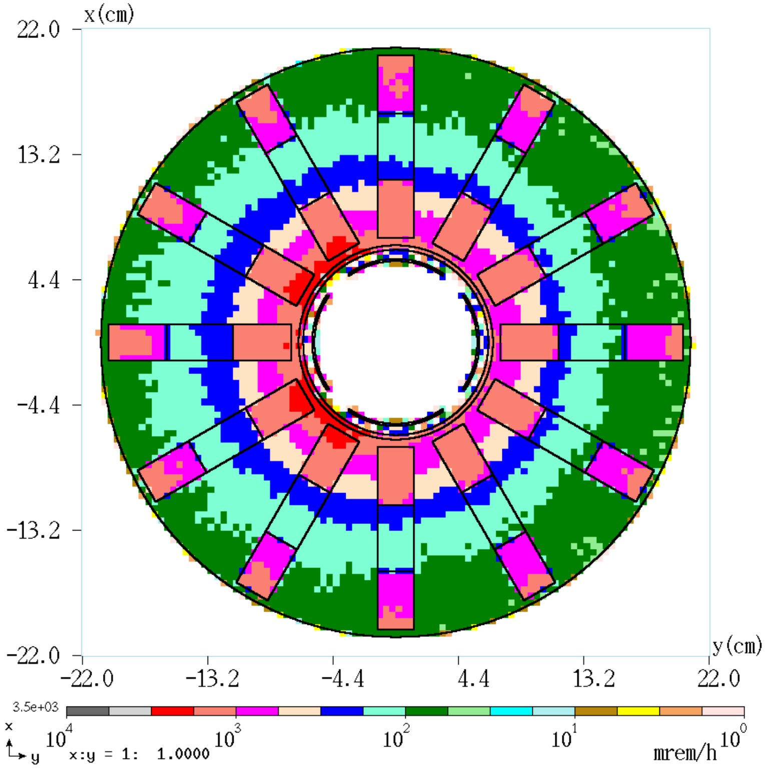
Good practice limit = 100 mrem/h

Magenta-beige boundary

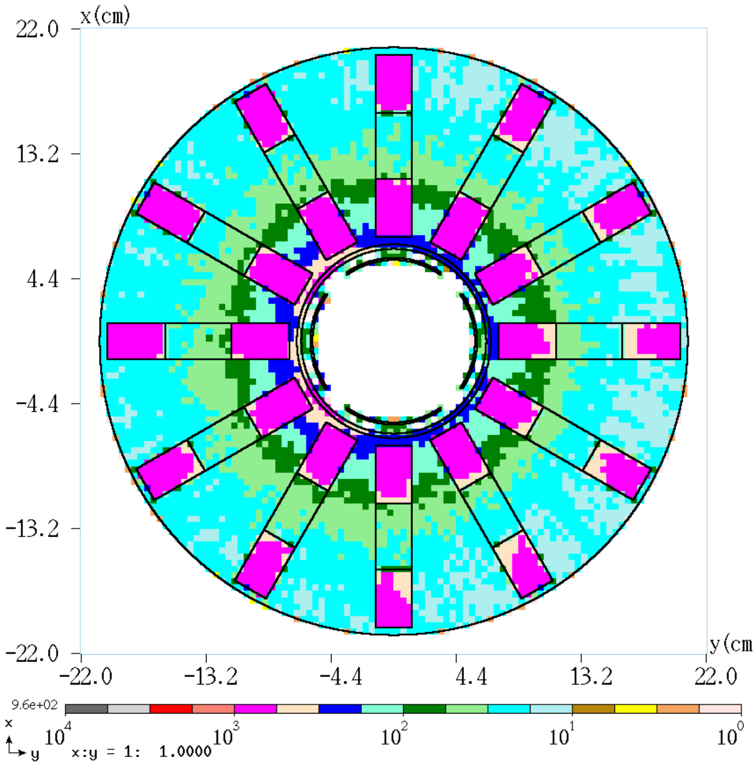
We are safely within this limit with increased shielding required by the sump water activation criterion.

Residual Dose Rate on Contact (100d/4h) at Entrance To Downstream Corrector

T_0=1.016cm



$4 \cdot T_0$



Note substantial reduction of dose rate with thicker primary collimator.

Conclusions

- Calculated collimation efficiency for the given initial data and configuration ranges from 87% ($T_0 \approx 1$ cm) to 95% ($T_0 \approx 4$ cm), compared to the current single collimator efficiency of 50% (as declared by the Booster team). The final decision here is to be made based on thermomechanical analyses.

- For the proposed design of collimator unit and provided beam scraping conditions, acceptable scraping rates are
  - $2.14 \cdot 10^{11}$ p/s for variant with horizontal primary collimator.
  - $2.25 \cdot 10^{11}$ p/s for variant with vertical primary collimator.

  The limitation is imposed by regulation rules requiring to keep flux of high energy hadrons (E>30MeV) in sump water immediately outside tunnel walls below $3 \cdot 10^{4}$ $cm^{-2} \cdot s^{-1}$.

- The use of the collimator unit with scraping rate of $3.89 \cdot 10^{12}$ p/s would require increase of the steel shielding by 1.2 ft.

- Increase of the primary collimator thickness increases the cleaning efficiency and makes the scattered proton energy spectra at the exit of the collimation unit softer. This leads to decrease of particle fluxes (and derivative characteristics) in the downstream region.

  Recommendation : Consider design with “primary collimator” with thick jaws and downstream mask.