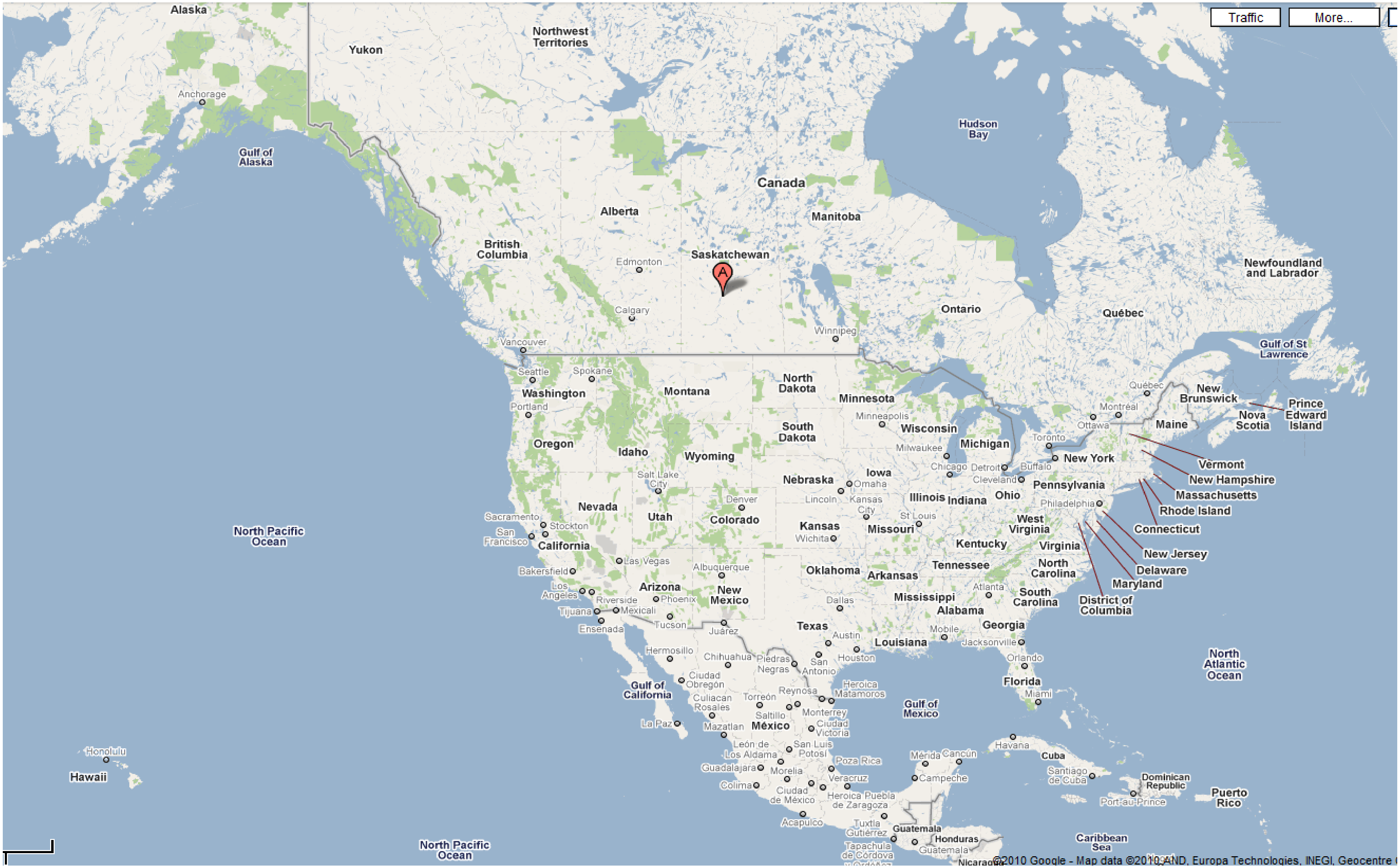
Radiation Safety Assessment of the CLS Beamlines Using FLUKA Monte-Carlo Code

Mo Benmerrouche
Fluka Advanced Workshop - Oct 07, 2010
Ericeira, Portugal

Where is the CLS Located?
Saskatoon, Saskatchewan, CANADA

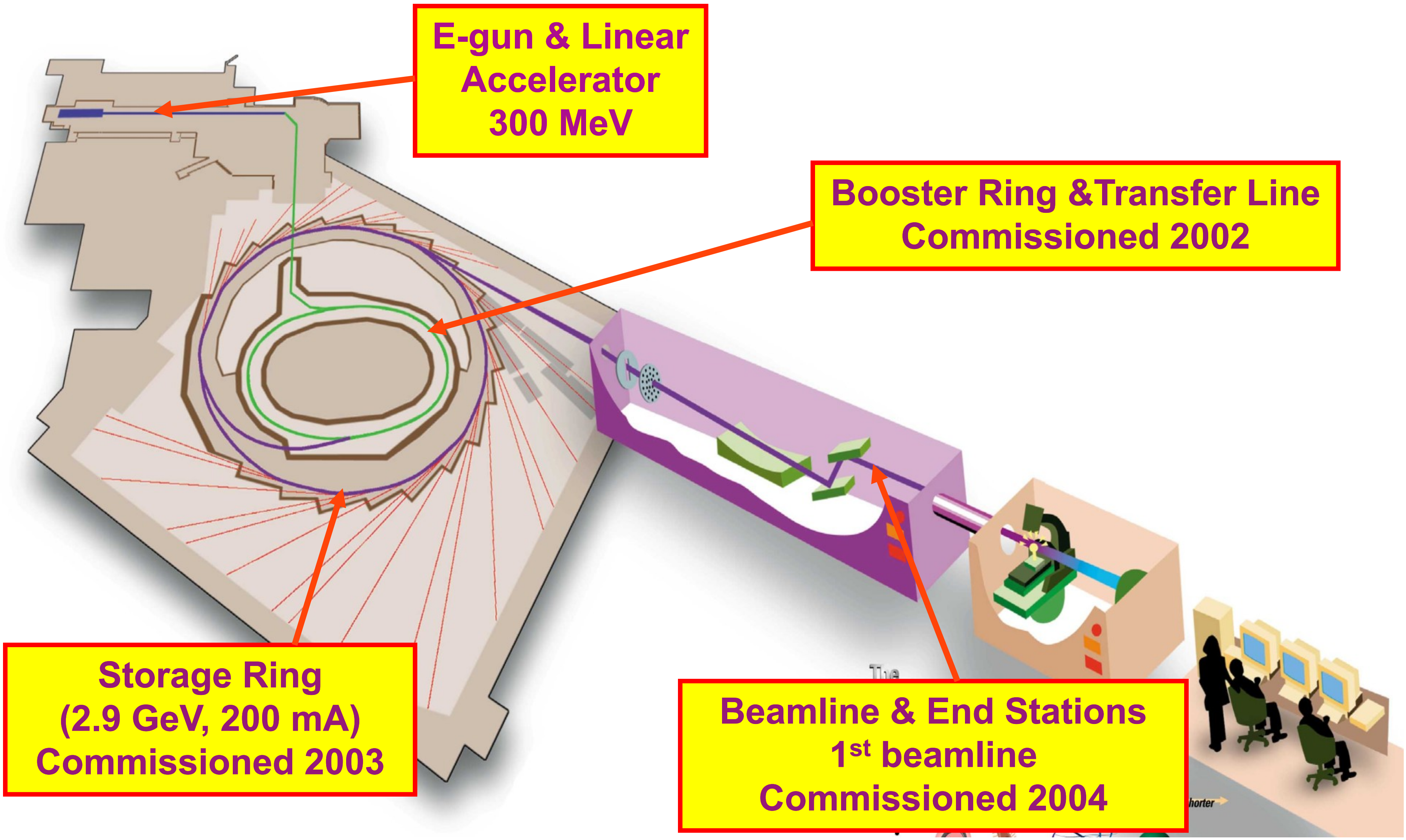


CLS Facility on the UofS Campus

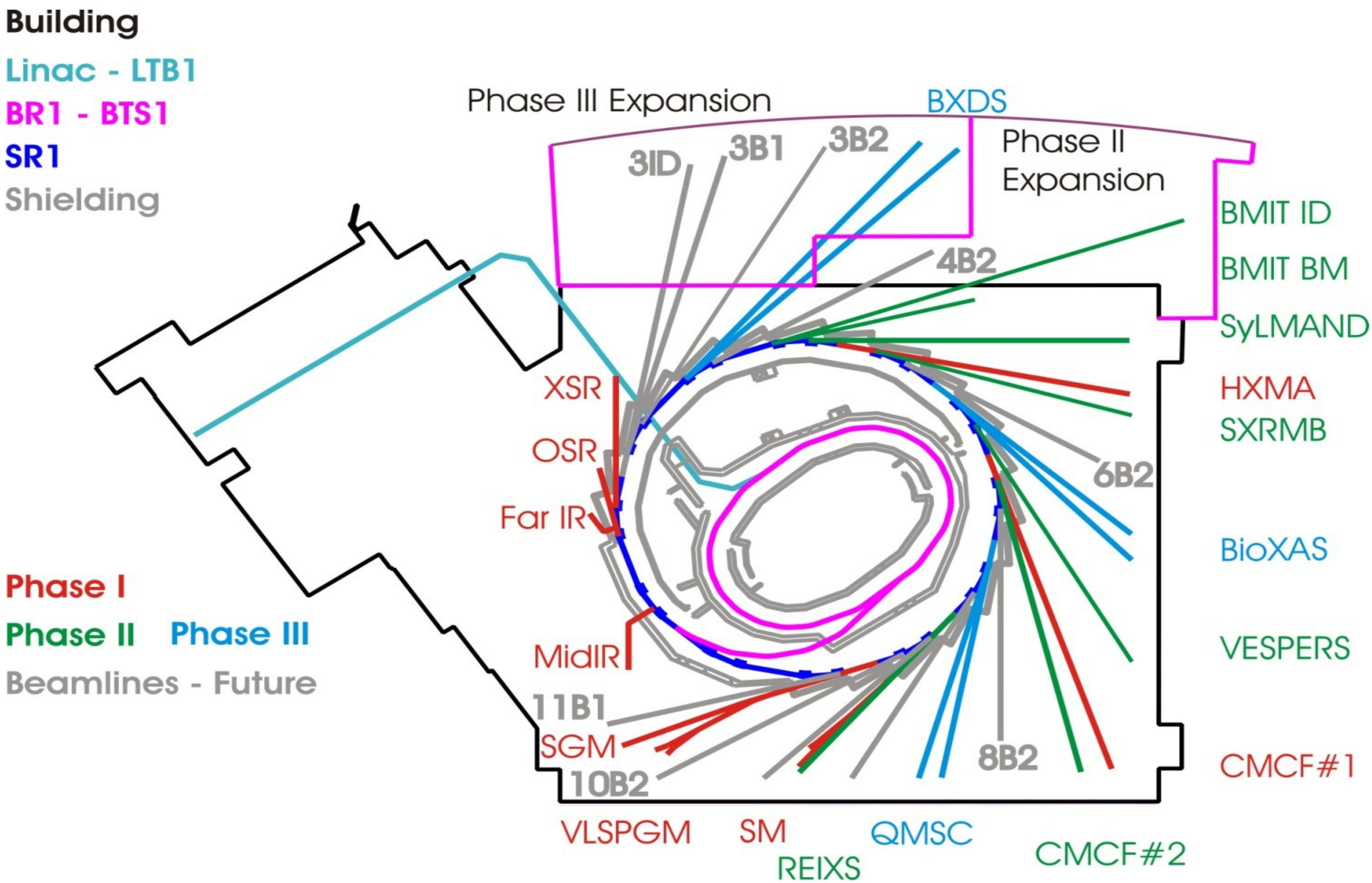
CLS Facility

- Located on the University of Saskatchewan campus
- CLSI has the responsibility for operating the synchrotron facility in Canada and providing infrastructure support for the Canadian synchrotron research community as well as contributions to international synchrotron projects.
- It includes:
  - Linac - a 250 MeV electron accelerator, which was part of the former SAL,
  - Booster Ring - a 250 MeV to 2.9 GeV electron accelerator,
  - Storage Ring - a 2.9 GeV storage ring and the source of the SR,
  - Beamlines - for transport of SR to experimental target stations, where scientific experiments or processes requiring SR are carried out (infrared to hard X-rays, 0.01 eV – 100 keV)
- Facility Conventional Construction
  - began ~ June 1999 and completed ~ January 2001
  - Bulk shielding completed April 2001
  - Building expansion on the north-east to accommodate BMIT beamlines completed in December 2007
- Accelerator commissioning
  - began ~ June 2001 and completed ~ May 2004
- Routine Operation
  - began in August 2004 and includes 7 research beamlines and 2 diagnostic beamlines (Phase I)
  - Users other than CLSI staff were allowed to access synchrotron beamlines for research
- Top-up mode
  - Preliminary radiological studies completed in December 2005
- Phase I beamlines
  - The CLS Phase I project was finished in 2005 and included first set of 7 beamlines.
- Phase II Beamlines Projects
  - 7 additional Phase II beamlines are in the final stages of commissioning.
  - Expected to be available for general users by the end of 2009.
- Phase III Beamlines Projects
  - Three projects together comprise five new beamlines and are in planning/design/Early construction phase
  - Commissioning phase to start by 2012.
  - Building expansion required to house some of the Phase III beamlines

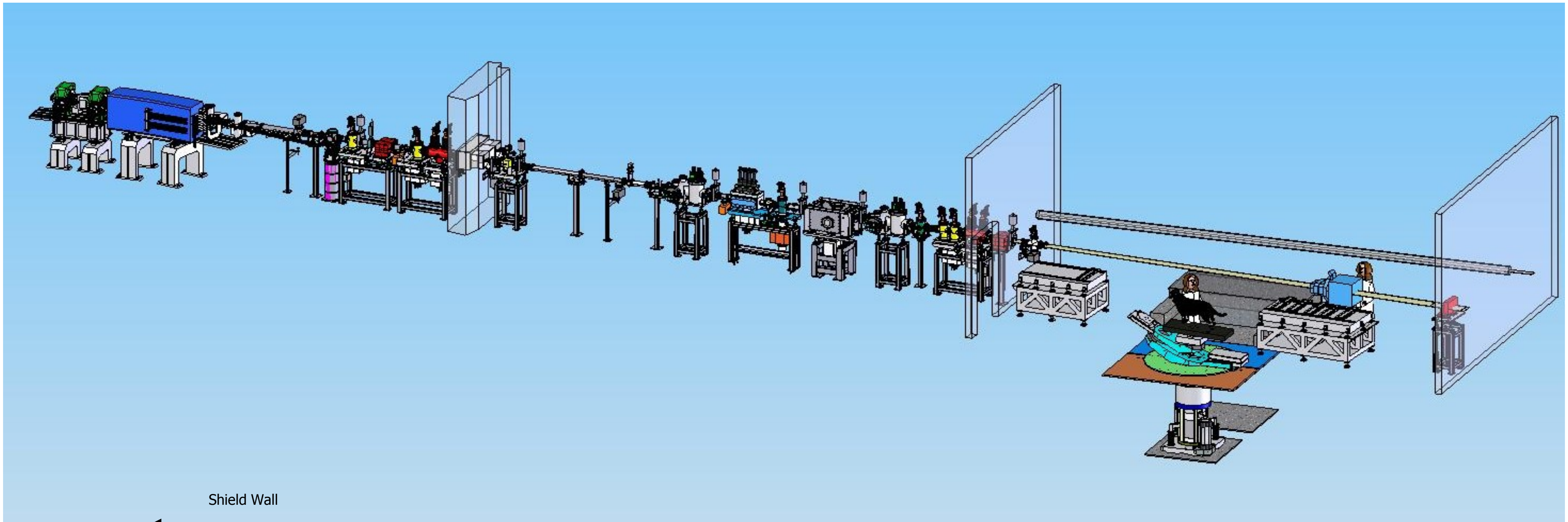
CLS Facility Main Components
Accelerators & beamlines

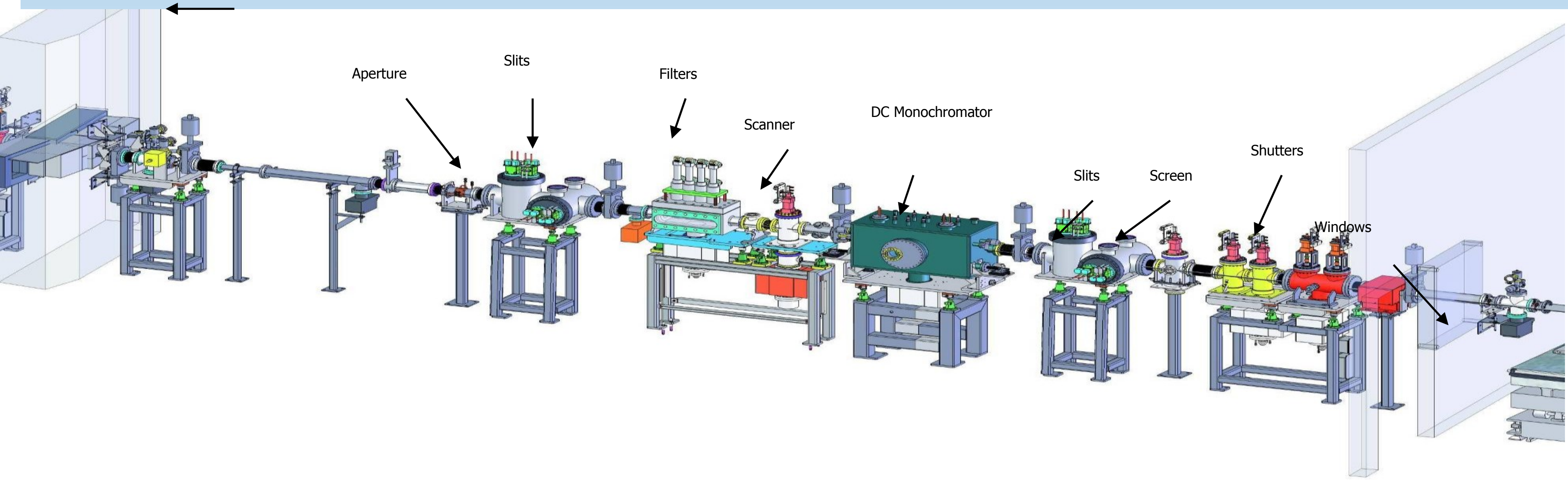


CLS Beamlines
Existing, Planned, and Future



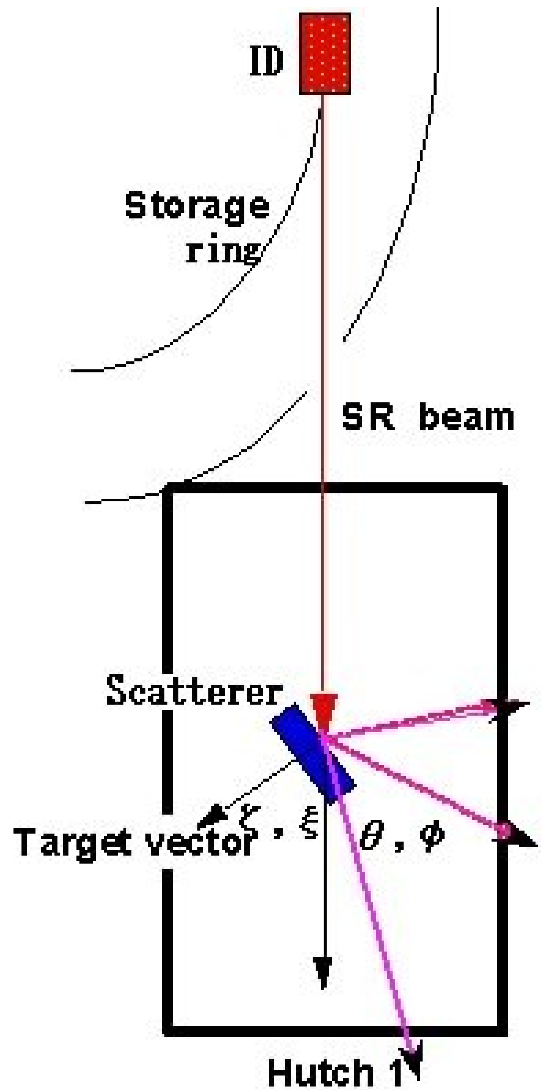
Some Components of Front-End and Beamines





Sources of Radiation For Beamlines Enclosure Shielding

- Gas Bremsstrahlung:
  - Production rate well described by Koch/Motz formula [Rev. Mod Phys 31, 1959]
  - Depends on
    - energy of circulating electrons and stored current
    - residual gas composition and pressure
    - length of straight section
- Synchrotron Radiation:
  - Bending magnet or Insertion Device (Wiggler or undulator)
  - Depends on
    - electron energy and stored current
    - SR source parameters such as magnetic field strength, critical energy, no of poles
  - Fluka simulations performed for the bending magnet beamline



GB: Fluka Transport/Physics/Biasing Cards

MULSOPT Type: ▼ Optimize: off ▼
h/μ steps: 0 e-e+ steps: 0 h/μ Corr: No corrections ▼ e-e+ Corr: no MCS ▼
Mat: AIRPLOW ▼ to Mat: ▼ Step:

Physics

EMFCUT Type: ELPO-THR ▼ e-e+ Brem: 0.0 γ Bhabha/Moller: 4.0
Photonuc: 0.0 Mat: AIRPLOW ▼ to Mat: ▼ Step:

EMFCUT Type: ▼ e-e+: -4.0 γ: 0.0
Old bremss.: off ▼ Bremsstrahlung: off ▼ Pair Prod.: off ▼ e+ ann @rest: off ▼
Compton: off ▼ Bhabha&Moller: off ▼ Photo-electric: off ▼ e+ ann @flight: off ▼
Reg: EX6 ▼ to Reg: ▼ Step:

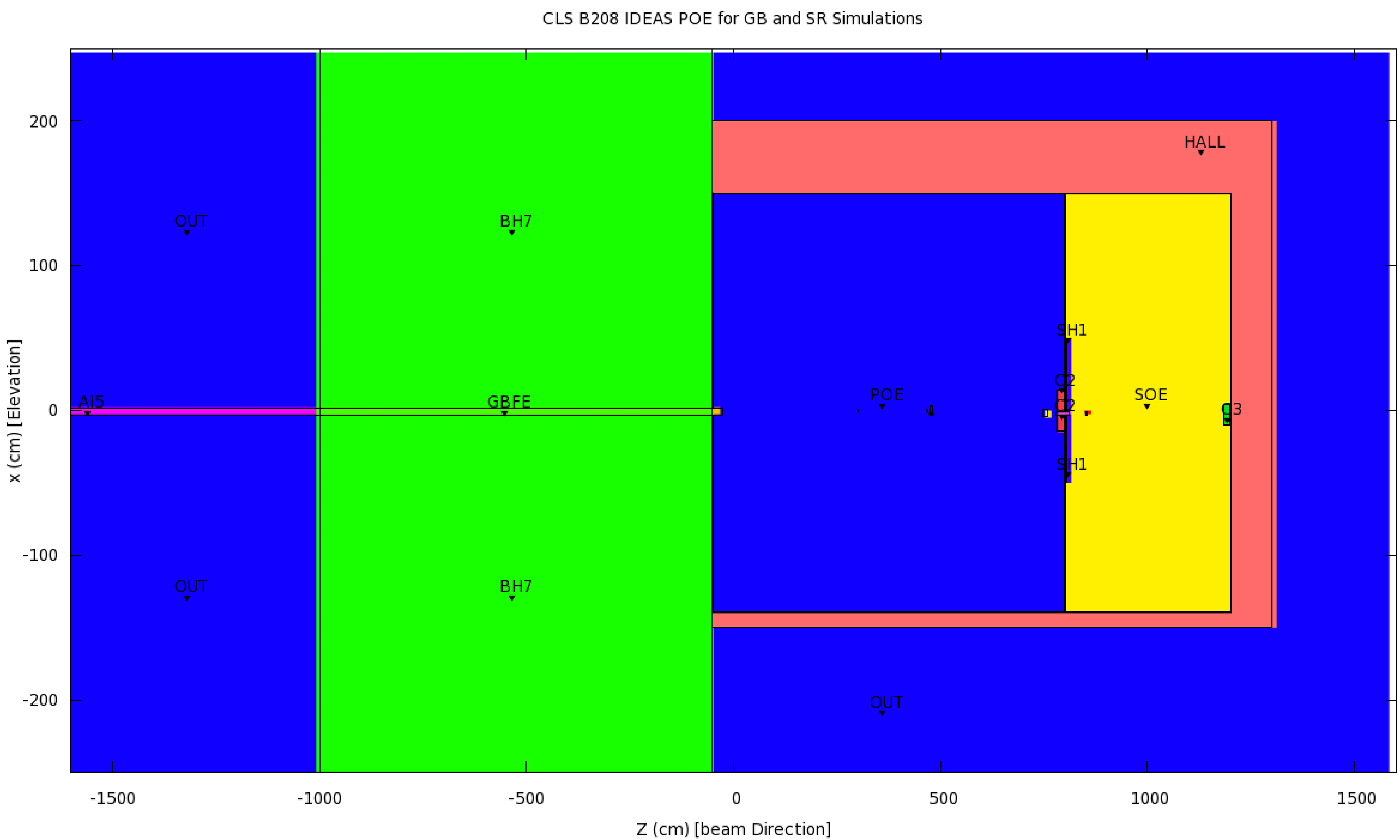
EMFCUT Type: ▼ e-e+: -0.0005 γ: 0.00001
Old bremss.: off ▼ Bremsstrahlung: off ▼ Pair Prod.: off ▼ e+ ann @rest: off ▼
Compton: off ▼ Bhabha&Moller: off ▼ Photo-electric: off ▼ e+ ann @flight: off ▼
Reg: PSH ▼ to Reg: ▼ Step:

PHOTONUC Type: ▼ All E: off ▼
E>0.7GeV On ▼ Δ resonance On ▼ Quasi D On ▼ Giant Dipole On ▼
Mat: LEAD ▼ to Mat: ▼ Step:

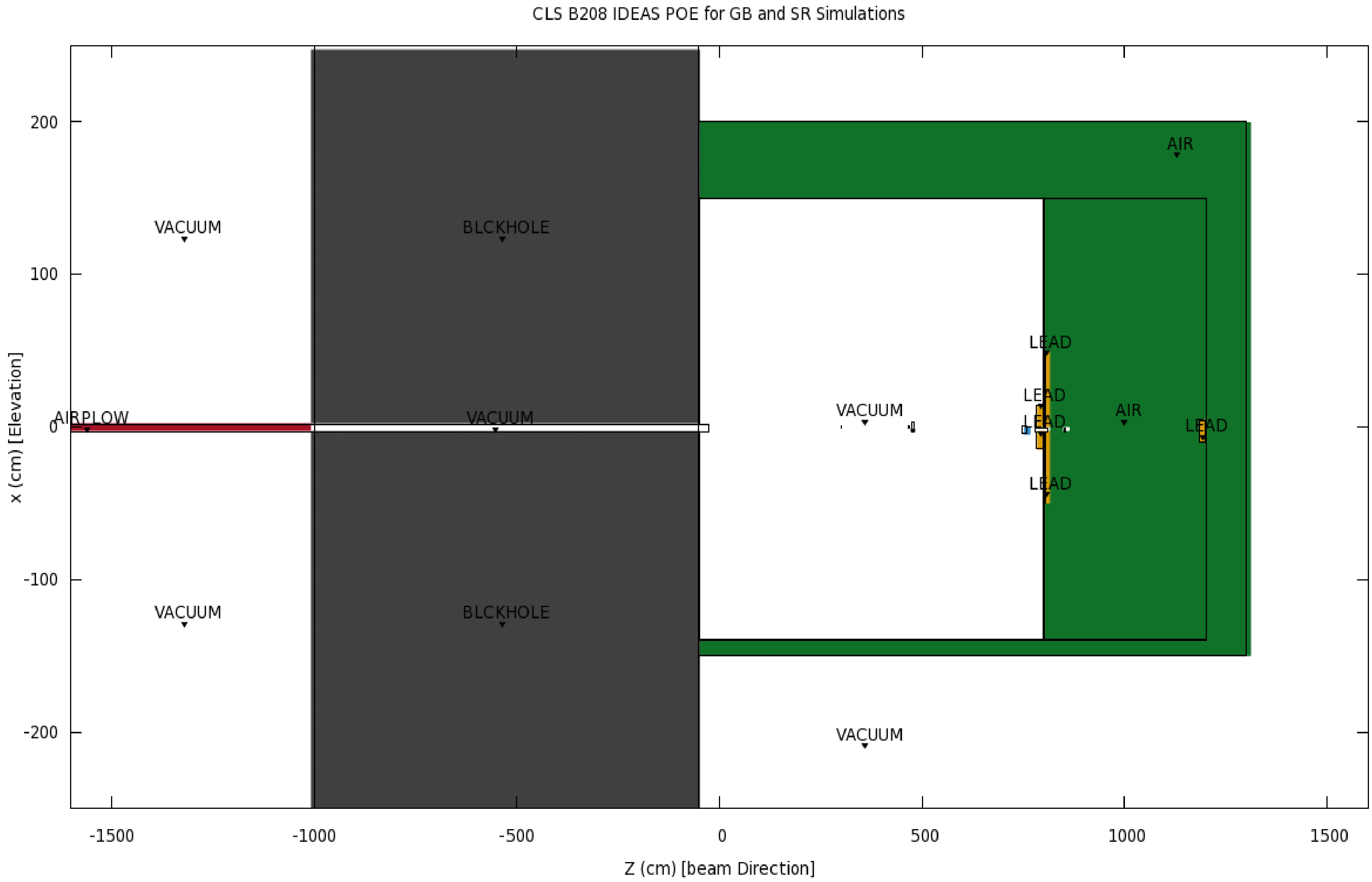
reduce inelastic interaction length of photons by 0.02

LAM-BIAS Type: ▼ ÷ mean life: 0.0 ÷ λ inelastic: 0.02
Mat: ▼ Part: PHOTON ▼ to Part: ▼ Step:

Geometry Region View
IDEAS Bending Magnet Beamline



Geometry Material View
IDEAS Bending Magnet Beamline



Materials

Materials			
MATERIAL	Name: AIRPLOW	# 26.0	ρ: 0.0001205
Z:	Am:	A:	dE/dx: ▼
COMPOUND	Name: AIRPLOW ▼	Mix: Mass ▼	Elements: 1..3 ▼
f1: 0.78084	M1: NITROGEN ▼	f2: 0.20946	M2: OXYGEN ▼
f3:	M3: ▼		
Set pressure in the air column to 0.1 atm.			
MAT-PROP	Type: ▼	Gas pressure: 0.1	RHOR: 0.0
Ionization: 0.0	Mat: AIRPLOW ▼	to Mat: ▼	Step:
276 Water liquid H2_O			
Chemical Formula: H -- O -- H			
MATERIAL	Name: WATER	#	ρ: 1.0
Z:	Am:	A:	dE/dx: ▼
COMPOUND	Name: WATER ▼	Mix: Atom ▼	Elements: 1..3 ▼
f1: 2.0	M1: HYDROGEN ▼	f2: 1.0	M2: OXYGEN ▼
f3:	M3: ▼		
MAT-PROP	Type: ▼	Gas pressure:	RHOR:
Ionization: 75.0	Mat: WATER ▼	to Mat: ▼	Step:
STERNHEI	Cbar: 3.5017	X0: .24	X1: 2.8004
Mat: WATER ▼	a: .09116	m: 3.4773	δ0:
104 Air dry (near sea level)			
MATERIAL	Name: AIR	#	ρ: .00120484
Z:	Am:	A:	dE/dx: ▼
COMPOUND	Name: AIR ▼	Mix: Mass ▼	Elements: 4..6 ▼
f1: 0.0001248	M1: CARBON ▼	f2: 0.755267	M2: NITROGEN ▼
f3: 0.231781	M3: OXYGEN ▼	f4: 0.012827	M4: ARGON ▼
f5:	M5: ▼	f6:	M6: ▼
MAT-PROP	Type: ▼	Gas pressure:	RHOR:
Ionization: 85.7	Mat: AIR ▼	to Mat: ▼	Step:
STERNHEI	Cbar: 10.5961	X0: 1.7418	X1: 4.2759
Mat: AIR ▼	a: 0.10914	m: 3.3994	δ0:

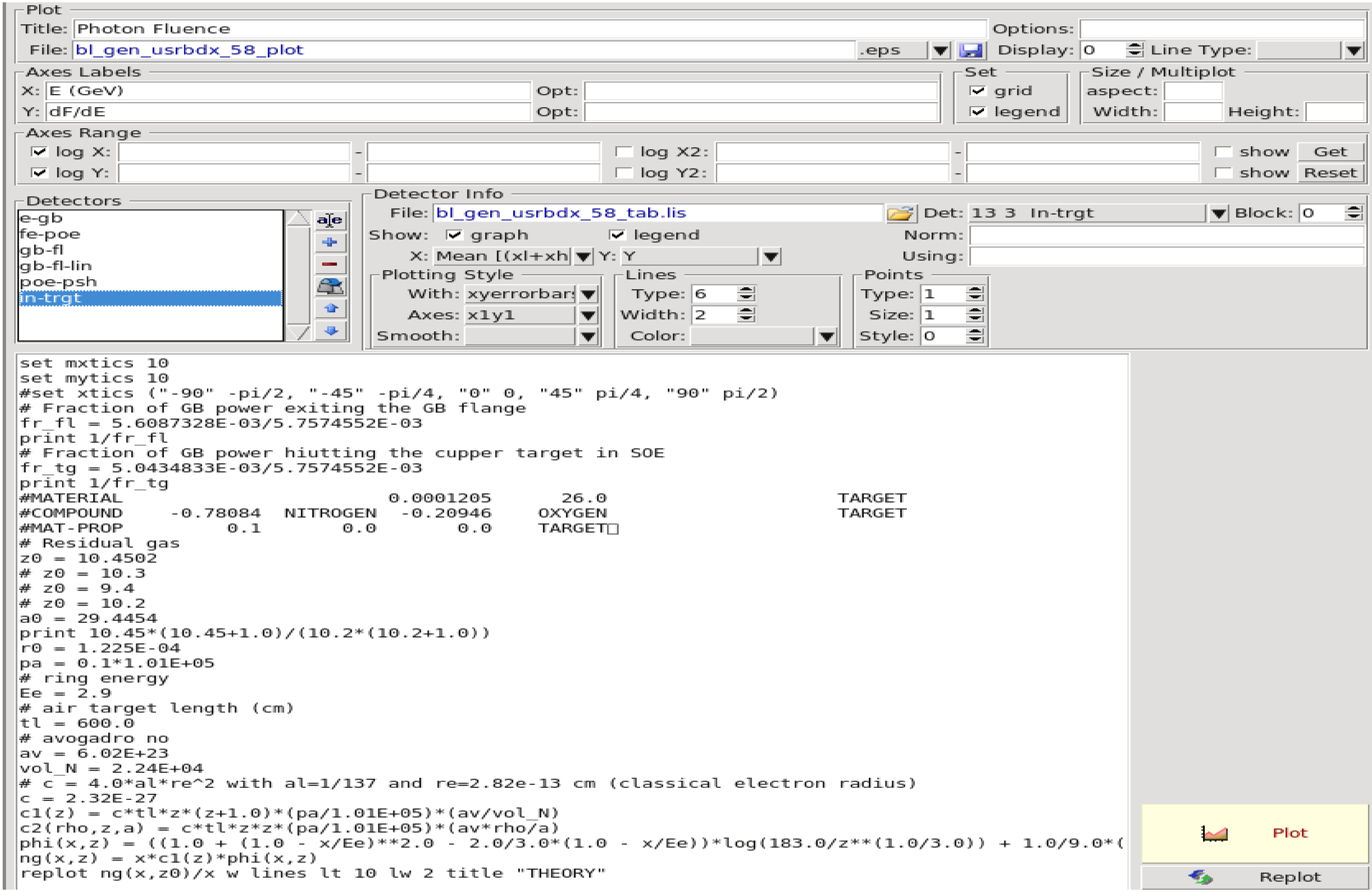
Usbdx Scoring

USRBDX							
				Unit:	58 BIN ▼	Name:	gb-fl
Type:	Φ1,LogE,LinΩ ▼	Reg:	GBPOE ▼	to Reg:	GBFL ▼	Area:	1.0
Part:	PHOTON ▼	Emin:	1.0E-06	Emax:	3.0	Ebins:	50.0
		Ωmin:		Ωmax:		Ωbins:	1.0

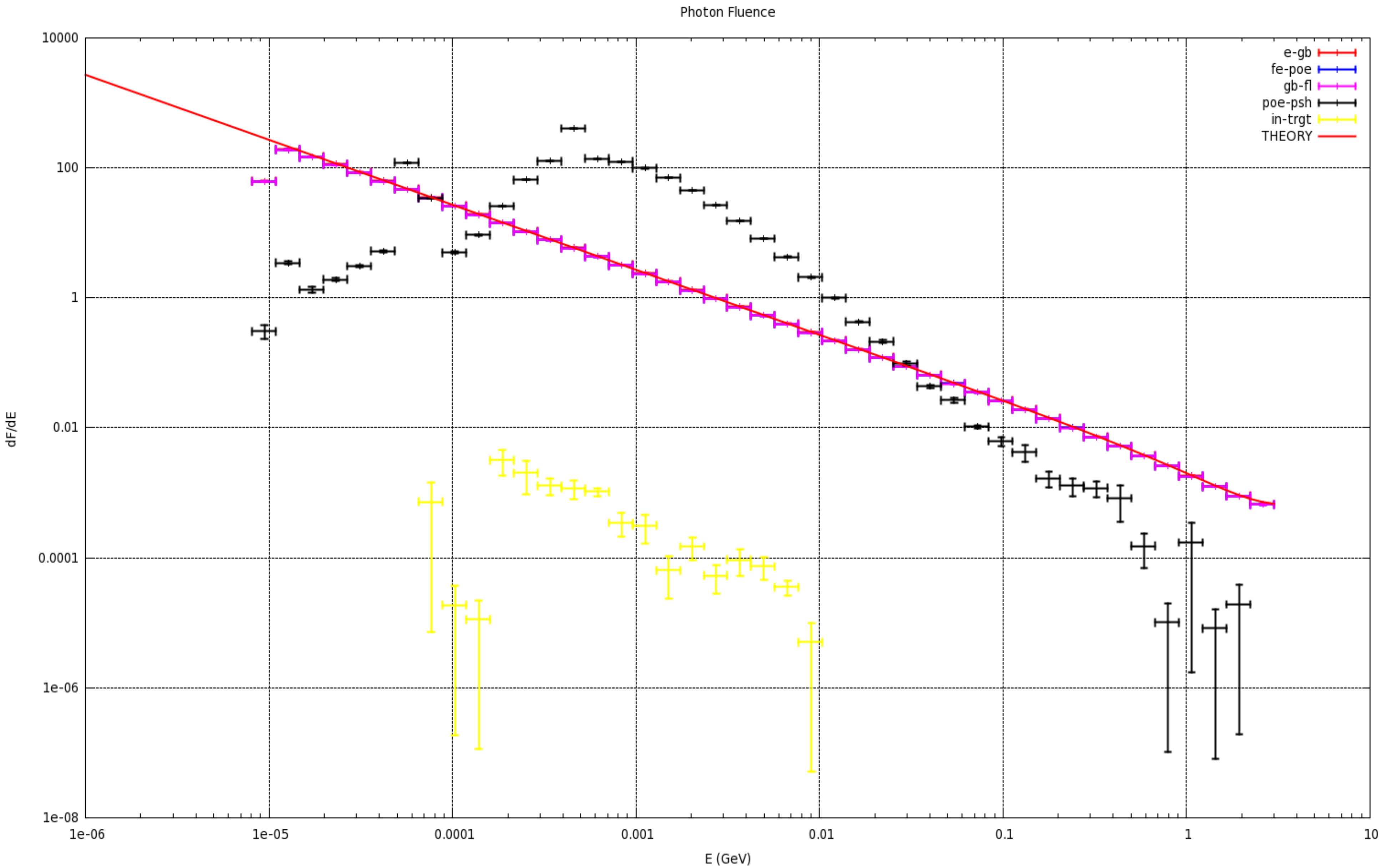
USRBDX							
				Unit:	58 BIN ▼	Name:	gb-fl-lil
Type:	Φ1,LinE,LinΩ ▼	Reg:	GBPOE ▼	to Reg:	GBFL ▼	Area:	1.0
Part:	PHOTON ▼	Emin:	1.0E-06	Emax:	1.0E-03	Ebins:	100.0
		Ωmin:		Ωmax:		Ωbins:	1.0

USRBDX							
				Unit:	58 BIN ▼	Name:	gb-fl-lih
Type:	Φ1,LinE,LinΩ ▼	Reg:	GBPOE ▼	to Reg:	GBFL ▼	Area:	1.0
Part:	PHOTON ▼	Emin:	1.0E-03	Emax:	3.0	Ebins:	100.0
		Ωmin:		Ωmax:		Ωbins:	1.0

Flair USBDX Plots/Analysis



Photon Fluence



Flair USBIN Plots/Analysis

ambient dose

USRBIN Unit: 60 BIN ▾ Name: gde_in
Type: X-Y-Z ▾ Xmin: 200.0 Xmax: 1200.0 NX: 400.0
Part: DOSE-EQ ▾ Ymin: -150.0 Ymax: 150.0 NY: 100.0
Zmin: -100.0 Zmax: 150.0 NZ: 100.0

AUXSCORE Type: USRBIN ▾ Part: PHOTON ▾ Set: AMB74 ▾
Det: gde_in ▾ to Det: ▾ Step:

Plot
Title: Photon Ambient Dose Equivalent Options:
File: bl_gen_usrbin_60_plot .eps ▾ Display: 0 Line Type: ▾

Axes Labels
X: Z (cm) [Beam Direction] Opt:
Y: X (cm) [Elevation] Opt:
CB: uSv/hr Opt:

Set
☑ grid
☑ legend

Size / Multiplot
aspect:
Width: Height:

Binning Detector
File: bl_gen_usrbin_60 Title: CLS B208 Beamline (IDEAS) POE/SOE
Cycles: 7 Primaries: 70000000 Weight: 70000000.0 Time: ***** Sum file *****

Binning Info
Det: 1 gde_in ▾ X: [200 .. 1200] x 400 (2.5) Min: 2.62916515E-08
Type: 10: X-Y-Z Y: [-150 .. 150] x 100 (3) Max: 0.0193166174
Score: DOSE-EQ Z: [-100 .. 150] x 100 (2.5) Int: 169.365624

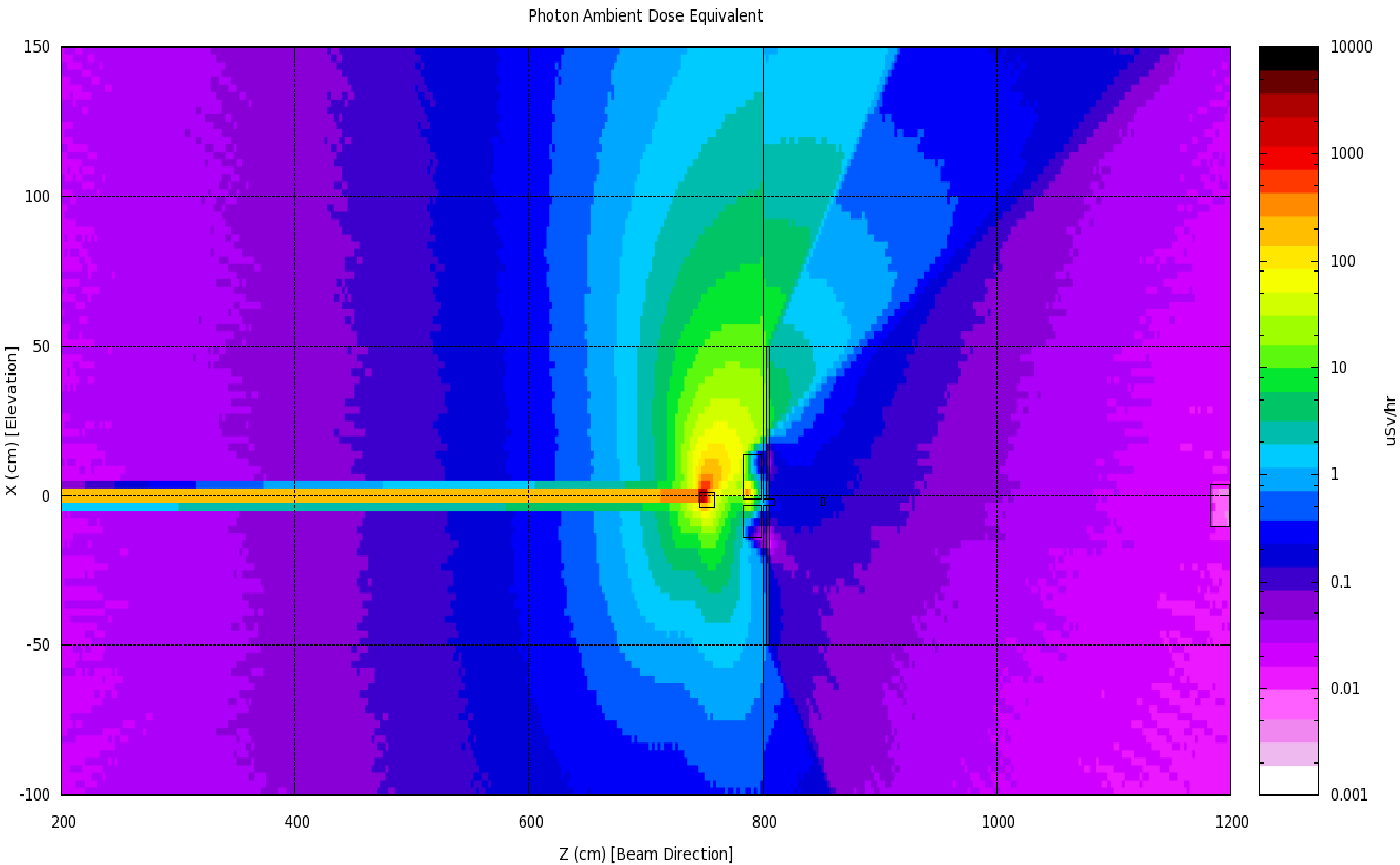
Projection & Limits
○ X: ▾ 1 ▾ Get
◉ Y: -15 ▾ 1 15 ▾ ☑ swap
○ Z: ▾ 1 ▾ ☐ errors
Norm: 1.3158E-11*1.1235E+22*1.0E-06*1.175 ☑ log

Type: 2D Projection ▾

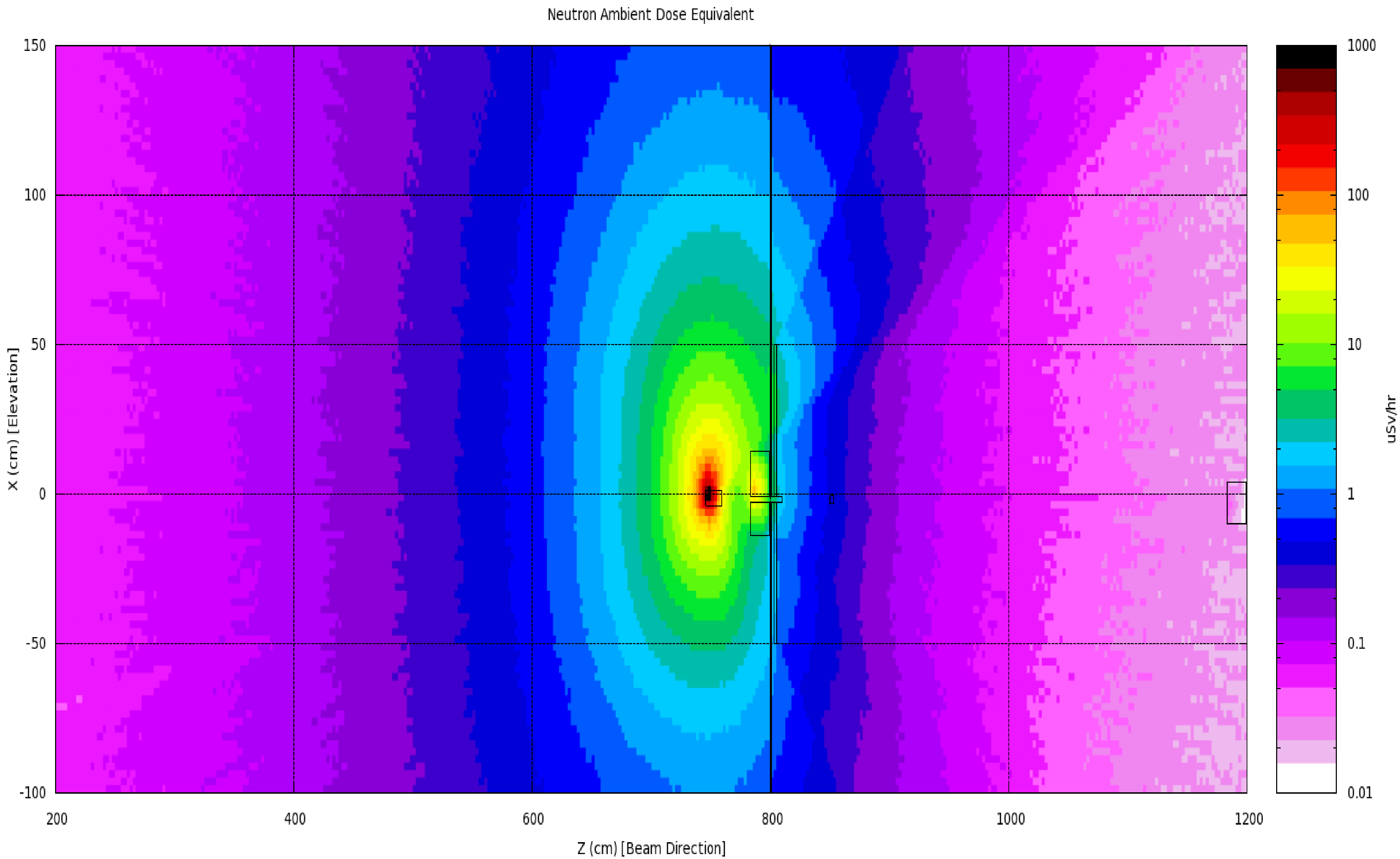
Color Band
Min: Max:
CPD: 3 Colors: 30
Palette: FLUKA ▾ ☑ Round

Geometry
Use: -Auto- ▾
Pos: 0.0
Axes: X-Z ▾

Photon Ambient Dose Profile (6 m long straight)



Neutron Ambient Dose Profile (6 m long straight)



Comparison with earlier shielding Calculations for GB Only

Bending Magnet POE Shielding Requirements (GB Only)

	EGS	FLUKA
Back-wall:	10 mm Pb (+20 mm Pb locally)	5 mm Fe (+25 mm Pb locally)
Side-wall:	5 mm Pb	3 mm Fe
Roof:	5 mm Pb	3 mm Fe

- EGS dose estimates based on energy deposited in water phantom while FLUKA uses AMB74 ambient dose equivalent.
- EGS results assumes 12 cm long straight (BM) while FLUKA are based on a 6m long straight – factor of about 50 reduction
- Both are for 500 mA stored current and 2.9 GeV electron energy.
- EGS assumes an effective z for residual gas to be 8.1 while FLUKA uses an effective z of about 10.5.

Fluka simulation of SR Bending Magnet

- Source parameters: E=2.9 GeV, B= 1.354 T, 7.572 keV
- Use Spectrum generated by STAC8 as input for FLUKA simulations using source.f file

Beam: pencil beam of photons up at 500 keV

BEAM	Beam: Energy ▼	E: 0.0005	Part: PHOTON ▼
Δp: Flat ▼	Δp: 0.0	Δϕ: Flat ▼	Δϕ: 0.0
Shape: Rectangular ▼	Δx: 0.0	Δy: 0.0	Weight: 1.0
SOURCE	#1: 1.0	#2: 1.0E-06	#3: 5.0E-04
sdum: sr_bm	#4:	#5:	#6:

---------- *MATERIAL ... AUXSCORE : 140 cards hidden* ----------

Beam starts at (299.9 cm, 0, 0) (i.e., on the x axis) and travels in +x direction

BEAMPOS	x: 299.9	y: 0.0	z: 0.0
	cosx: 1.0	cosy: 0.0	Type: POSITIVE ▼

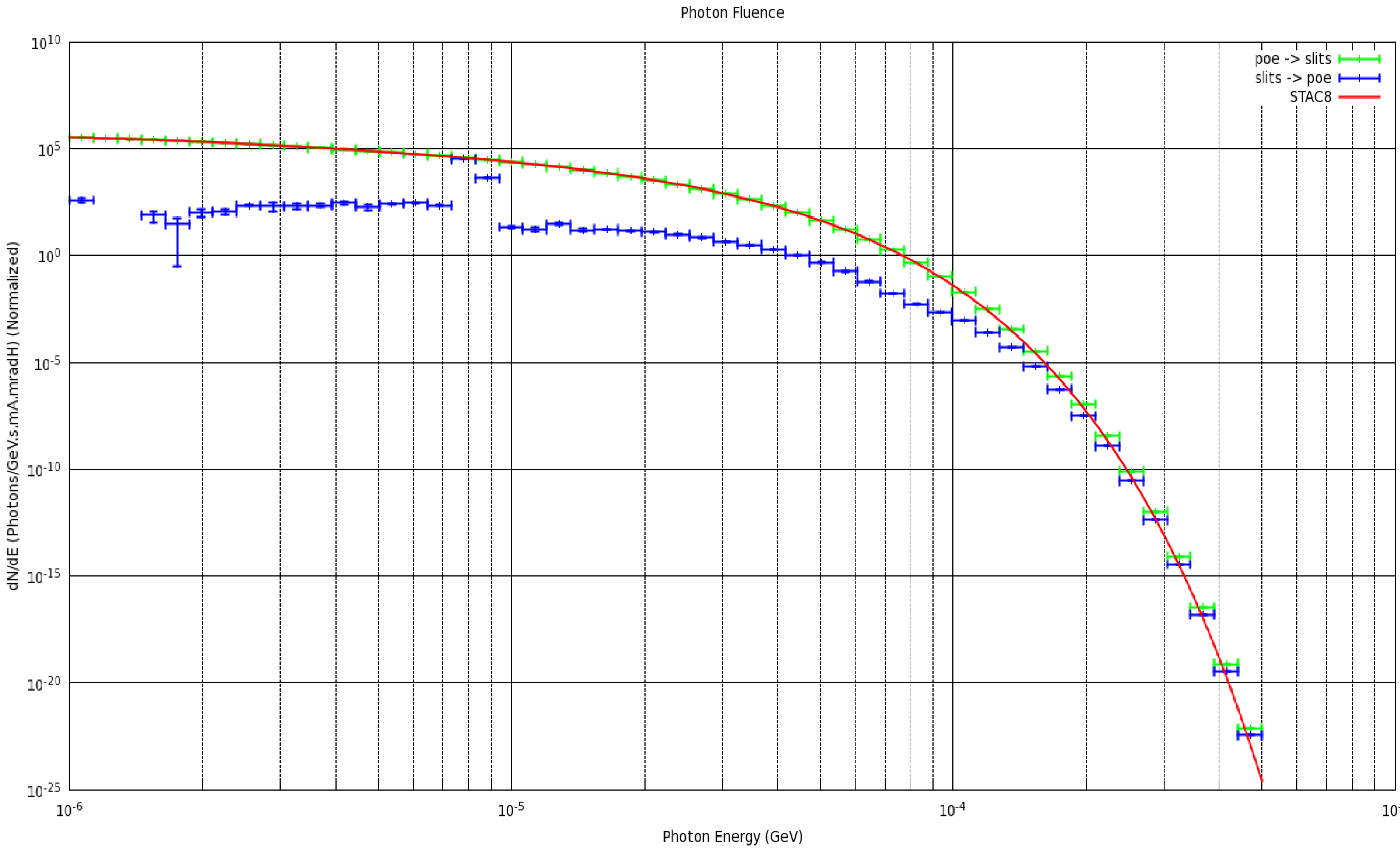
Source.f

```
DO 2 I = 1, NPOINT
        READ(81,*,END=999) SR_E(I), SR_S(I)
        SR_E(I) = SR_E(I)*EFAC
        WRITE(LUNOUT,*)I,SR_E(I),SR_S(I)
 2      CONTINUE
 999    CONTINUE
       SR_I(1) = ZERZER

Calculate the cumulative function
      DO I = 2, NPOINT
       SR_I(I) = SR_I(I-1) + HLFHLF*(SR_S(I)+SR_S(I-1))*
   $       (SR_E(I) - SR_E(I-1))
        WRITE(LUNOUT,*) I, SR_E(I), SR_I(I)
      END DO

      SUM = SR_I(NPOINT)
      DO I = 2, NPOINT
        SR_I(I) = SR_I(I)/SUM
        WRITE(LUNOUT,*)I,SR_E(I),SR_I(I)
      END DO
    END IF
*   Push one source particle to the stack. Note that you could as well
*   push many but this way we reserve a maximum amount of space in the
*   stack for the secondaries to be generated Npflka is the stack counter: of course any time source is called it must be =0
    RAN_E = FLRNDM(TKESUM)
    ENERGY = ENMIN + (ENMAX - ENMIN) * RAN_E
    DO 3 I = 1, NPOINT - 1
      IF(ENERGY .GT. SR_E(I) .AND. ENERGY .LE. SR_E(I+1)) THEN
        WEIGHT = SR_S(I) + (SR_S(I+1) - SR_S(I)) *
   &                    (ENERGY - SR_E(I))/(SR_E(I+1) - SR_E(I))
        GO TO 4
      END IF
 3  CONTINUE
 4  CONTINUE
    NPFLKA = NPFLKA + 1
*   Wt is the weight of the particle
c$$$      WTFLK  (NPFLKA) = ONEONE
    WTFLK  (NPFLKA) = WEIGHT
    WEIPRI = WEIPRI + WTFLK (NPFLKA)
```

Synchrotron Radiation Photon Fluence Bending Magnet



Conclusions/Remarks

- Need to understand the differences between EGS and FLUKA for the GB calculations
  - Run comparison using same input, target, geometry, etc…
- Radiation experiments have been conducted exposing Luxels to radiation inside a Bending magnet primary enclosure
  - Data is being analyzed
  - Compare results with FLUKA and STAC8 (SR Radiation)

Future Use of Fluka

- Phase III Beamlines (CLS)
  - Compare radiation measurements during beamline commissioning with Fluka predictions
  - Brochouse beamline shielding design
- Top-up mode of Operation Radiation Analysis (CLS)
  - Radiation analysis of Front-ends and beamlines
- Medical Isotope Project (CLS)
  - Low Energy High Power electron Linac (35 MeV, 35 kW) shielding
  - Activation of accelerator components, target, cooling water and surrounding air
  - Estimate of Mo-99 from Mo-100 target
- Accelerator specific radiation analyses (CLS)
  - Booster to Storage ring collimator and scraper
  - Revisit local shielding in the Booster injection area
- Elinac project (Triumf)
  - Collaboration with Anne Trudel and Mike Trinczek

Acknowledgment

- Fluka:
  - Fluka organization for providing the FLUKA Code
  - "The FLUKA code: Description and benchmarking" G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso`, J. Ranft, Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab 6--8 September 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49, (2007)
  - "FLUKA: a multi-particle transport code" A. Fasso`, A. Ferrari, J. Ranft, and P.R. Sala, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773
- FLAIR:
  - Vasilis Vlachoudis
- SimpleGeo:
  - Theis C., Buchegger K.H., Brugger M., Forkel-Wirth D., Roesler S., Vincke H., "Interactive three dimensional visualization and creation of geometries for Monte Carlo calculations", Nuclear Instruments and Methods in Physics Research A 562, pp. 827-829 (2006).
- STAC8:
  - Yohishiro Asano for providing the STAC8 code
  - Developed by Y. Asano for shielding SR beamlines at SPring8
  - STAC8 Refs:
    - 1. "Development of shielding design code for synchrotron radiation beam line," Yoshihiro Asano and Nobuo Sasamoto, Radiation Physics and Chemistry, v.44, no.1-2, Jul-Aug 1994; p.133-137. Also in Proceedings of the 1st Physics Conference; Nov 15-19 1992; Qena, Egypt.
    - 2. Yoshihiro Asano, "A Study on Radiation Shielding and Safety Analysis for a Synchrotron Radiation Beamline," JAERI-Research 2001-006, March 2001.
- Radiation Measurements:
  - Pavi Selvaraj and Lyndon Cowles for carrying out the radiation experiments on SXRMB bending magnet beamline.