Simulation for Radiation Protection

L. Nicolas, S. H. Rokni, M. Santana[+], S. Xiao

1: SLAC National Accelerator Laboratory
+: msantana@slac.stanford.edu

Outline

- Computation tools
- FLUKA
- Prompt dose studies
- Undulator damage studies
- Beam Loss Monitors
- Activation studies and calculations
- Residual dose
- Air activation, ozone concentration
- Other studies

RP computations

- Extensive use of Monte Carlo codes (FLUKA, MARS, MCNPX) and analytic tools (SHIELD11, STAC8)
- Calculation of shielding in accelerators (LCLS, SSRL, FACET, ASTA, ESA,…), computation of prompt dose fields, residual dose rates, damage to electronics and permanent magnets, radioisotope production, etc.

FLUKA history

The beginning

1962: **Johannes Ranft (Leipzig) and Hans Geibel (CERN): Monte Carlo for high-energy proton beams**

Early 70's to ≈1987: **J. Ranft and coworkers (Leipzig University) with contributions from Helsinki University of Technology (J. Routti, P. Aarnio) and CERN (G.R. Stevenson, A. Fassò)**

Link with EGS4 in 1986, later abandoned

The modern FLUKA

Since 1989: mostly INFN Milan (A. Ferrari, P.R. Sala): little or no remnants of older versions. Link with the past: J. Ranft and A. Fassò

1990: **LAHET / MCNPX: high-energy hadronic FLUKA generator** No further update

1993: **G-FLUKA (the FLUKA hadronic package in GEANT3).** No further update

1998: **FLUGG, interface to GEANT4 geometry**

2000: **grant from NASA to develop heavy ion interactions and transport**

2001: **the INFN FLUKA Project**

2003: **official CERN-INFN collaboration**

2011: **FLUKA.2011.23 Latest available version**

The Physics Content of FLUKA

- **Nucleus-nucleus interactions 100 MeV/n – 10000 TeV/n**
  New thresh. (under development): from Coulomb Barrier
- **Hadron-hadron and hadron-nucleus: 0 – 10000 TeV**
- **Electromagnetic and μ interactions 100 eV – 10000 TeV**
- **Charged particle transport**
- **Transport in magnetic fields**
- **Neutrino interactions**
- **Neutron multigroup transport and interactions 0 – 20 MeV: 260 groups**
- **Analog calculations, or with variance reduction**

FLUKA code complexity

- Inelastic h-N: ~**72000 lines**
- Cross sections (h-N / h-A), and elastic (h-N / h-A): ~**32000 lines**
- (G)INC and preequilibrium (PEANUT): ~**114000 lines**
- Evap./Fragm./Fission/Deexc.: ~**27000 lines**
- ν-N interactions: ~**35000 lines**
- A-A interactions:
  - ✓ FLUKA native (including BME): ~**8000 lines**
  - ✓ DPMJET-3: ~**130000 lines**
  - ✓ (modified) rQMD-2.4: ~**42000 lines**
- **FLUKA** in total (including transport, EM, geometry, scoring): ~**680000 lines**
- ... + ~**20000 lines** of ancillary off-line codes used for data pre-generation
- ... and ~**30000 lines** of post-processing codes

The FLUKA Code design - 1

Sound and updated physics models

- Based, as far as possible, on original and well-tested microscopic models
- Optimized by comparing with experimental data at single interaction level: **"theory driven, benchmarked with data"**
- Final predictions obtained with minimal free parameters fixed for all energies, targets and projectiles
- Basic conservation laws fulfilled "a priori"

➔ **Results in complex cases, as well as properties and scaling laws**, arise naturally from the underlying physical models

➔ **Predictivity where no experimental data are directly available**

It is a MC code of the "Condensed history" class, with the exception of possible use of single instead of multiple scattering

The FLUKA Code design - 2

- **Self-consinstency**
  - Full cross-talk between all components: hadronic, electromagnetic, neutrons, muons, heavy ions
  - Effort to achieve the same level of accuracy:
    - for each component
    - for all energies
  - ➔ Correlations preserved fully within interactions and among shower components
  - ➔ **FLUKA is NOT a toolkit! Its physical models are fully integrated**

(Pseudo)Random number periodicity: $>10^{43}$

Marsaglia's algorithm (64 bits since FLUKA2005.6 version, 48 bit before)

Lateral neutron shielding studies

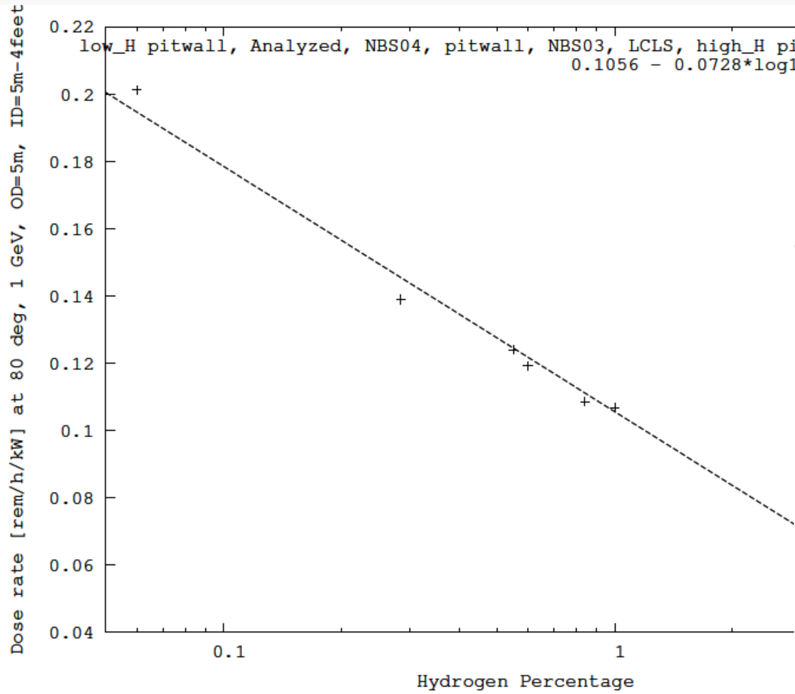


Figure 2: Effect of the hydrogen content on the neutron shielding efficiency of tl

Benchmarking of analytical codes as a function of the energy, angle and shielding thickness

ang [deg] / Quantity / Case	30 tot [rem/h/kW]	30 mid [%]	30 hen [%]	60 tot [rem/h/kW]	60 mid [%]	60 hen [%]	80 tot [rem/h/kW]	80 mid [%]	80 hen [%]
1 GeV	0ft	concrete							
F-EWT74	6.26	5.75	3.62	32.6	3.20	0.98	45.3	2.45	0.61
F-EWTMP	6.23	5.79	3.15	32.5	3.20	0.87	45.3	2.45	0.54
F-AMB74	7.80	4.14	1.41	41.0	2.40	0.24	57.4	1.85	0.24
SHIELD11	17.5	36.3	9.07	41.1	26.0	4.02	48.3	20.6	2.37
FAMB/SH11	*0.45*			*1.00*			*1.19*		
1 GeV	2ft	concrete							
F-EWT74	0.114	31.5	23.2	0.668	31.9	14.0	0.926	27.9	9.86
F-EWTMP	0.110	32.5	20.8	0.656	32.3	12.5	0.915	28.1	8.86
F-AMB74	0.102	31.0	12.7	0.644	29.3	7.28	0.935	24.8	4.95
SHIELD11	0.182	19.1	80.2	1.061	49.9	39.2	1.338	52.8	25.4
FAMB/SH11	*0.56*			*0.61*			*0.70*		
1 GeV	4ft	concrete							
F-EWT74	1.31E-2	38.4	25.5	0.108	41.0	22.4	0.136	42.6	19.8
F-EWTMP	1.27E-2	39.4	23.0	0.105	42.1	20.4	0.132	43.8	18.1
F-AMB74	1.12E-2	39.5	14.7	0.093	41.7	13.1	0.119	42.8	11.4
SHIELD11	1.36E-2	1.40	98.5	0.131	19.9	80.2	0.154	32.6	65.6
FAMB/SH11	*0.82*			*0.71*			*0.77*		
1 GeV	6ft	concrete							
F-EWT74	1.94E-3	39.5	25.3	2.56E-2	40.6	24.7	3.47E-2	42.4	22.8
F-EWTMP	1.87E-3	40.8	23.0	2.48E-2	41.9	22.5	3.38E-2	43.2	20.7
F-AMB74	1.64E-3	40.9	14.9	2.18E-2	41.7	14.5	2.98E-2	43.0	13.4
SHIELD11	1.23E-3	0.08	99.9	2.77E-2	4.66	95.3	3.37E-2	10.6	89.3
FAMB/SH11	*1.33*			*0.79*			*0.88*		
100 MeV	4ft	concrete							
F-EWT74	3.53E-5	5.39	-	7.53E-4	11.4	-	1.78E-3	10.0	-
F-EWTMP	3.53E-5	5.39	-	7.53E-4	11.4	-	1.78E-3	10.0	-

Systematic studies to determine shielding characteristics of different concrete types and analysis of root differences

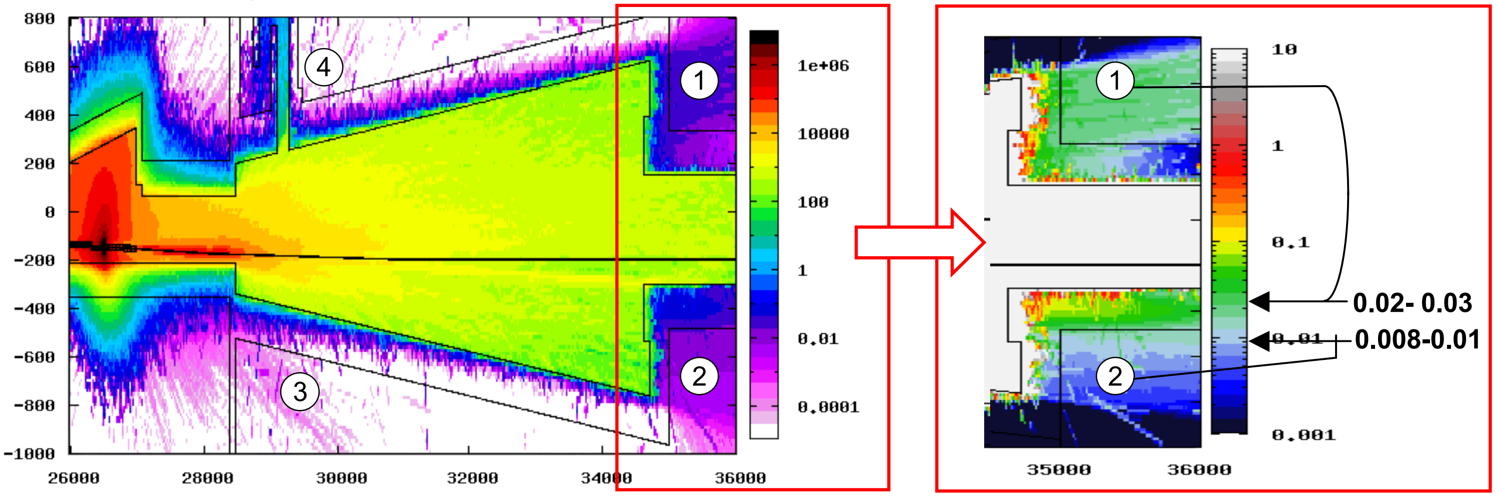
REF: M. Santana, *Comparison of SHIELD11 and FLUKA neutron ambient dose estimators*, **RP-10-16**

Muon production and attenuation studies

Benchmarking of FLUKA photo-muon: Comparison of predictions with measurements at LCLS single beam dumper, 430 W-14 GeV

General view from TDKIK to end plugs

head house end plugs

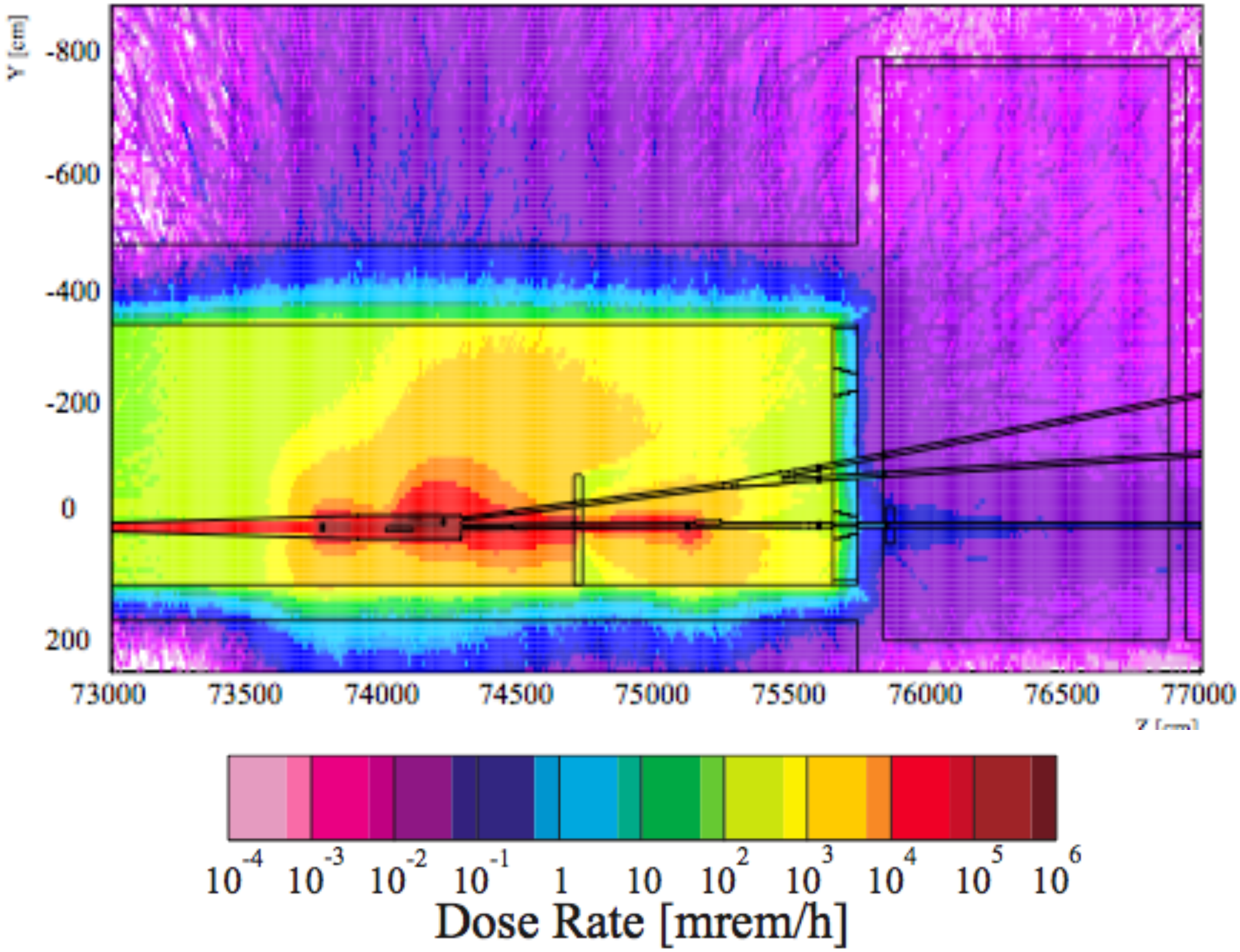


[mrem/h]	Point (1)	Point (2)	Point (3)	Point (4)
Simulation	0.02-0.03	0.008-0.01	~<1E-3	Less than (3)
Measurement(*) JAN 2010	0.03	0.01	<0.01	Less than (3)

Excellent agreement ! → Photomuon dose field benchmark

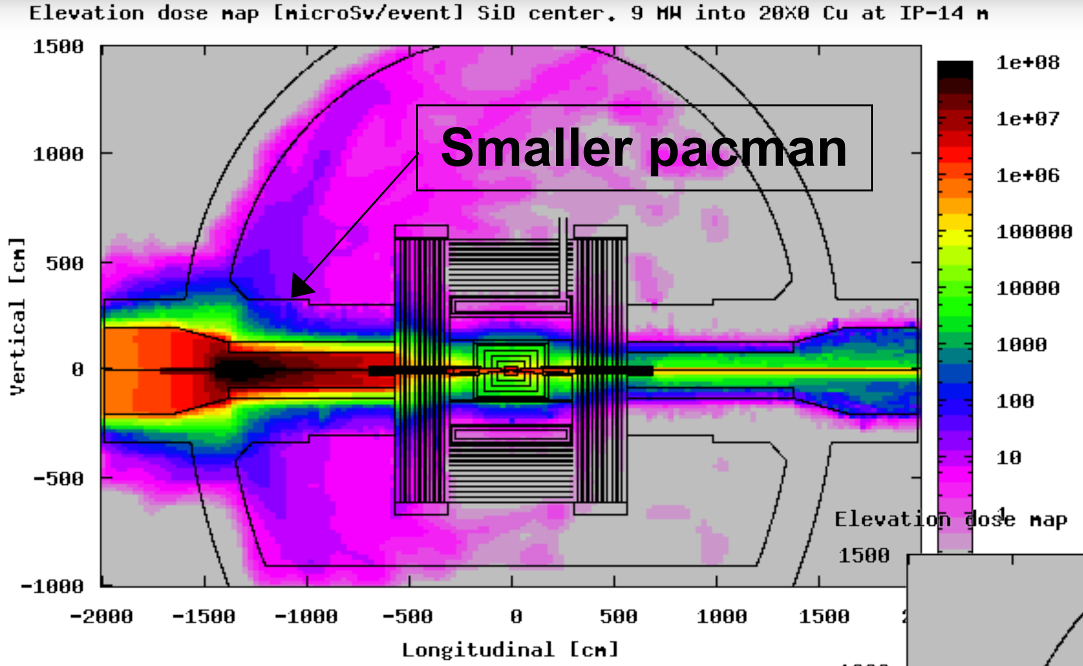
REF: S. Mao, *Radiation Survey for LCLS Undulator Complex 120 Hz (430 W) Operation*, **RP-RPG-110107-MEM-01**

Bremsstrahlung production and leakage



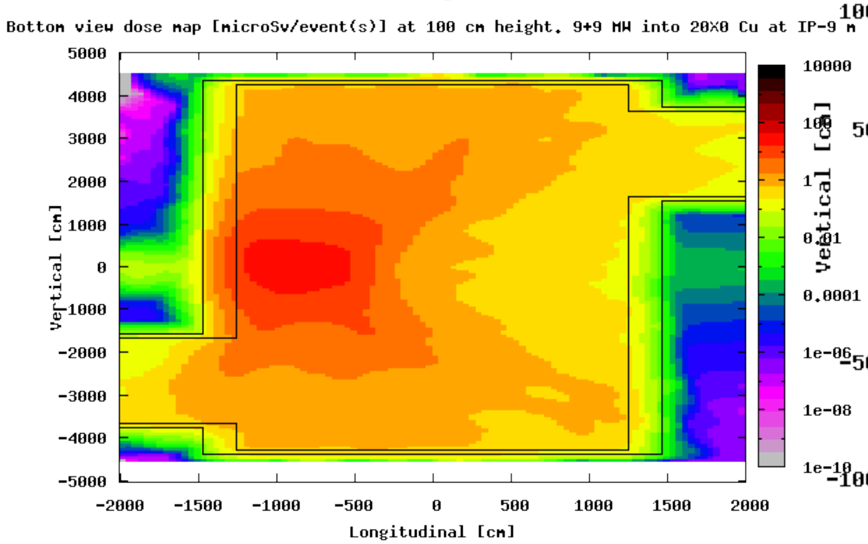
For different situations and sources, computation of Bremsstrahlung power into LCLS Front End Enclosure and dose rate in the Near End Hall.

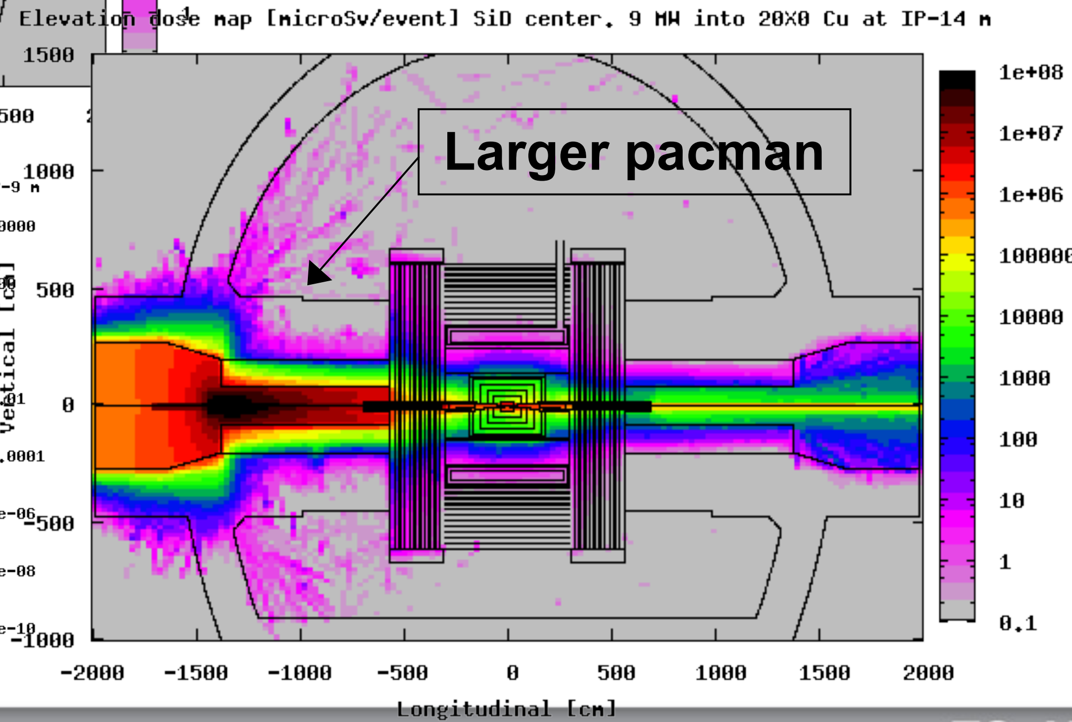
Study of SiD detector for ILC: pacman, penetrations…



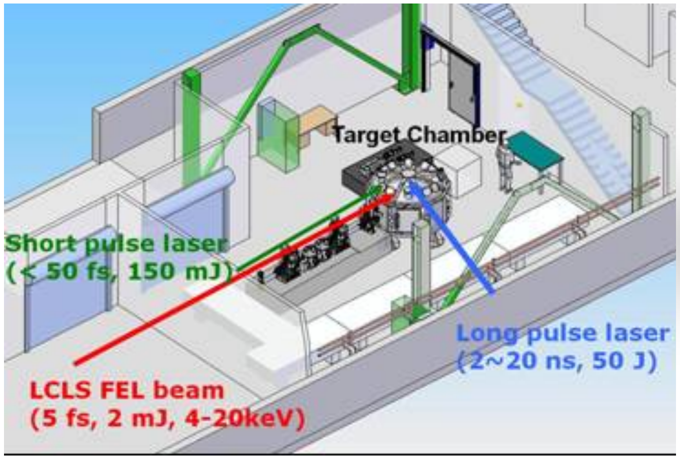
Prompt dose for beam on 20 R.L. target in IP-14 m.

2010 Linear Collider Workshop & International Linear Collider Meeting
Tsinghua University, Beijing university, Institute of Theoretical Physics, University of Sciences and Technologies of China

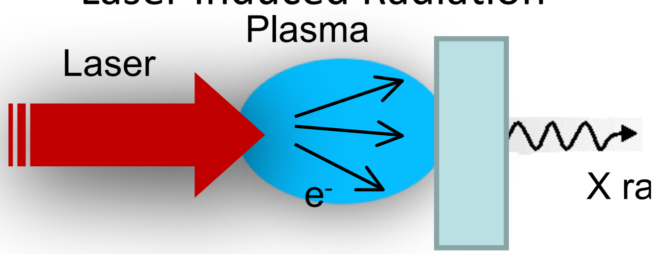


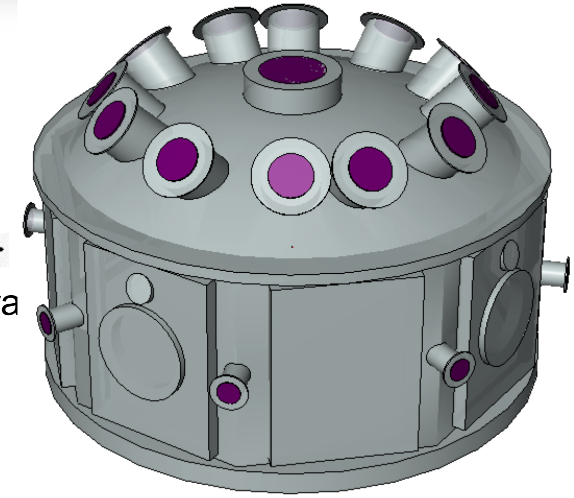


Matter in Extreme Conditions Instrument

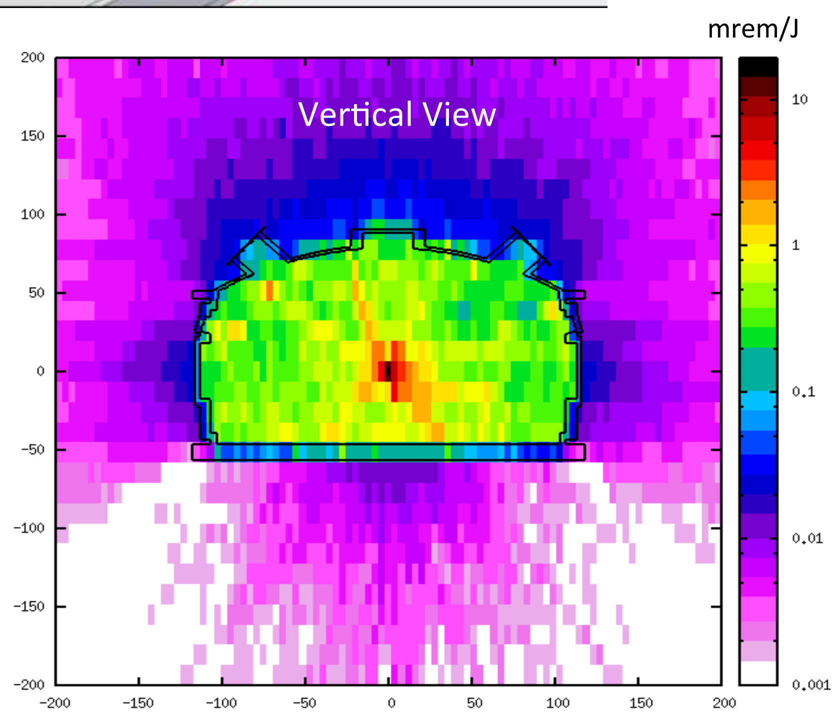


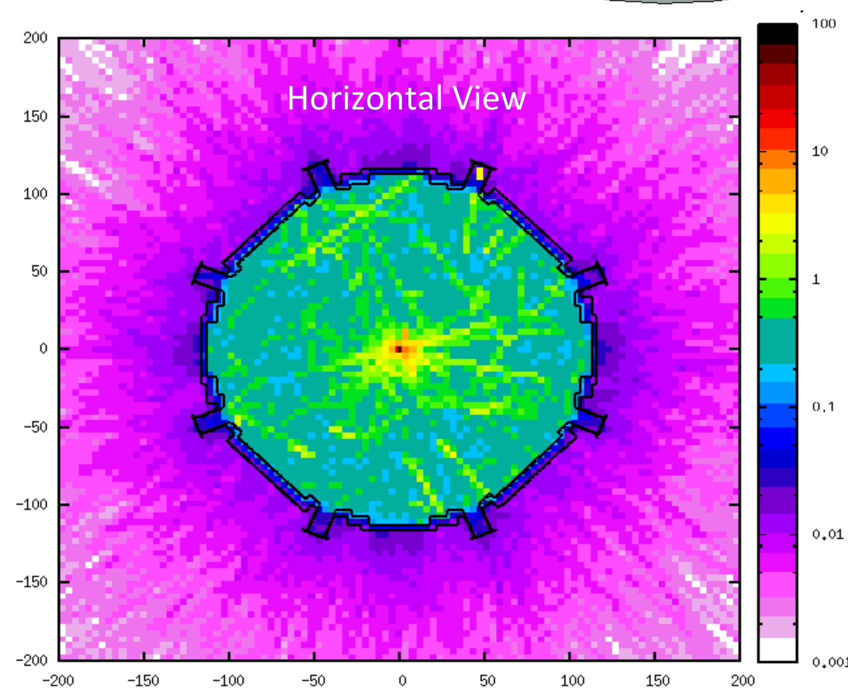
Laser Induced Radiation



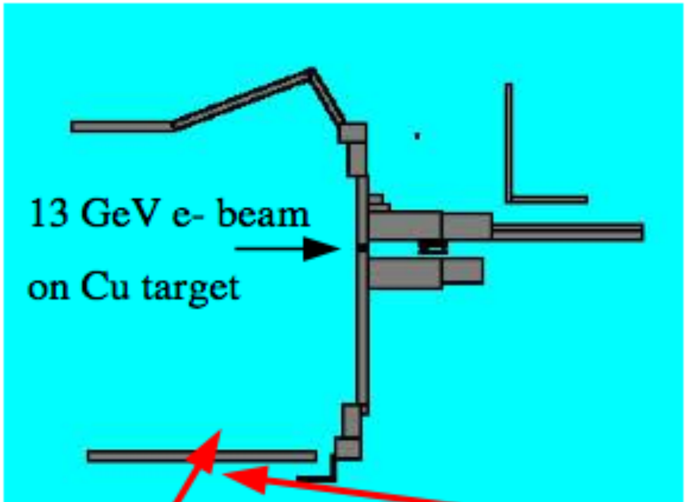


20 µm Al foil target
Electron temperature = 400 keV



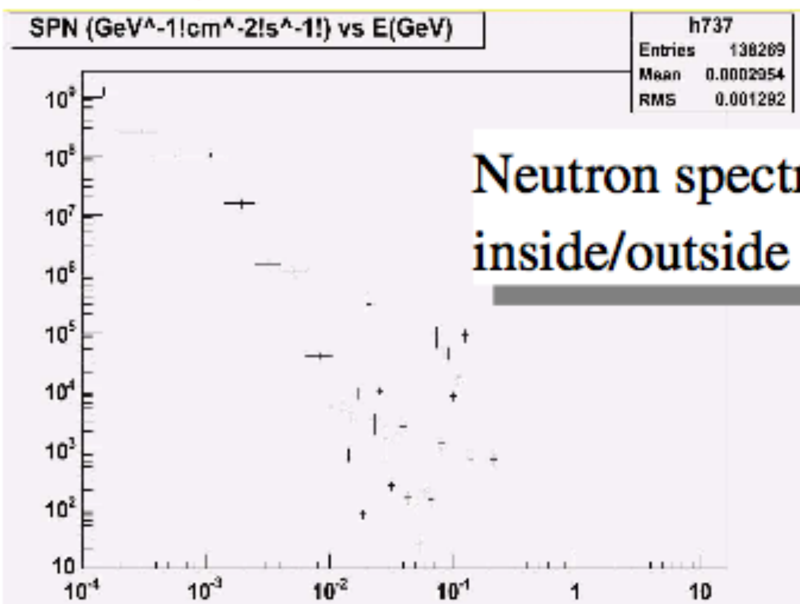


MARS simulations for shielding of ESA

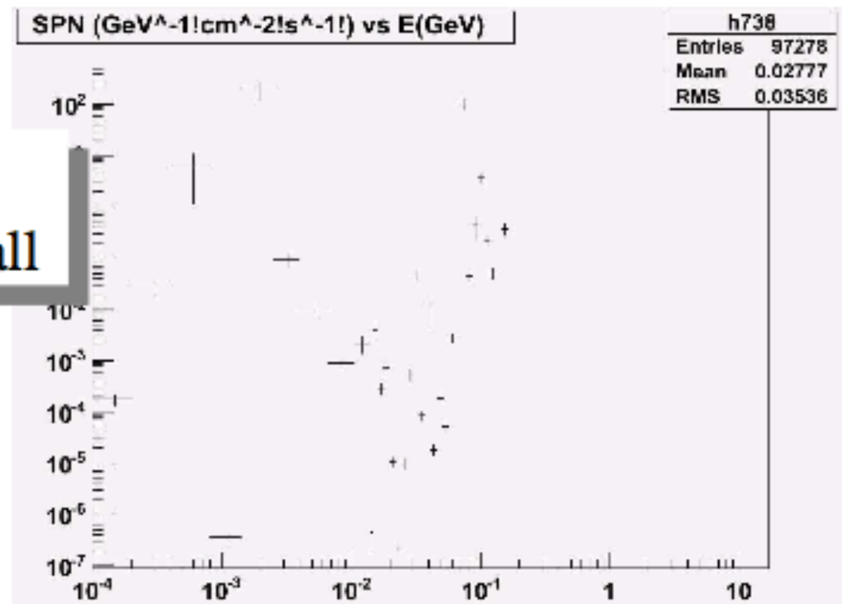


MARS is a Monte Carlo code for inclusive and exclusive simulation of three-dimensional hadronic and electromagnetic cascades, muon, heavy-ion and low-energy neutron transport in accelerator, detector, spacecraft and shielding components in the energy range from a fraction of an electronvolt up to 100 TeV.

Used at SLAC for calculations of radiation backgrounds and shielding design, e.g. ESA experimental hall for new experiments.

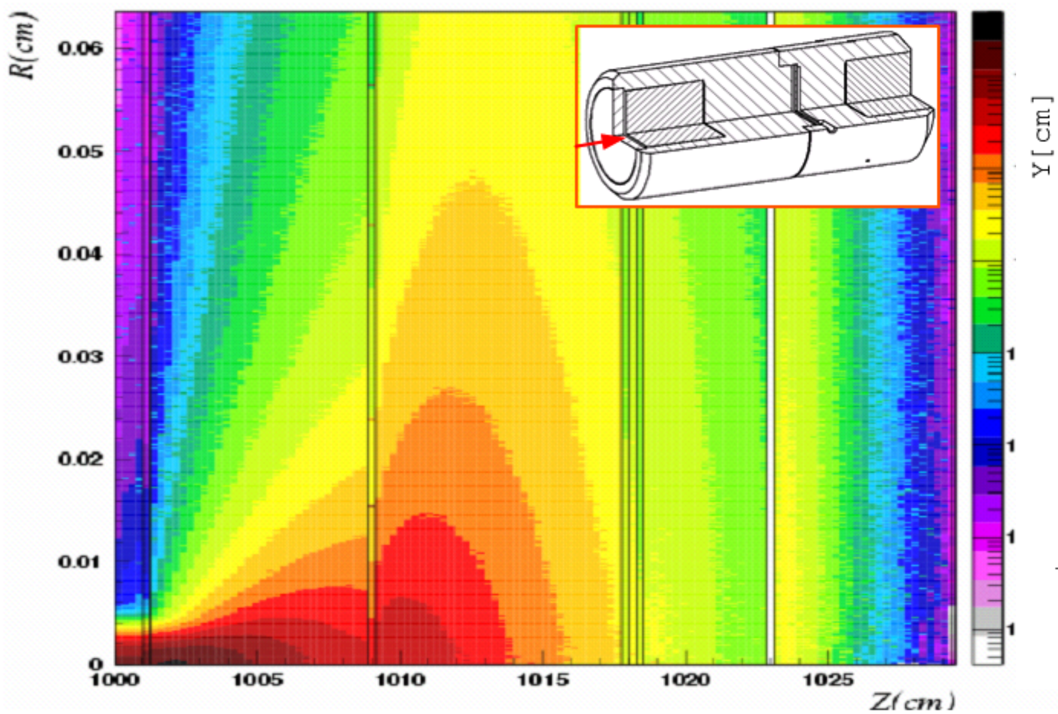


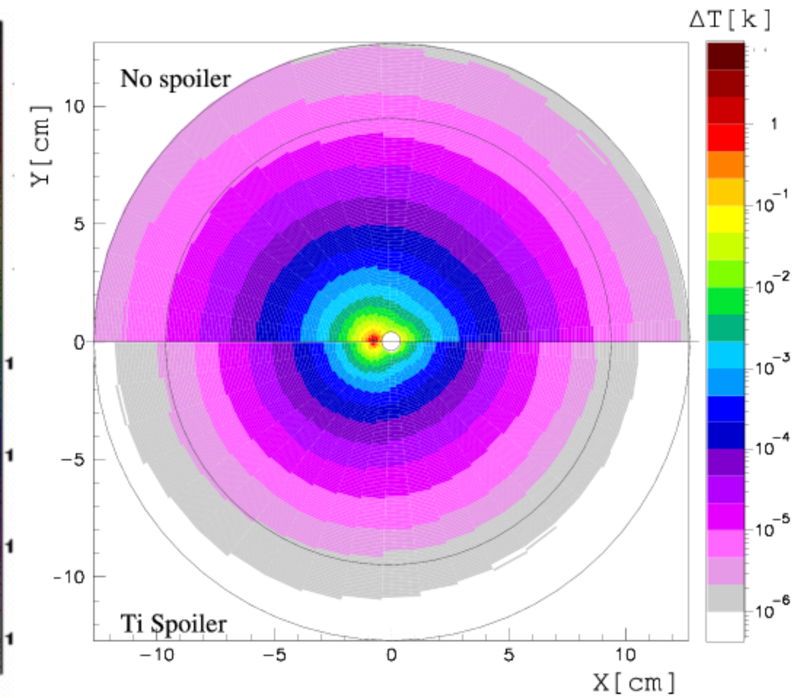
Neutron spectra inside/outside wall



Heat deposition studies for safety devices

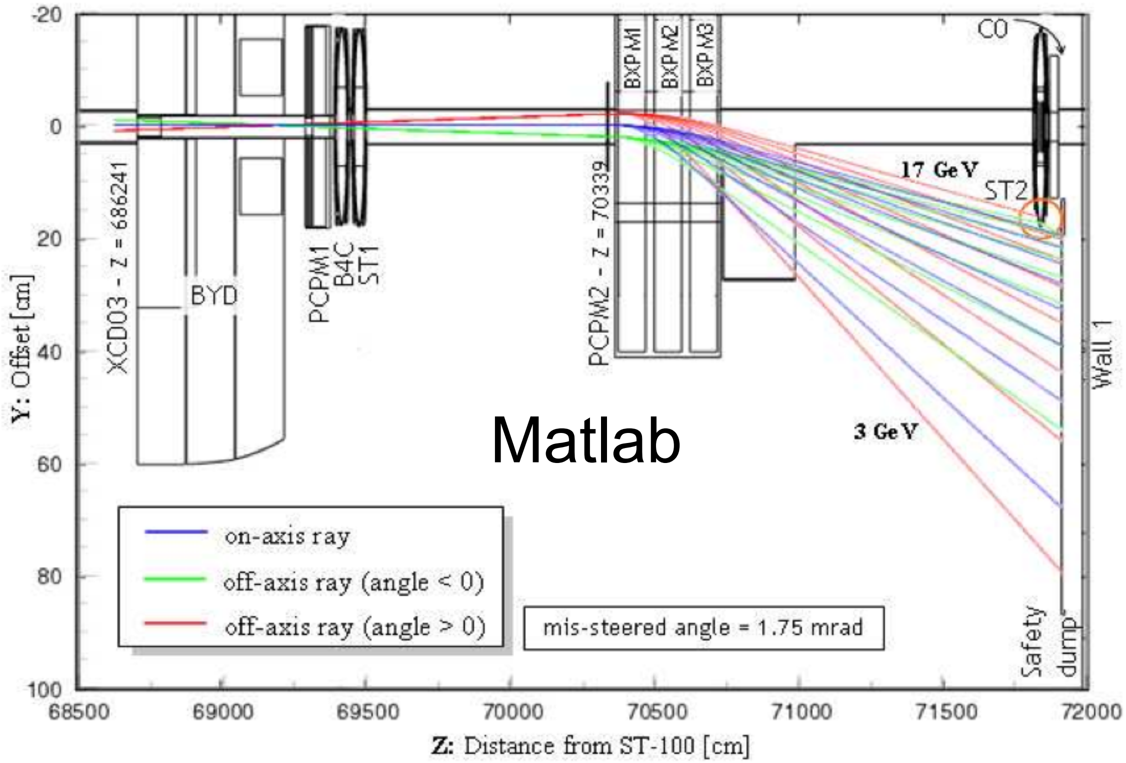
Validation of instantaneous thermal spikes in LCLS ST stoppers

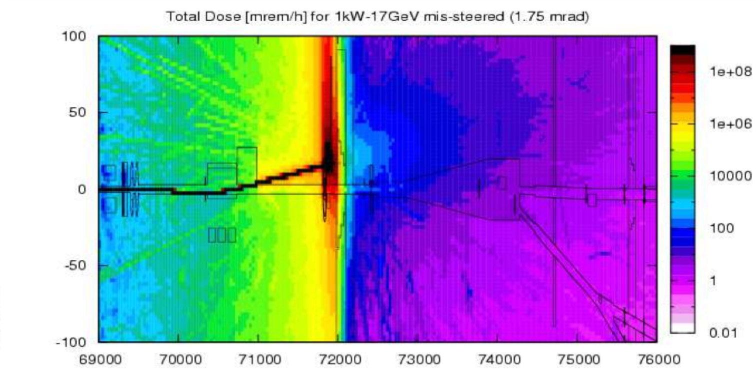


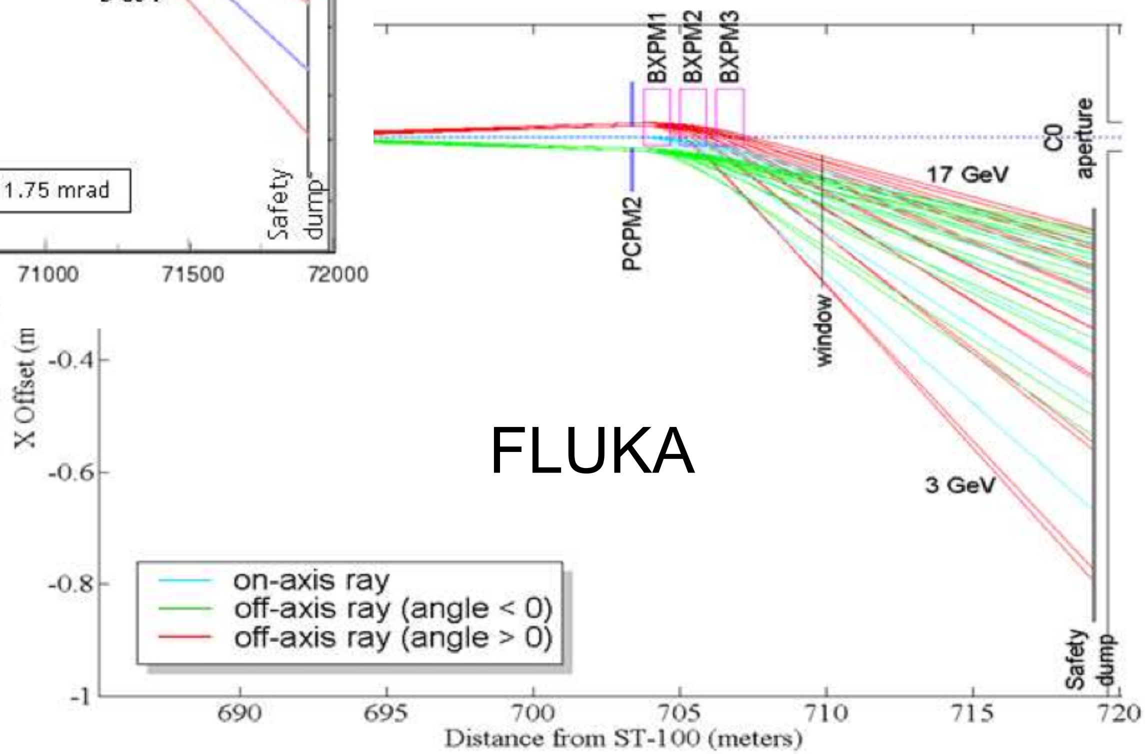


Computation of instantaneous peak temperature rise for several stopper and configurations

Tracking of mis-steered rays into safety dump

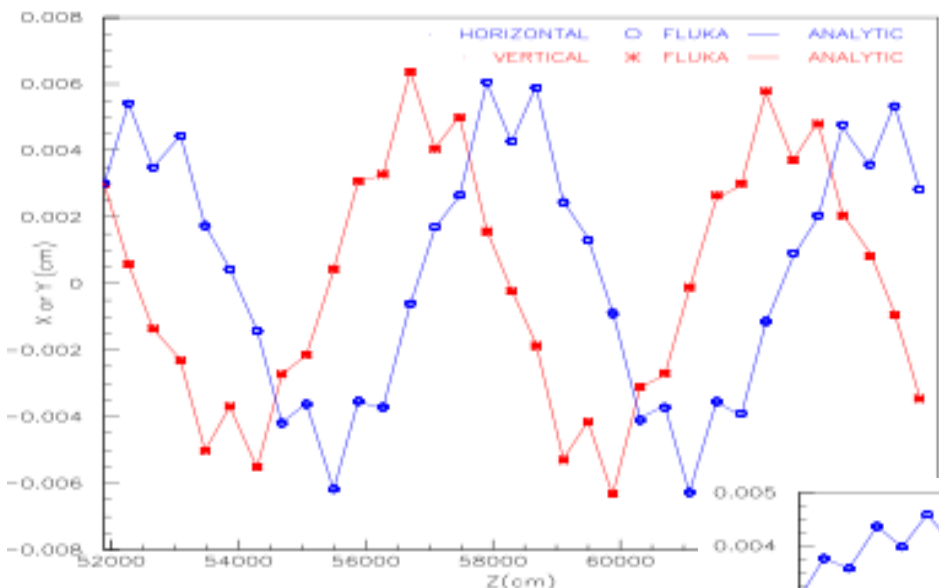






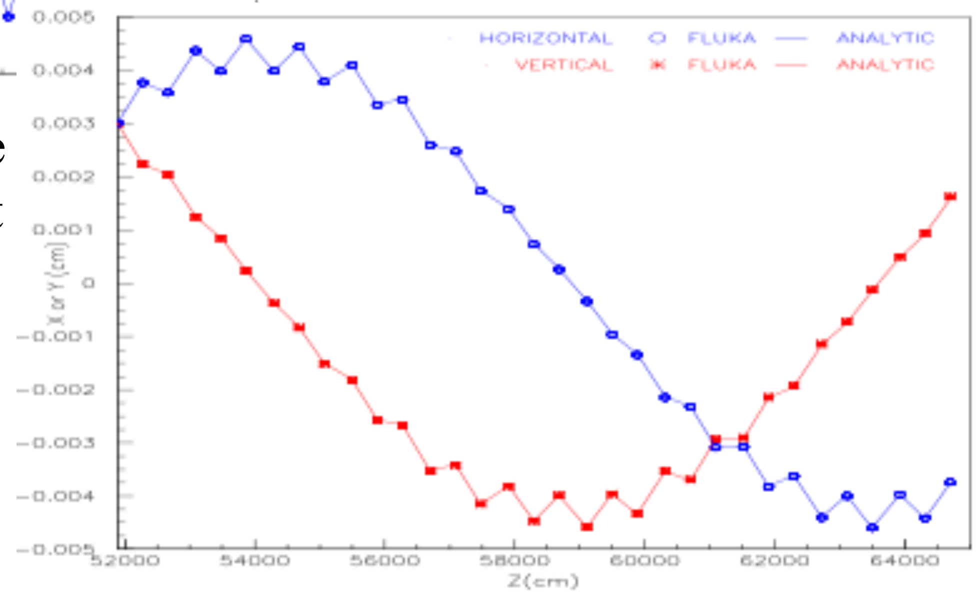
Verification with Matlab and FLUKA of safety dump line and simulation of dose in case of mis-steering

Beam tracking, e.g: LCLS undulator



Quadrupole focusing in the 132 m undulator section was implemented both in FLUKA and MARS15.

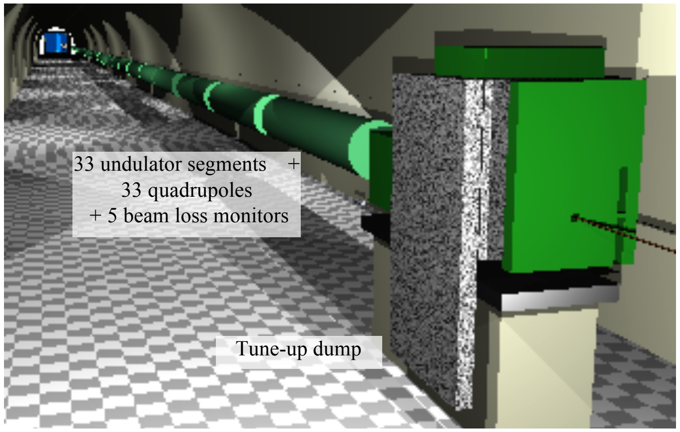
Step-sizes were adjusted to maintain optimal tracking with moderate CPU use

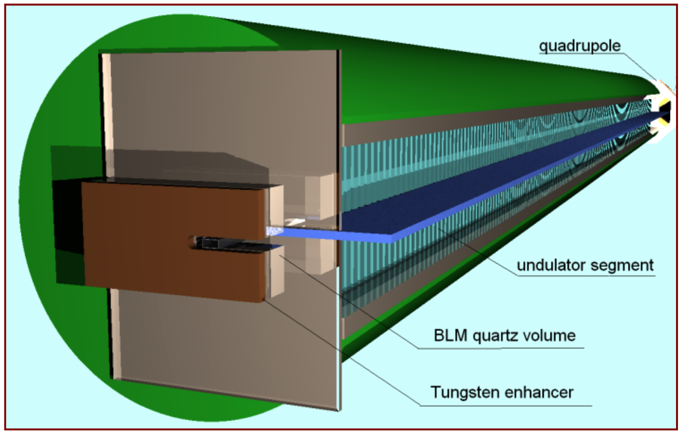


Betatron oscillations along the undulator were checked against analytical data in the two transverse planes and for the two extreme energies of LCLS, 4 GeV and 17 GeV. Perfect agreement was found.

Implementation of the LCLS undulator

- **FLUKA** intra nuclear cascade code was used to model almost the entire LCLS for **radiation protection studies**.
- A dedicated **MARS15 model** of the undulator was created at ANL to validate and supplement the results provided by FLUKA.
- Models describe **in detail** the undulator including all the segment magnets and poles, interstitial quadrupoles, the beam loss monitors, tunnel, etc.
- A virtual gallery was created in the FLUKA model for 'cyber-storage' of the prototypes, and *lattice* **mapping** instructions were coded to replicate the prototypes along the tunnel.
- **Variance reduction techniques** used: leading particle biasing, multiple EM scattering, enhanced interaction in thin devices, biased photoneutrons.



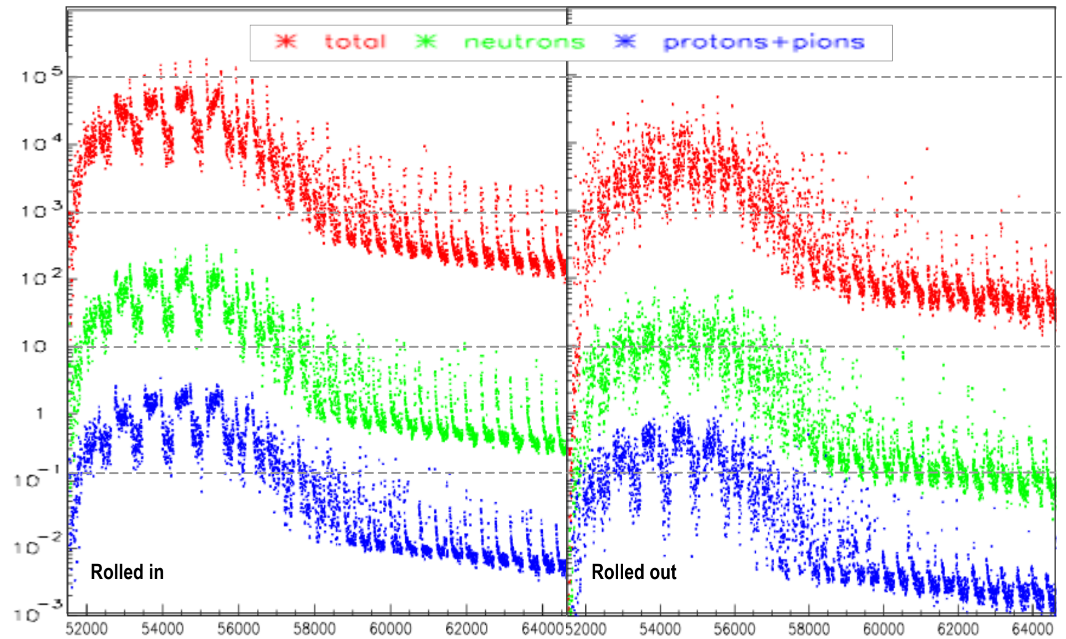


Povray raytracing of the LCLS undulator hall, and the undulator segment prototype, as implemented in FLUKA

Radiation to LCLS undulator magnets

e.g. insertion of a 40 micron beam finder wire before the 1st undulator

Fluence [cm-2/s] in the undulator magnets when the undulators are IN or rolled OUT

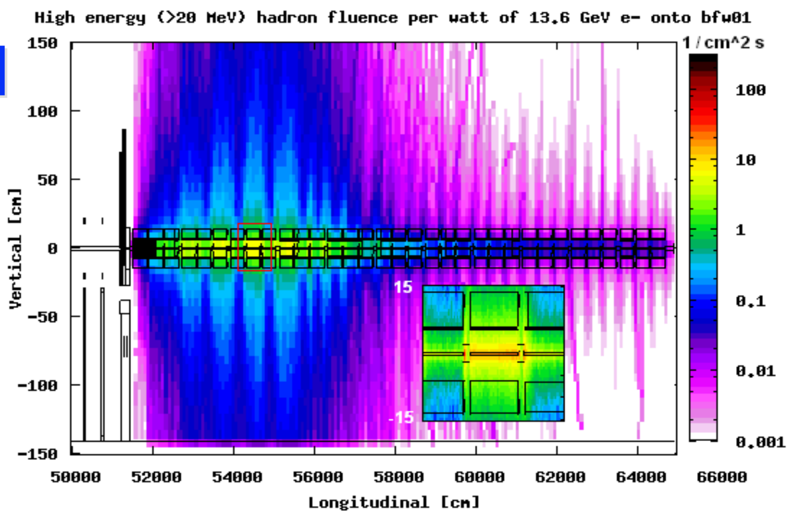


Undulator IN		Undulator rolled OUT	
Regions	[% (γ,n)]	Regions	[% (γ,n)]
und magnets	48.9	quadrupoles	49.5
und poles	24.7	und magnets	14.7
und pipe	15.3	und pipe	14.4
quadrupoles	5.7	other und regions	11.2
other und regions	3.2	beam pipe	10.0
beam pipe	1.9	other	0.2

Share [%] of photoneutron reactions along the LCLS undulator (as a function of the undulators position) for a 13.6 GeV e- beam intercepted by 40 mm beam finder wire BFW01

Fluence fields to LCLS undulators

1



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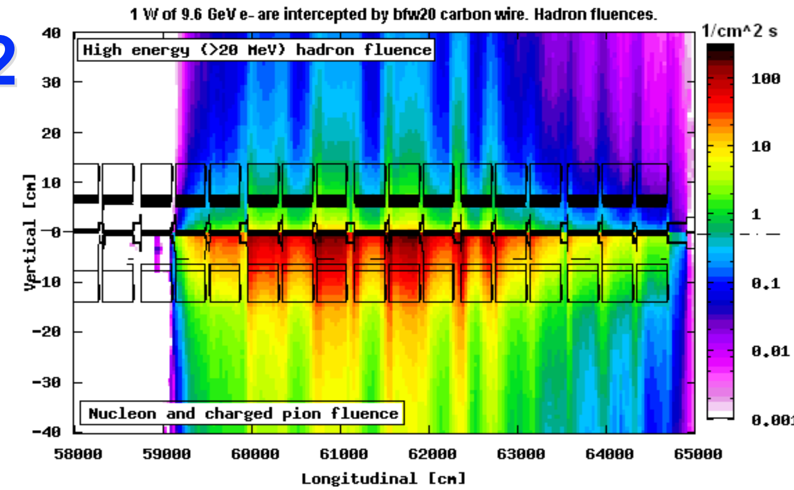

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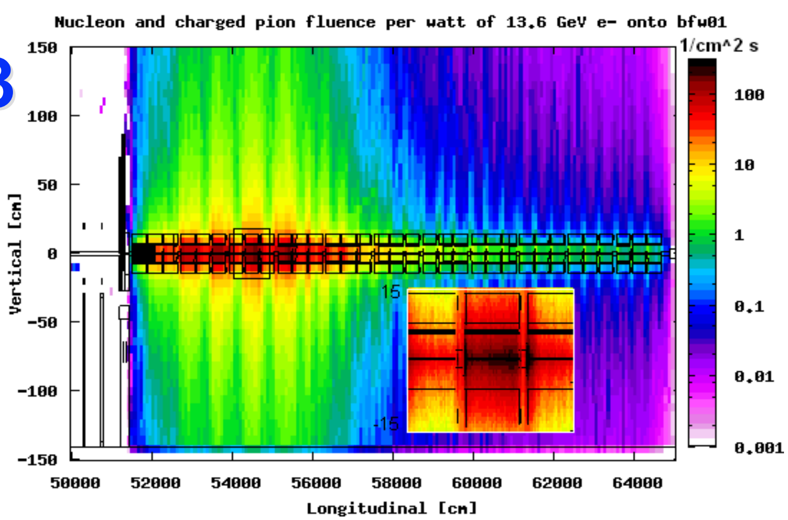

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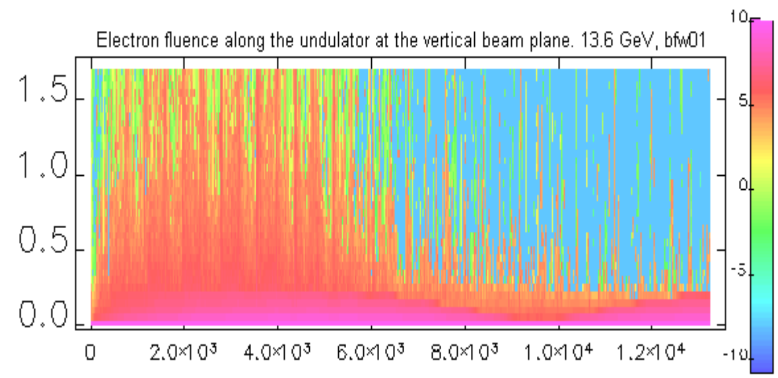
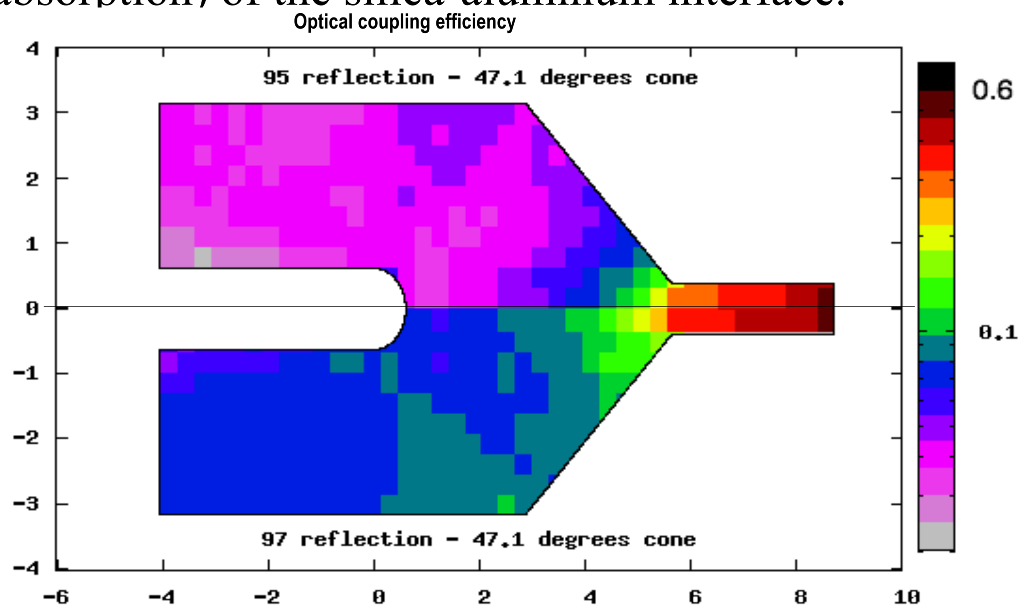


1-3: Generated with FLUKA. Plotted with FLAIR

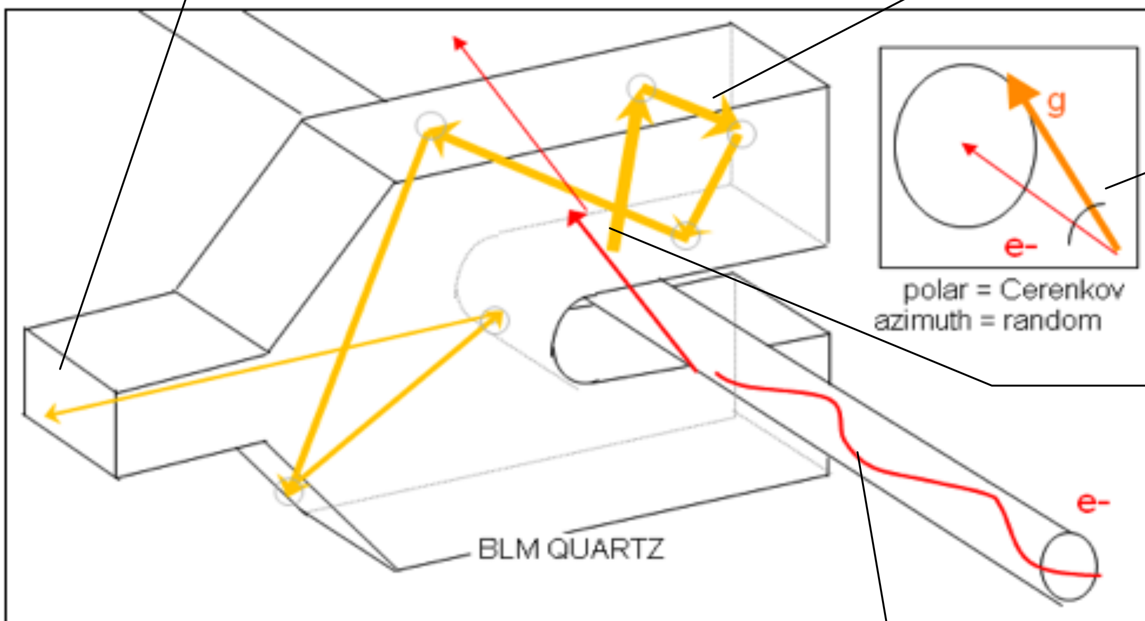
4: Generated with MARS15

BLM optical efficiency studies

- The **RIBO Monte Carlo code** was used to compute the Čerenkov transport through the beam loss monitor silica to the photocathode.
- The same fork geometry of BLM implemented in FLUKA and MARS was written for RIBO.
- Initial studies were performed to understand the optical coupling (transmission efficiency) of the BLM as a function several parameters:
  - Reflection coefficient (absorption) of the silica-aluminum interface.
  - e^- impact position.
  - Energy of the electron.
  - Geometry of the BLM.
- Impinging position was sampled uniformly in the front face of the BLM, electrons were assumed perpendicular (i.e. high energy)



BLM signal and undulator damage studies



6 WRITE tracks & collisions as a function of starting {x,y,z}

5 TRACK Čerenkov reflections/absorption until photocathode

4 SAMPLE Čerenkov photon generation

3 DUMP electron coordinates & velocity entering BLM

1 BEAM conditions and BEAM LOSS assumptions (e.g. beam finder wire inserted)

2 SHOWER generation and tracking up to BLM's and magnets

Expected signal in the LCLS BLMs

The results of the RIBO generation and random walk of the Čerenkov photons and the associated fluence in the undulators are:

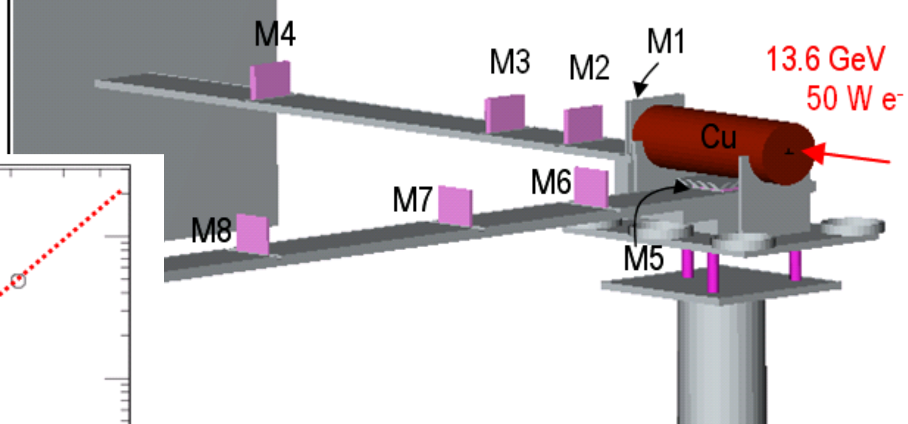
BLM	$\langle Ee^-_{BLM} \rangle$ [MeV]	$\langle \theta_z \rangle$ [°]	$\langle \eta_c \rangle$ $\cdot 10^4$	$\frac{e^-_{BLM}}{e^-_B}$	$\frac{\gamma_{BLM}}{e^-_B}$	$F_h/e^-_B/\gamma_{PC}$ [$cm^{-2}s^{-1}$]
01	15.7	53	7	5.6E-6	6E-4	2.1E7
09	20.4	42	176	7.6E-4	0.29	2.0E3
17	20.7	37	102	7.7E-5	0.03	3.3E4
25	24.5	34	166	2.0E-5	8E-3	7.7E4
33	19.1	41	207	1.2E-5	5E-3	1.0E5

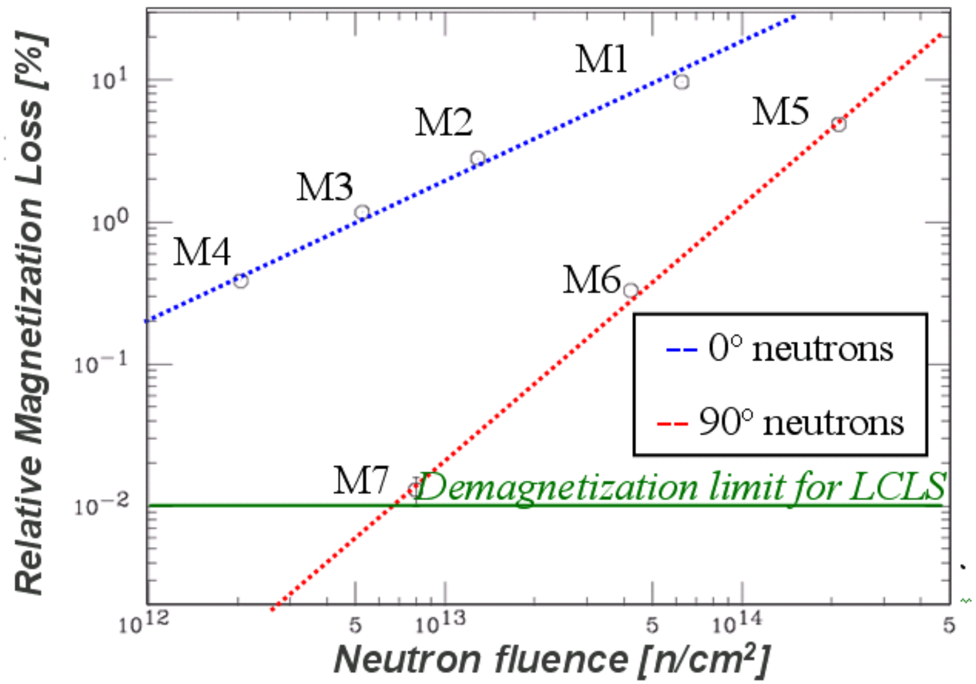
Average properties of electrons entering the BLMs (O_z: angle with respect to z-axis, E: energy), optical coupling (n_c), electrons reaching the BLM (e-BLM) per beam electrons (e^-B), Čerenkov photons generated in BLM (g_{BLM}) per beam electrons, and ratio of expected peak of high-energy hadron fluence in segment 9 (F_h) versus number of photons that reach the phototubes (g_{PC}), per 13.6 GeV e- intercepted by bfw01

Studies of radiation-induced demagnetization

Setup of experiment at ES-A

M	1	2	3	4	5	6	7	8	9
d[cm]	15	28	43	79	7	24.9	50.4	88.4	149
axis	z	z	z	z	x	-y	-y	-y	-y

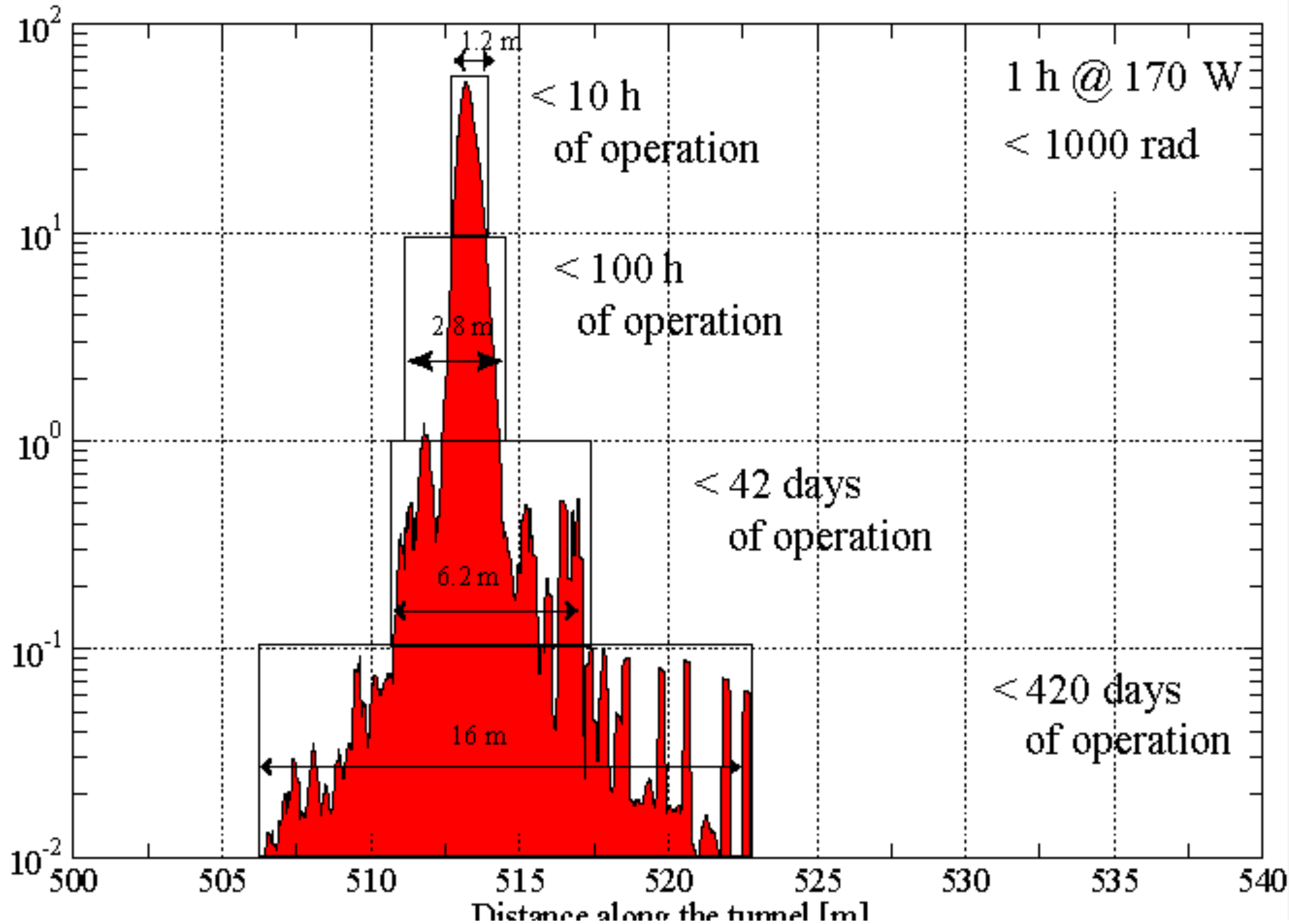




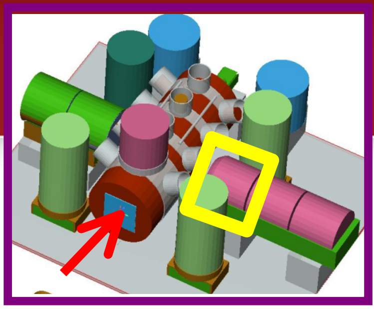
Demagnetization studies

Radiation damage to electronics

Calculation of lifetime of electronics equipment as a function of the distance to Tune up dump in LCLS



Activation benchmark: SLAC concrete



REF: M. Santana et al ARIA11

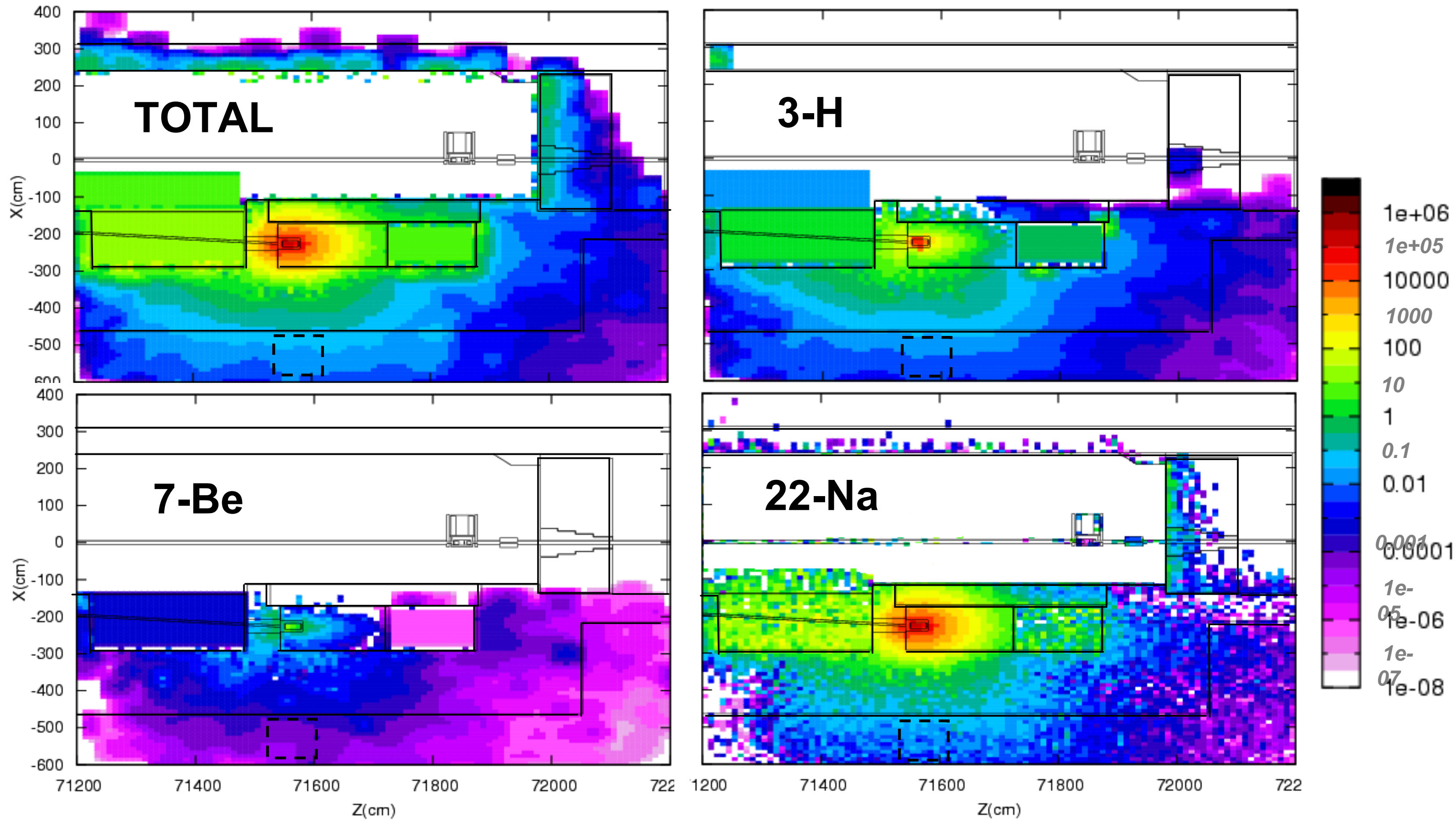
- Irradiation experiments to benchmark FLUKA activation / spectroscopy
- E.g: SLAC concrete --> fairly good agreement
- Discrepancies: ^{58}Co, ^{85}Sr, ^{86}Rb

			experimental result		FLUKA simulation		FLUKA/experiment	
nuclei	**half life**	**Decay**	**[Bq/g]**	**%error**	**[Bq/g]**	**%error**	**average**	**%error**
7Be	53 days	e	0.083	1.38	9.6E-02	1.18	1.2	2.56
22Na	2.6 years	e+b+	3.3E-02	0.82	2.2E-02	1.01	0.64	1.83
46Sc	83.9 days	b-	7.0E-03	1.9	4.6E-03	4.59	0.67	6.49
51Cr	27.8 days	e	4.0E-03	15.7	4.4E-03	3.54	1.1	19.24
54Mn	303 days	e+b+	4.5E-02	0.42	2.5E-02	1.55	0.55	1.97
56Co	77.3 days	e+b+	1.7E-04	12.1	2.7E-04	23.77	1.6	35.87
58Co	71.3 days	e+b+	1.4E-03	5.33	4.9E-04	10.54	0.35	15.87
59Fe	45 days	b-	6.3E-04	21.5	3.1E-04	17.54	0.5	39.04
60Co	5.26 years	b-	2.8E-04	30.3	1.6E-04	31.02	0.58	61.32
85Sr	64 days	e	5.8E-03	3.41	1.7E-03	7.2	0.3	10.61
86Rb	18.6 days	b-	1.6E-03	22.7	4.8E-05	18.58	0.031	41.28
88Y	107 days	e+b+	6.3E-04	10.9	8.7E-04	11.05	1.4	21.95
95Nb	35 days	b-	3.5E-04	22.5	3.5E-04	14.78	1	37.28
TOTAL			**1.8E-01**	1.9	**1.6E-01**	1.7	**0.85**	3.5

0.8=<F/E=<1.2 | **0.4=<F/E<0.8 1.2<F/E=<1.6** | **0.2=<F/E<0.4** | **F/E<0.2**

Environmental Studies

Activation of ground water, LCW activation, air activation…



Residual dose studies and benchmarks

T489 (2007) collaboration experiment CERN-SLAC carried out in ES-A to measure activation of metals and benchmark residual dose rates

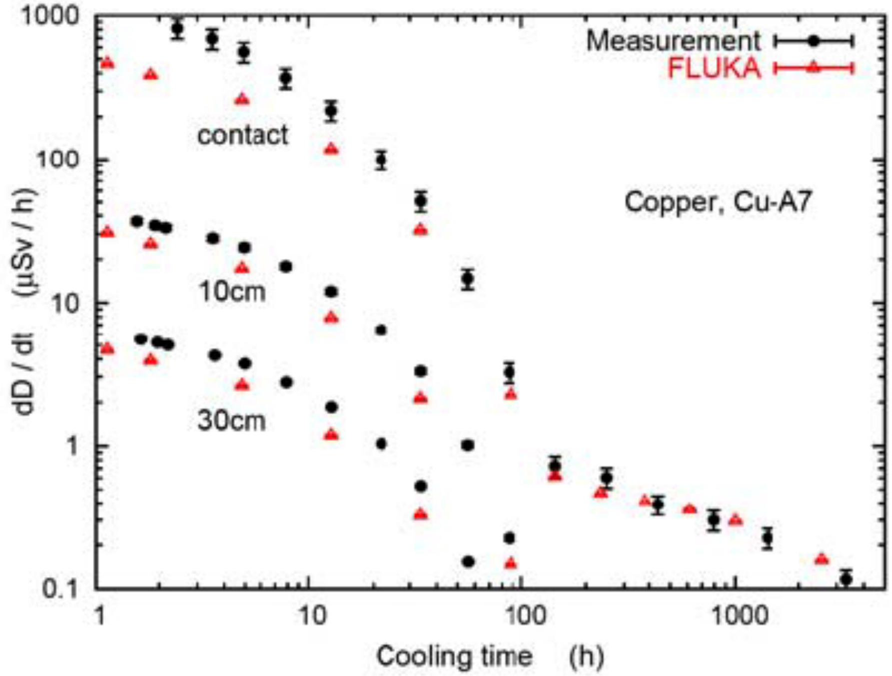
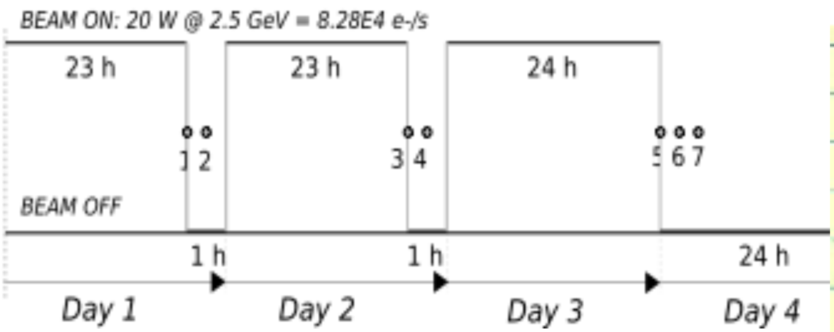


Fig. 2. Residual dose rates as measured for a copper sample irradiated downstream of the target are compared to the FLUKA results.

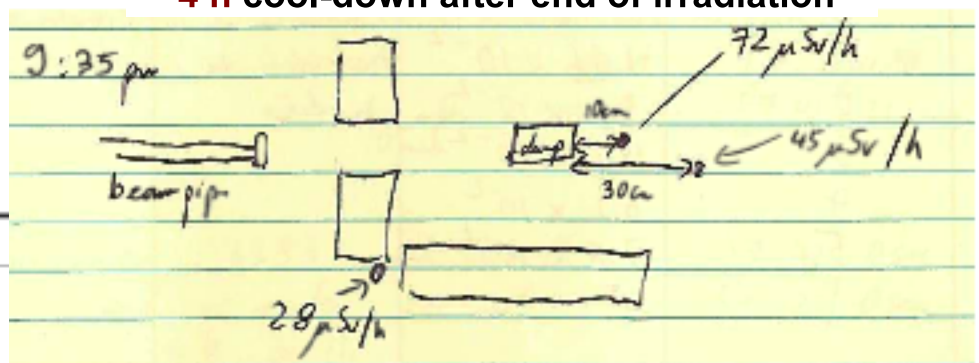
REF: J.M. Bauer et al, *Benchmark Study of Induced Radioactivity at a High Energy Electron Accelerator*, **Presented at ARIA 2008**

Residual dose calculation for sample retrieval

e.g.: ACTIVATION EXPERIMENT

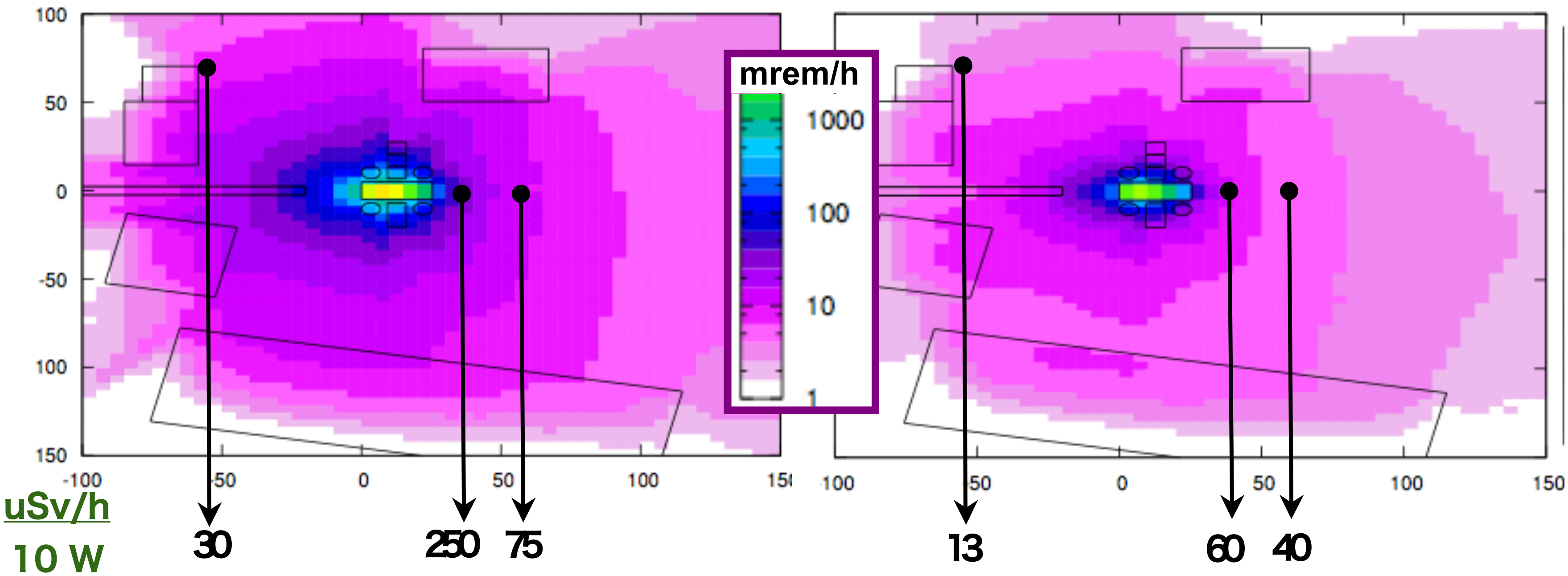


4 h cool-down after end of irradiation



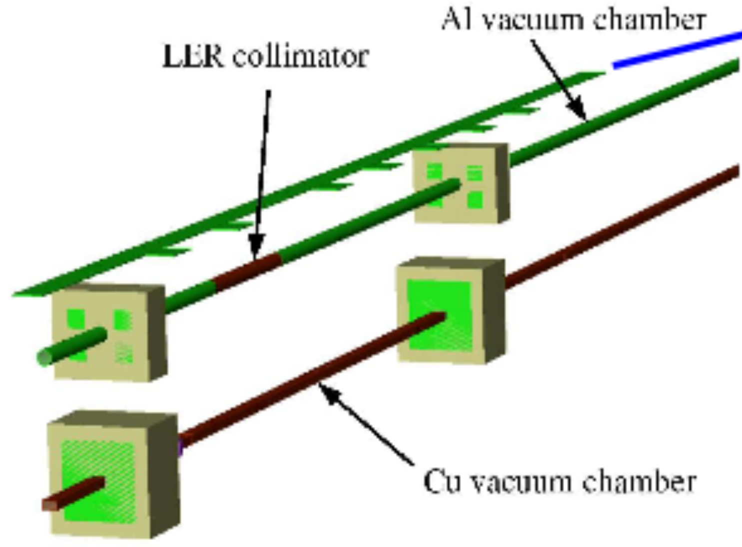
30 min cool-down after end of irradiation

8 h cool-down after end of irradiation

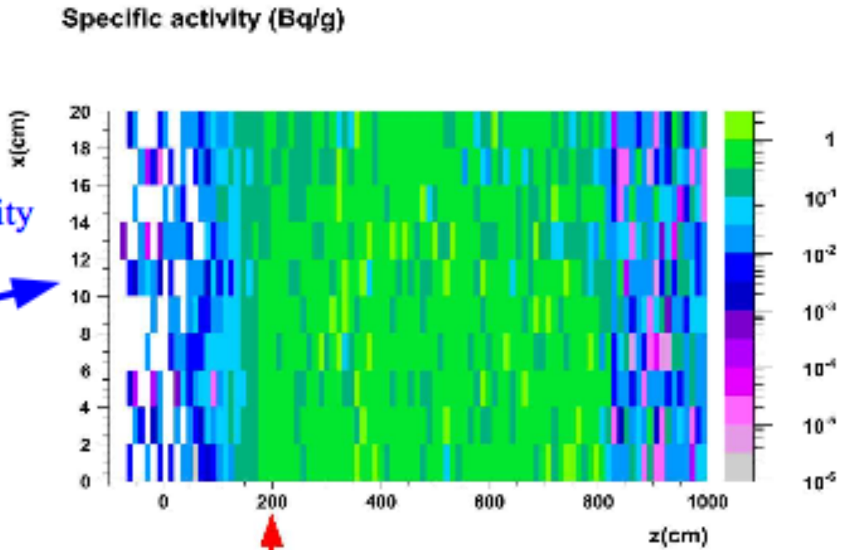


Simulations for decommissioning & dismantling

Used at SLAC for calculations of residual dose rates and induced radioactivity in PEP-II ring environment for material release.



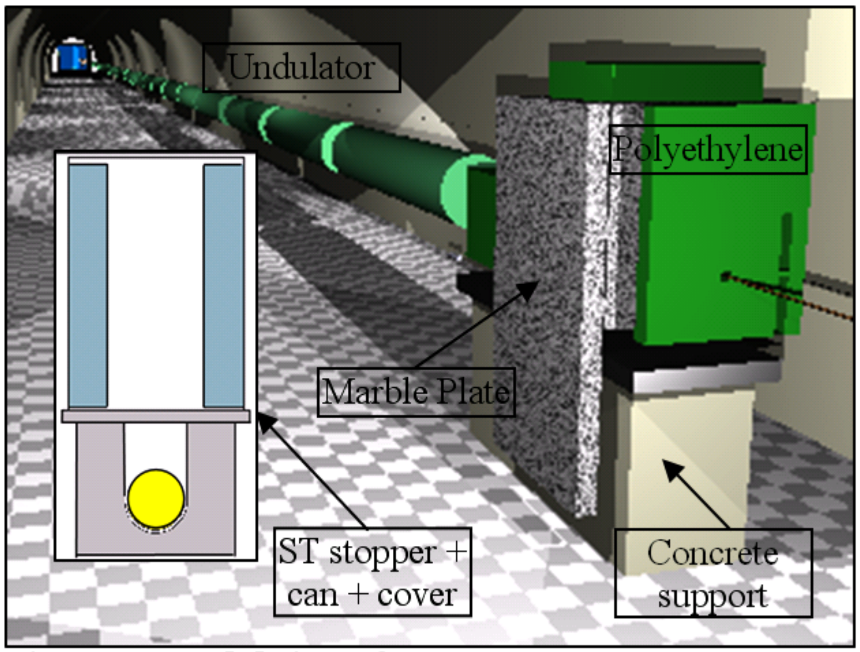
Induced activity in Al cables

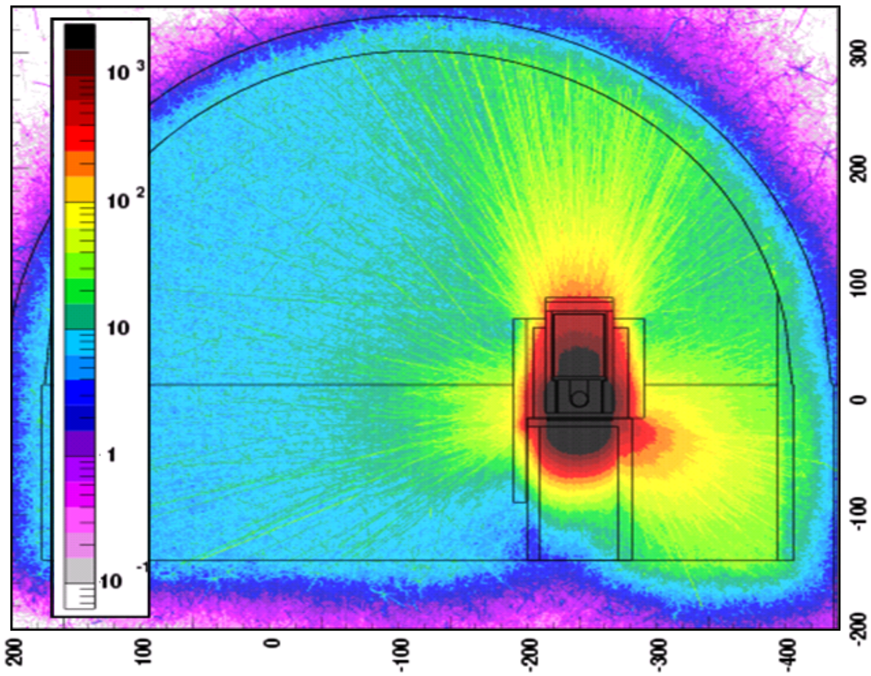


Radionuclide	$\mathcal{A}$ (Bq/g)
^{3}H	0.14
^{22}Na	0.42
^{54}Mn	0.03
^{55}Fe	0.16

List of residual radionuclides in the cables as predicted by FLUKA.

Design of shielding for residual radiation

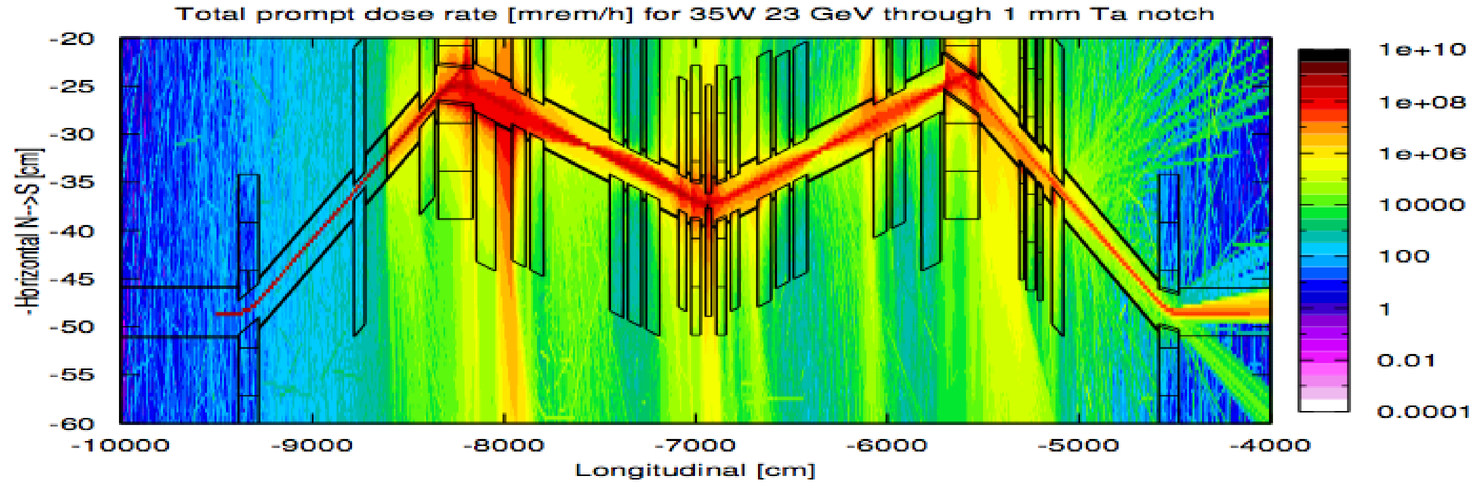


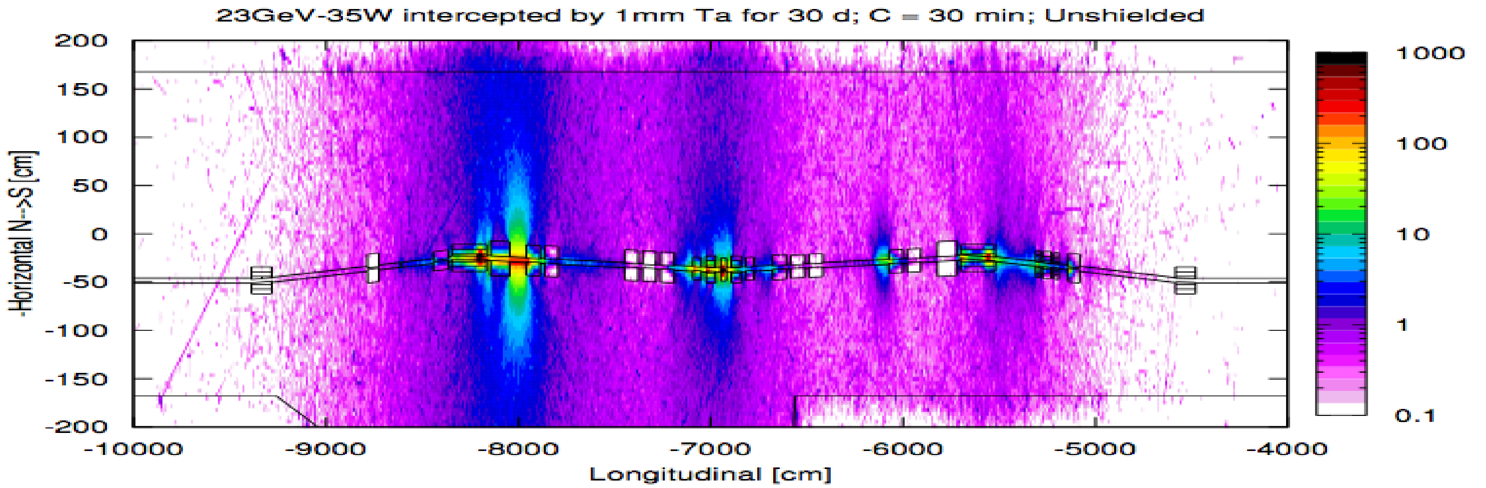


Calculation of residual dose rates for different cooling times. Surveys agree with calculations

Activation of chicanes: e.g. S20 in FACET

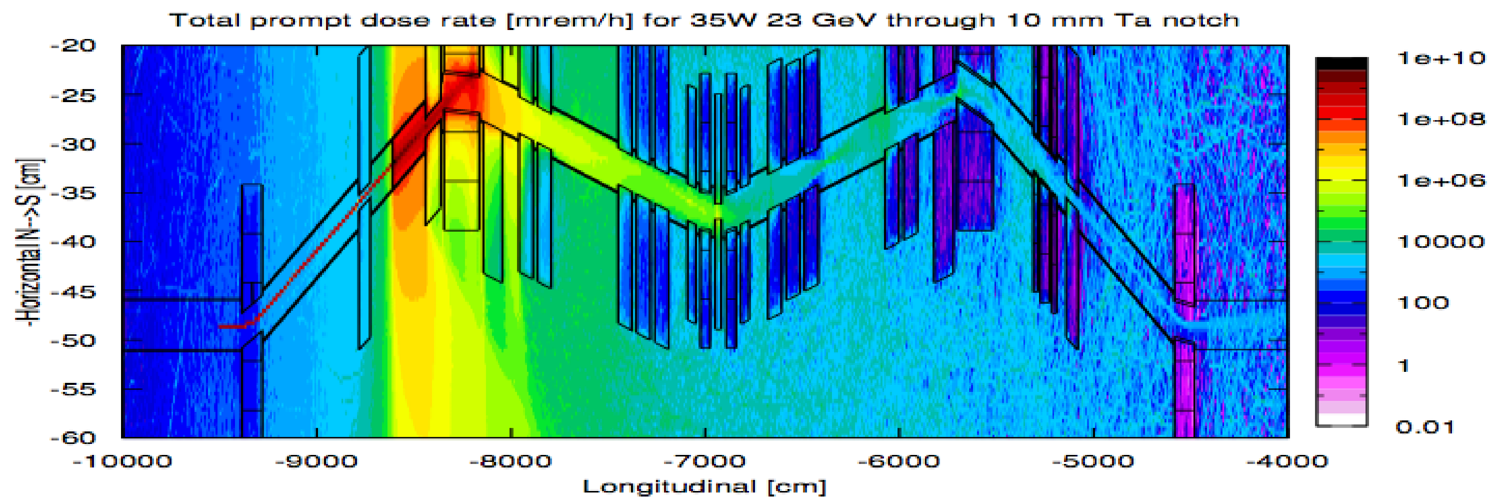
35 W through 1 mm Ta notch

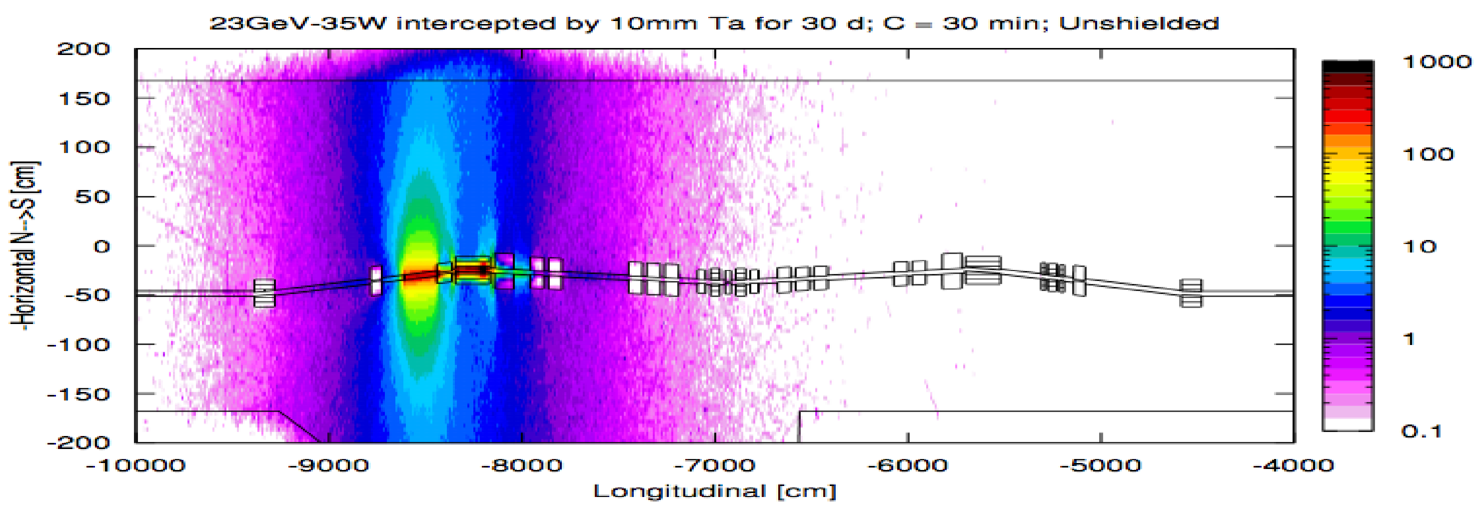




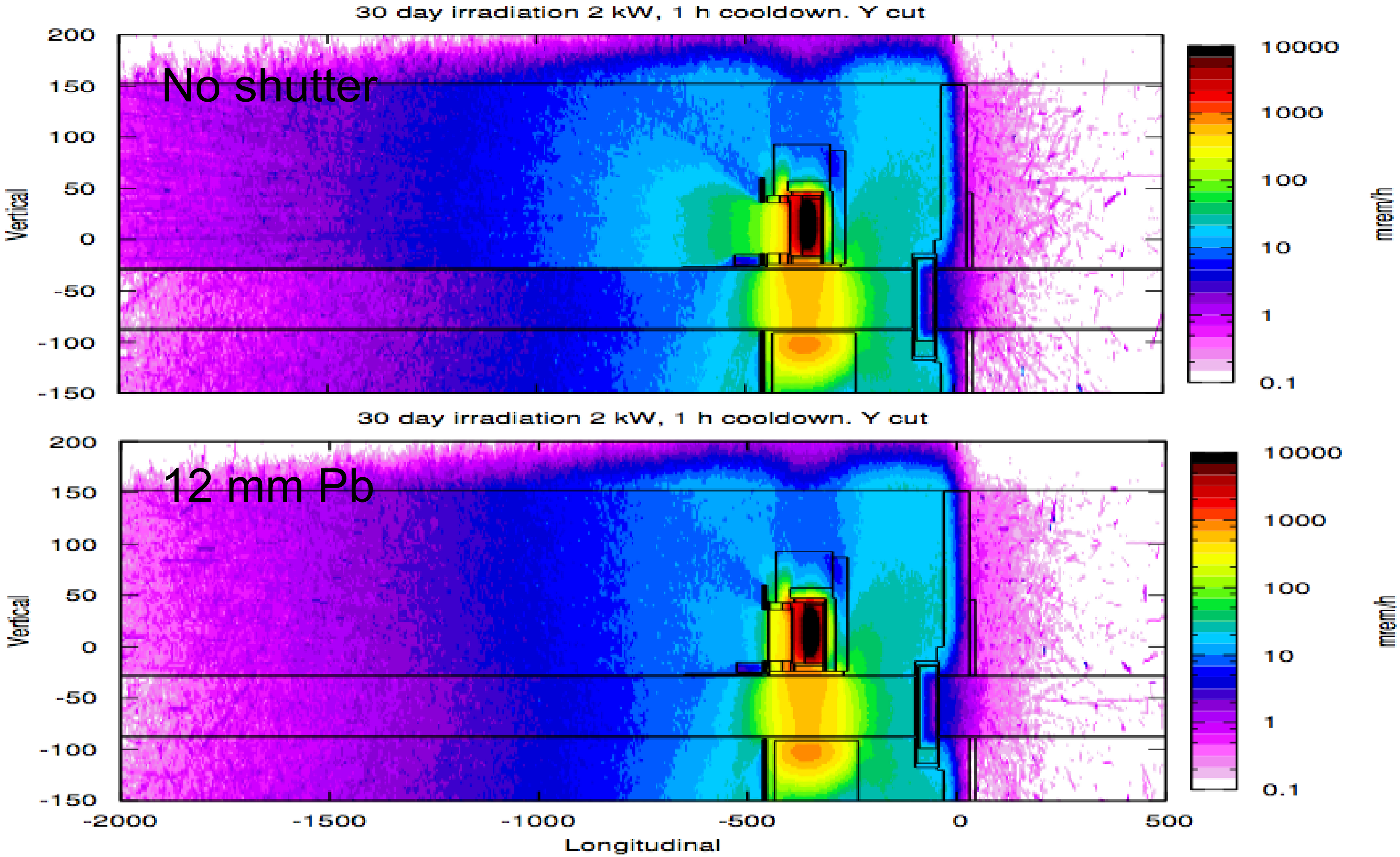
Activation of chicanes: e.g. S20 in FACET

35 W through 10 mm Ta notch





Residual dose with moving parts: FACET dump shutter

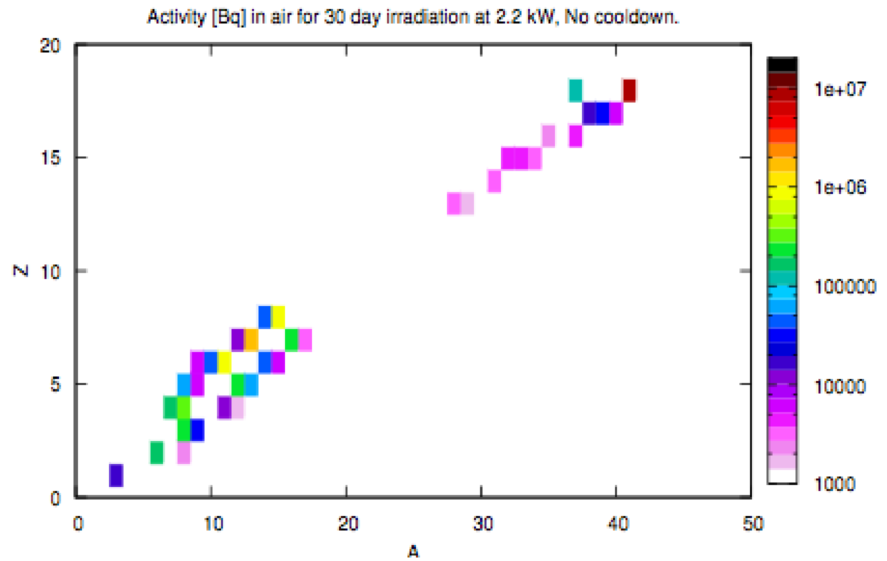


Studies of collected dose during interventions

Detailed evaluation of the dose collected during many different types of interventions of the LCLS main dump

CASE C: If the dump cavity requires access, the plug is removed (A12) and the dump may be even be transported away (B2). Thus LCW can be repaired at position 1 (see fig 1) with the dump cavity exposed with the dump IN (C1) or OUT (C2), or with the cavity plugged (C3). It might also be repaired from position 3 (C4). *Dose rates* and total doses are expressed in [mrem/h] and [mrem]		1 h	¾ h	6 h	6 h	6 h	6 h	1 h	8 ¾ h	8 h	6 h	
				REPAIR LCW					TOTALS			
				Worker at position 1								
				PLUG IS OUT								
		Remove plug and dump (if needed)	Move dump away from pit and back into pit area	DUMP is IN	DUMP is AWAY	PLUG in (DUMP in)	Worker above dump pit plate	Re-installation of plug (and dump if out)	$A_{12}\cdot t_{a12}$ + $C_1\cdot t_{c1}$ + $D_{12}\cdot t_{d12}$	$A_{12}\cdot t_{a12}$ + $B_2\cdot t_{b2}$ + $C_2\cdot t_{c2}$ + $D_{12}\cdot t_{d12}$	$C_3\cdot t_{c3}$	$C_3\cdot t_{c4}$
Cooling time	**Shielding [mm](Pb)**	**A12**	**B2**	**C1**	**C2**	**C3**	**C4**	**D12**				
	None		*60*							1025		
8 hours	**5**	*70*	*34*	*160*	*140*	*25*	*2*	*<70*	1100[4)]	1006	150	12
	10		*19*							994		
	None		*40*							386		
1 day	**5**	*28*	*22*	*55*	*50*	*12*	*0.5*	*28*	386	373	72	3
	10		13							366		

Air activation, e.g. FACET studies



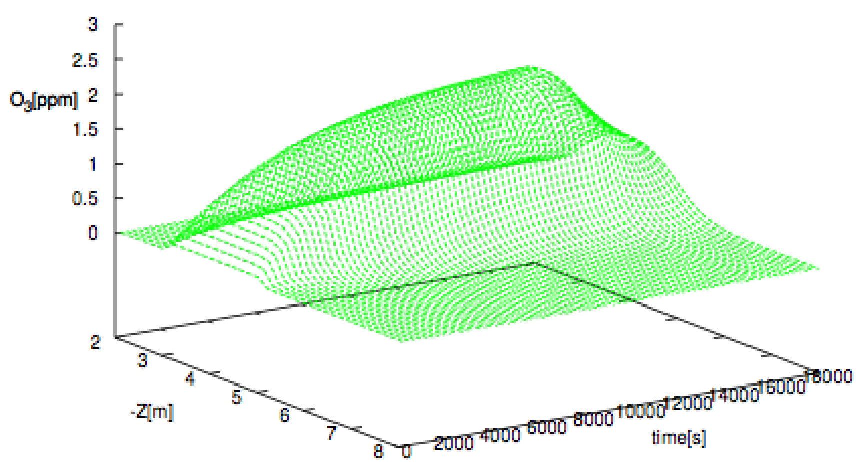
Simulations of air activation for several proposed beam-through-air designs, irradiation cycles and cool-down times. FLAIR can resulting plot isotope chart

$T_i = 30$ d Isotope	$T_c = 0$ half-life	Activity [Bq]	$T_i = 30$ d Isotope	$T_c = 1$ h half-life	Activity [Bq]
^{41}Ar	1.83h	$8.3 \cdot 10^6$	^{41}Ar	1.83h	$5.7 \cdot 10^6$
^{13}N	10m	$1.6 \cdot 10^6$	^{7}Be	53.3d	$1.7 \cdot 10^5$
^{15}O	124s	$7.8 \cdot 10^5$	^{37}Ar	35d	$1.1 \cdot 10^5$
^{11}C	20.3m	$7.7 \cdot 10^5$	^{11}C	20.3m	$1.0 \cdot 10^5$
^{8}Be	$6.7 \cdot 10^{17}$s	$3.1 \cdot 10^5$	^{14}C	5730y	$3.8 \cdot 10^4$
^{12}B	0.02s	$2.6 \cdot 10^5$	^{13}N	10m	$2.4 \cdot 10^4$
^{8}Li	0.855s	$2.4 \cdot 10^5$	^{3}H	12.26y	$1.5 \cdot 10^4$
^{16}N	7.2s	$2.2 \cdot 10^5$	^{39}Cl	55.5m	$1.5 \cdot 10^4$

Table 2: Activity [Bq] of top 8 radioisotopes in air near FACET dump after 30 day of irradiation (2.2 kW, 23 GeV e^-) and either no cool-down or 1 hour cool-down.

Ozone concentration, e.g. FACET studies

$$\frac{\Delta n_i(O_3)}{\Delta t} = \left(D \cdot \left(\frac{\frac{\Delta_{i-1,i} n(O_3)}{\Delta z} - \frac{\Delta_{i,i+1} n(O_3)}{\Delta z}}{\Delta z} \right) + \sigma \right) \cdot exp\left(\frac{-ln(2) \cdot \Delta t}{\bar{T}} \right)$$



(a) **4 h irradiation**

High concentrations of Ozone can be hazardous.

It depends on the generation (energy deposition in air), computed by FLUKA, the recombination (proportional to concentration) and diffusion, computed with finite-difference code 'RIBO-diffuse'

Other activities

- Design of mazes
- Design of local shielding in test facilities and evaluation of new penetrations, e.g. ASTA
- Shielding in photon beam lines (SSRL, LCLS)
- Calculation of leakage and spectra in small x-ray machines
- Design of zero-degree shielding in FEL facilities like LCLS and LCLS-II
- Calculation of cooling water activation

Upcoming / future MC development activities

- LCLS-II:
  - Cross-check between MC codes (i.e. FLUKA-MARS, FLUKA-GEANT4) for critical radiation calculations
  - Development of ray-tracing capabilities for FLUKA
  - Studies of dose rate for grazing losses versus full deposited beams → New BTH walls
- Studies of prompt dose as a function of number of stoppers and relative distances
- Code development, scripting:
  - Data translation between MC codes to be able to share post-processing tools
  - Synchrotron radiation production through FLUKA
- ES-A: Experimental measurements / benchmarking
  - Further activation and radiation damage experiments
  - HE neutron spectroscopy
  - Photomuon production, angular spectra

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