Dealing with MegaWatt Beams

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OUTLINE

- High-Power Accelerators and Challenges
- Toughest Systems: Targets, Absorbers, Collimators
- Modeling and Benchmarking
- Precision and Neutrino Experiments
- DPA Studies for MegaWatt Projects
- Summary

HIGH-POWER ACCELERATORS AND COLLIDERS

- **High-power accelerators**

  Operating: ISIS, PSI, J-PARC and SNS (0.2-1 MW, upgrade to 1-3 MW)

  Construction: CSNS (0.1 -> 0.2 MW)

  Design: FAIR and heavy-ion FRIB (<0.4 MW up to U)

  Plans: SPL, PS2 (CERN) and Project-X (FNAL) up to 4 MW

  Subcritical ADS (EA for power production, etc.): 10 MW

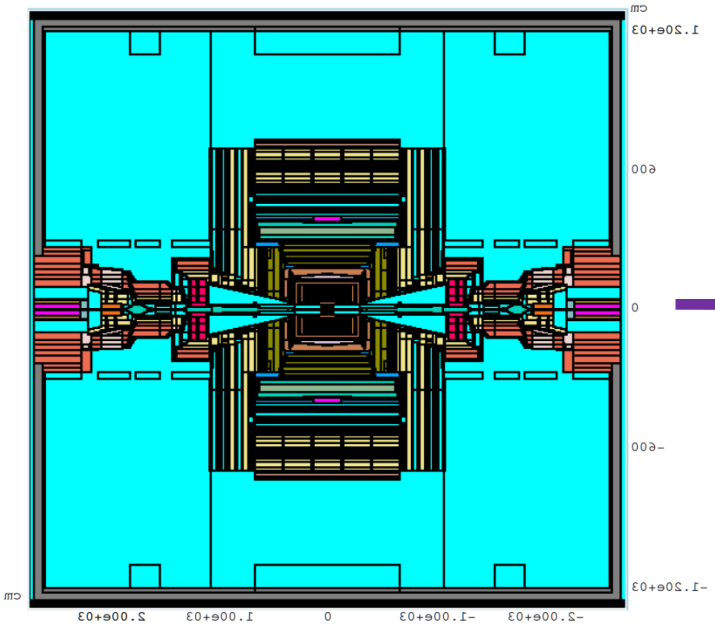
- **High-energy colliders**

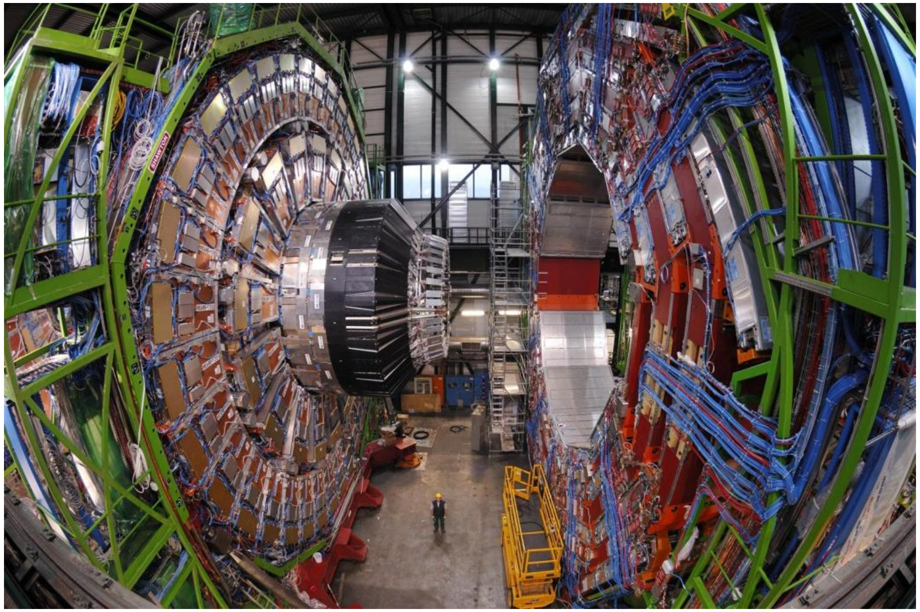
  Operating: Tevatron (~ 2 MJ) and LHC (up to 350 MJ)

  Plans: ILC and CLIC (up to 20 MW), muon collider (4 MW)

CHALLENGES

The next generation of accelerators and ever expanding needs of existing accelerators demand new developments to Monte-Carlo codes. Challenges arise from extremely high beam energies and/or beam power, increasing complexity of accelerators and experimental setups, as well as design, engineering and performance constraints.



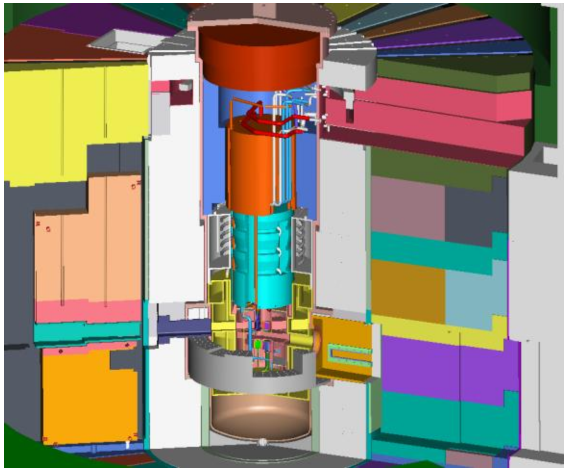


HIGH-POWER TARGETS

Principal issues include:

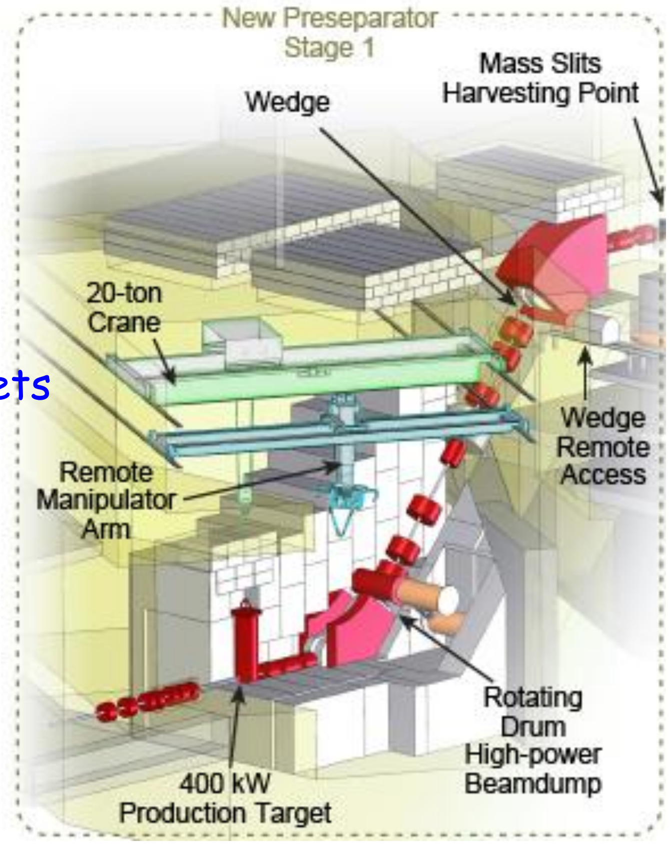
production and collection of maximum numbers of particles of interest; target and beam window operational survival and lifetime (compatibility, fatigue, stress limits, erosion, remote handling and radiation damage); protection of focusing systems; heat loads, radiation damage and activation of components; thick shielding and spent beam handling; prompt radiation and ground-water activation.

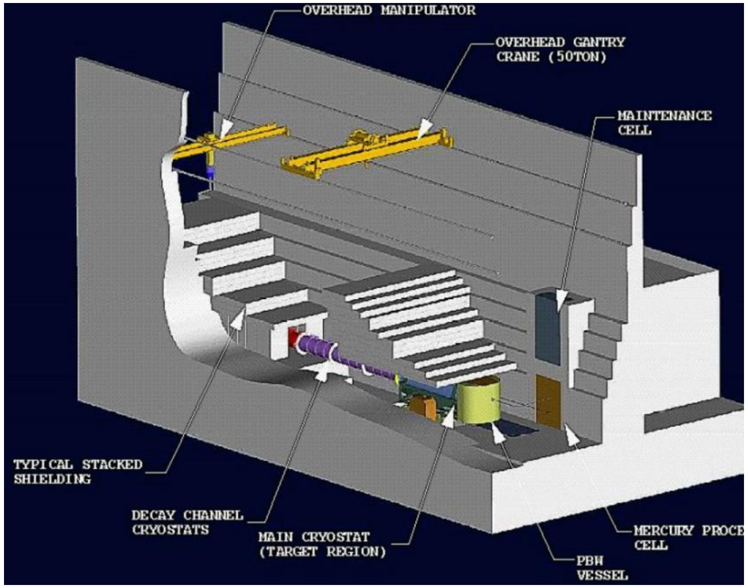
SNS, FRIB and υ-Factory High-Power Target Systems



1-GeV proton beam (1 MW)
on liquid mercury in SS vessel

0.2-GeV/u U beam (0.4 MW)
on sliced C and liquid Li targets





8-GeV proton beam (4 MW)
on open liquid mercury jet in
20-T solenoid

Peak Beam Power and Power Density at FAIR

Up to **200 times** the beam power and **100 times** higher energy density in the target will be available at FAIR

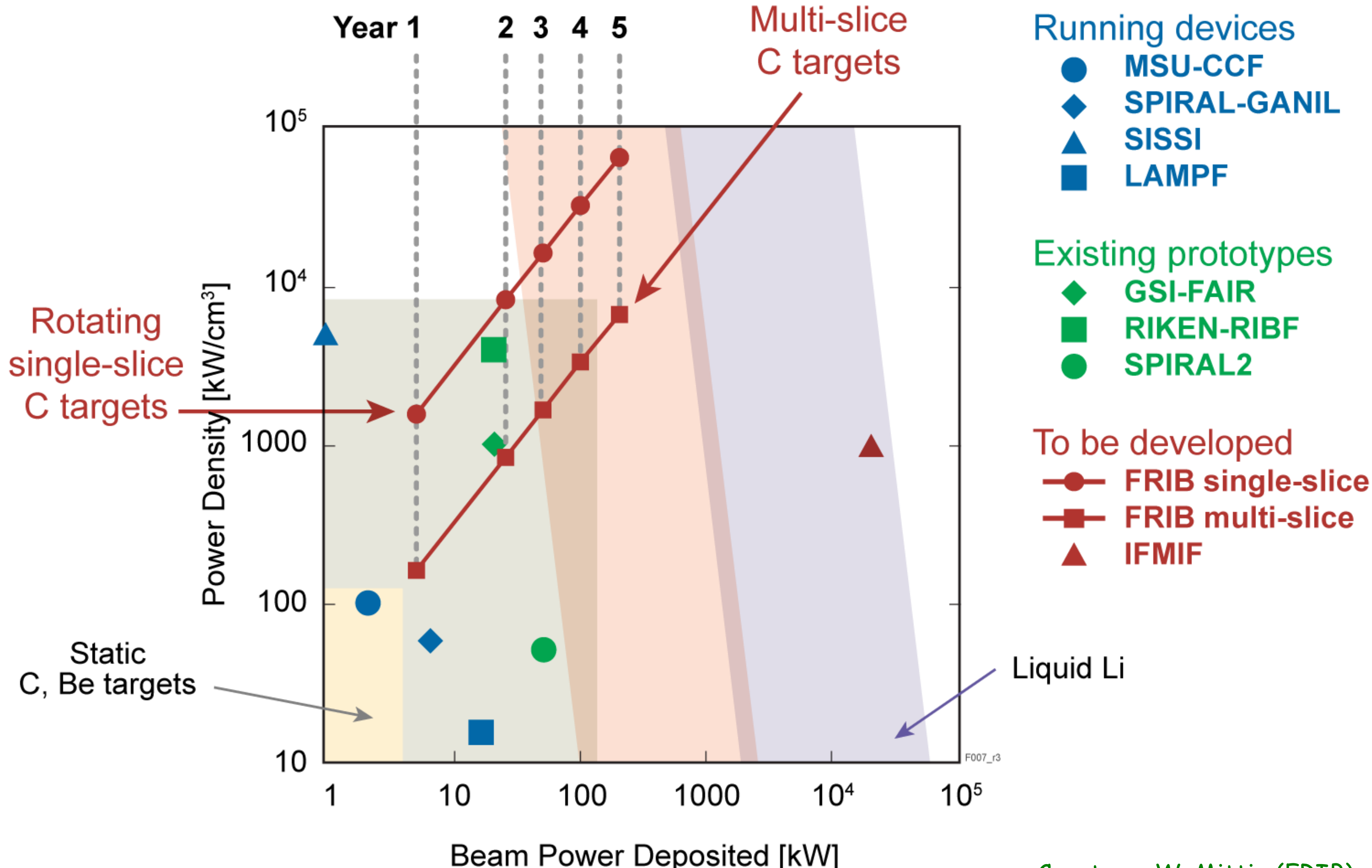
Ion beam U^{28+}	SIS-18	SIS-100	
Energy/ion	400MeV/u	0.4-27 GeV/u	
Number of ions	4.10^{9} ions	5.10^{11} ions	X100
Full energy	0.06 kJ	6 kJ	
Beam duration	130 ns	50 ns	
Beam power	0.5 GW	0.1TW	X200

Lead Target

Specific energy	1 kJ/g	100 kJ/g	X100
Specific power	5 GW/g	1 TW/g	X200
WDM temperature	~ 1 eV	10-20 eV	

only available at FAIR

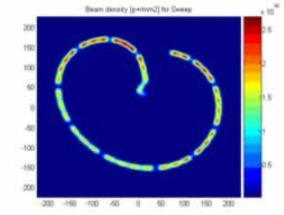
HIGH-POWER TARGET TECHNOLOGY



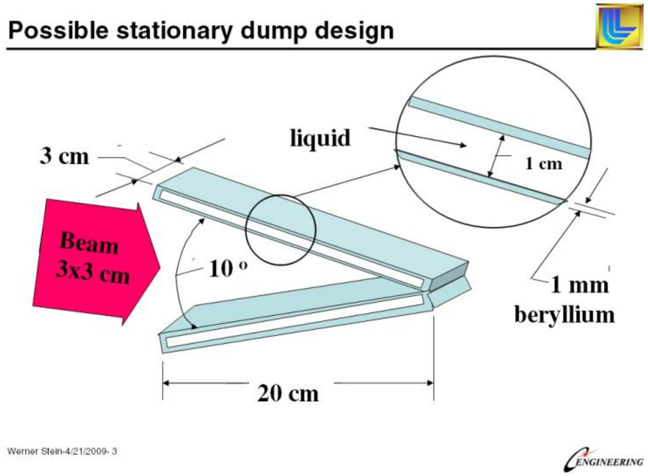
Courtesy: W. Mittig (FRIB)

HIGH-POWER BEAM ABSORBER TECHNOLOGIES

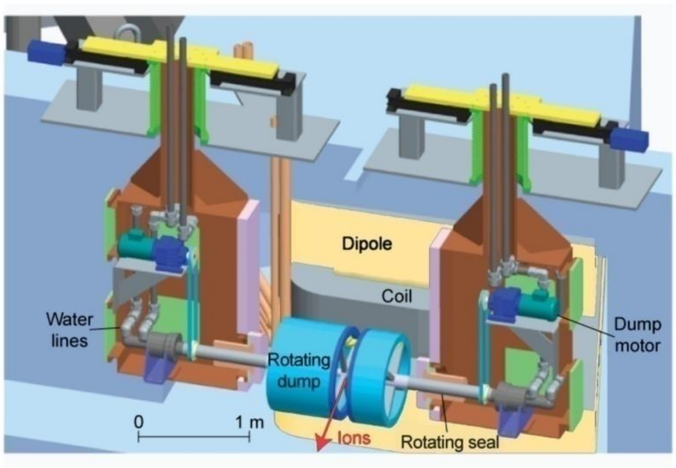
1. **Laminated graphite core** in cooled aluminum shell: >20 year operational experience at the Tevatron. Instantaneous ΔT ~1000 °C per pulse. Absorber cores are contained in steel shielding surrounded by concrete. Similar design at LHC with beam swept as



2. Al, Be or Ni wall **stationary liquid-cooled dump**. Lifetime due to rad damage ~3 months at 0.4 MW (FRIB)



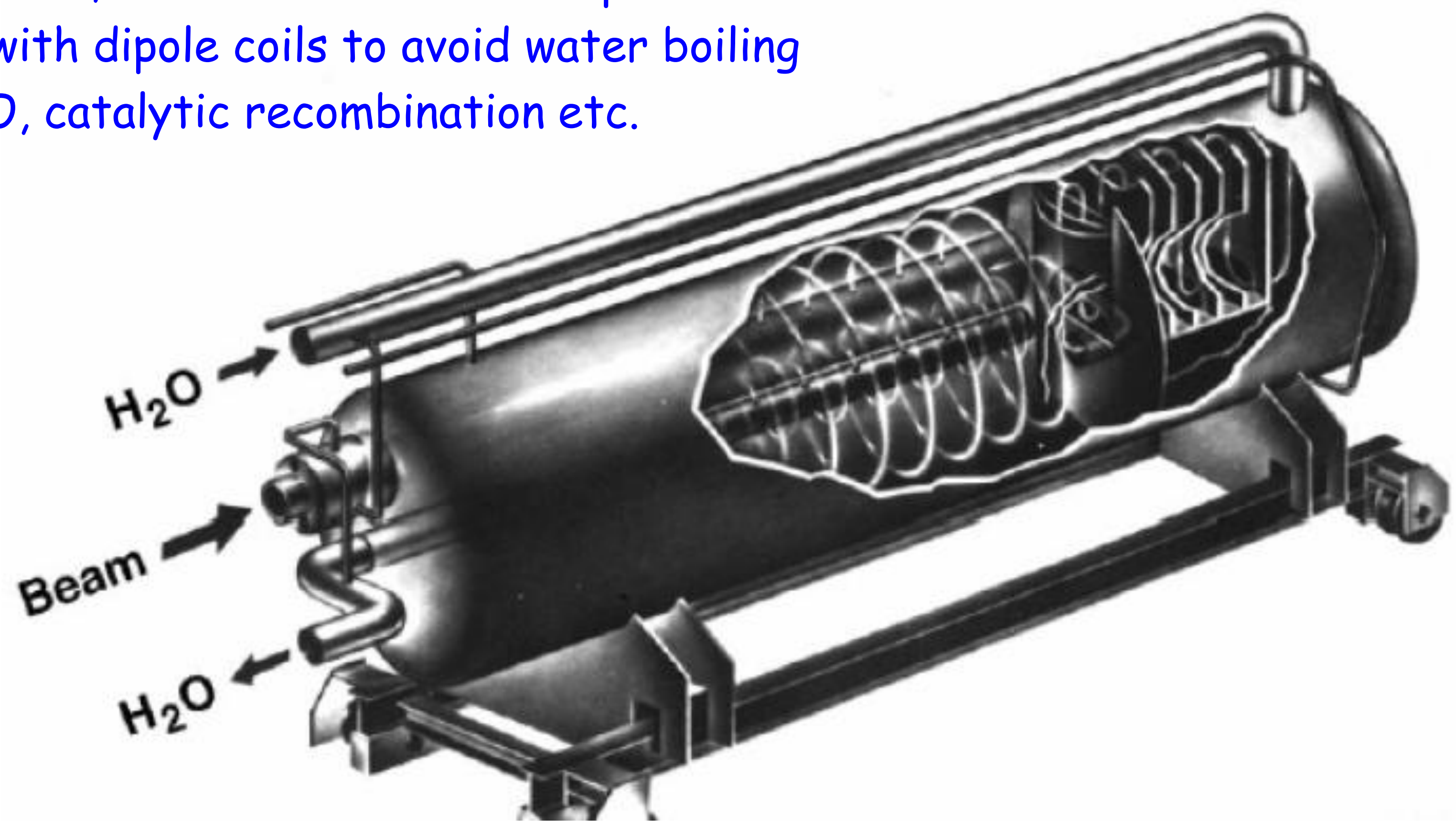
3. **Rotating water-filled Al**. Lifetime of 5 yrs at 1 DPA/y at 0.4 MW at FRIB



4. Water Vortex Beam Absorber

250-GeV 18-MW electron beam (ILC)

Window, 1mm thin, ~30cm diameter hemisphere
Raster beam with dipole coils to avoid water boiling
Deal with H, O, catalytic recombination etc.

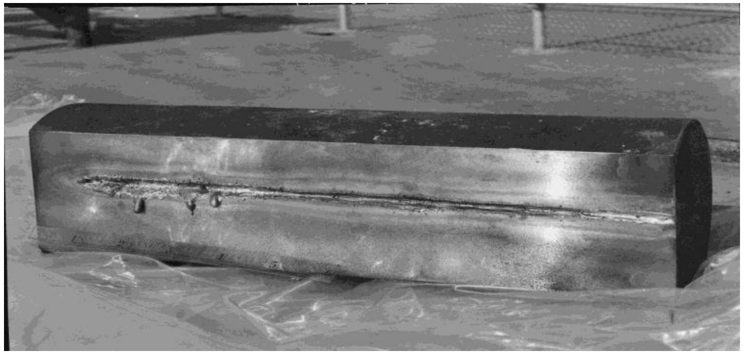


BEAM LOSSES AND COLLIMATION

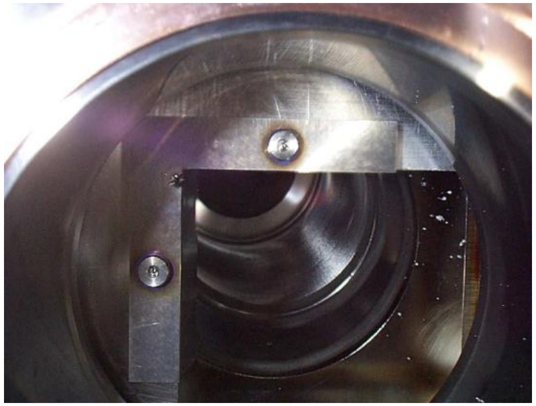
Only with a very efficient beam **collimation system** can one reduce uncontrolled beam losses in the machine to an allowable level, thus protect personnel and components, maintain operational reliability over the life of the machine, provide acceptable hands-on maintenance conditions, and reduce the impact of radiation on environment, both at normal operation and accidental conditions.

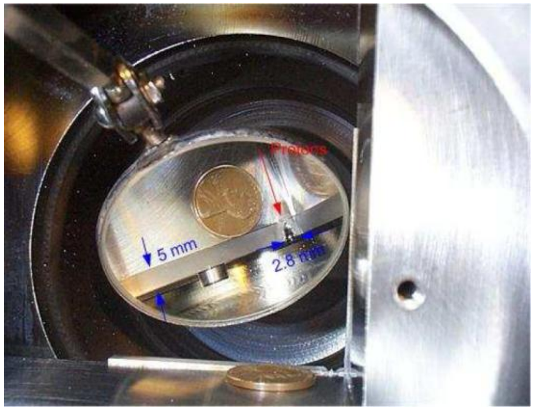
COLLIMATOR AS A LAST LINE OF DEFENSE

All collimators must withstand a predefined fraction of the beam hitting their jaws and - at normal operation - survive for a time long enough to avoid very costly replacements.



0.5-MW, 2-mm diam e-beam, grazing on 60-cm Cu; it took 1.5 s to melt in





2-MJ 1-TeV p-beam drilled a hole in W primary collimator, created a 1-ft groove in SS secondary one, and quenched 2/3 of the ring, all in a few ms. Abort system fired in 10 ms.

COLLIMATION AT LHC: 0.5 MW to 5 TW

Collimators are the LHC defense against unavoidable losses:

Irregular fast losses and failures: Passive protection.

Slow losses: Cleaning and absorption of losses in super-conducting environment.

Radiation: Managed by collimators.

Particle physics background: Minimized.

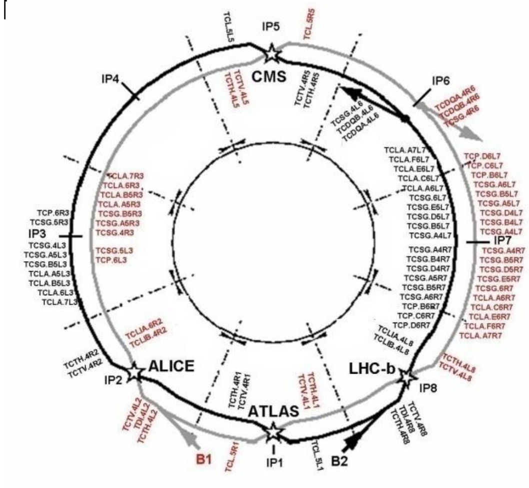
Specified 7 TeV peak beam losses (maximum allowed loss):

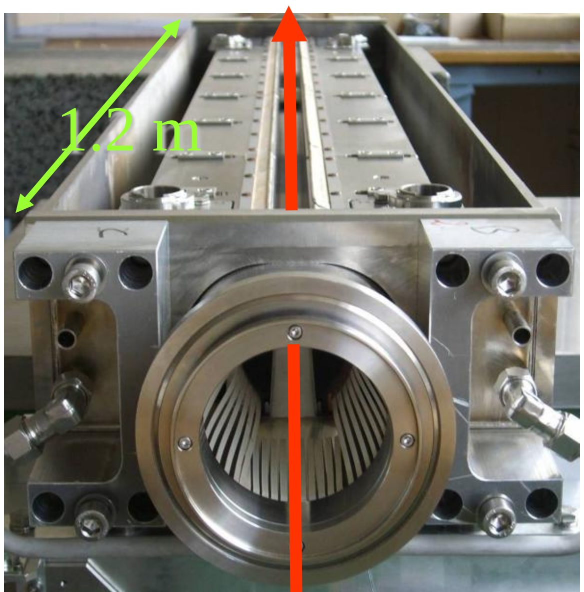
Slow: 0.1% of beam per s for 10 s **0.5 MW**

Transient: 5 10^{-5} of beam in ~10 turns (~1 ms) **20 MW**

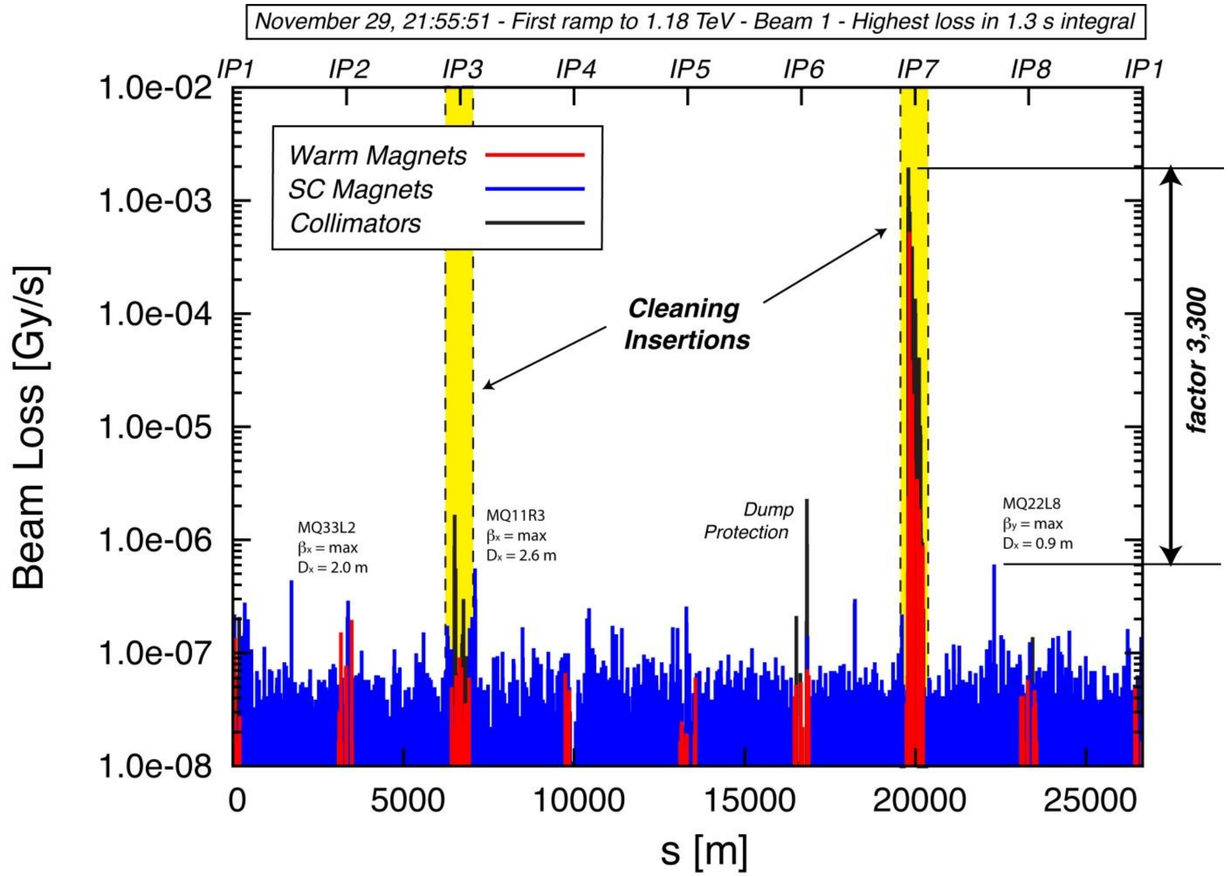
Accidental: up to 1 MJ in 200 ns into 0.2 mm^2 **5 TW**

LHC COLLIMATION GOAL: EFFICIENCY ε > 99.9%





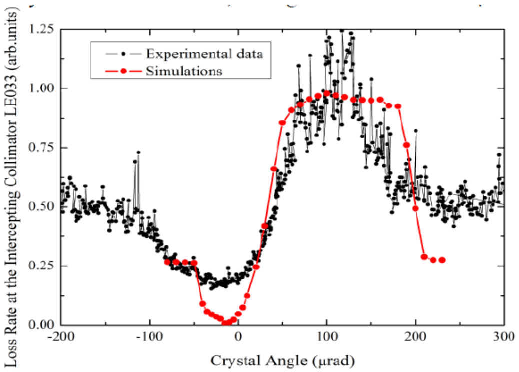
360 MJ proton beam



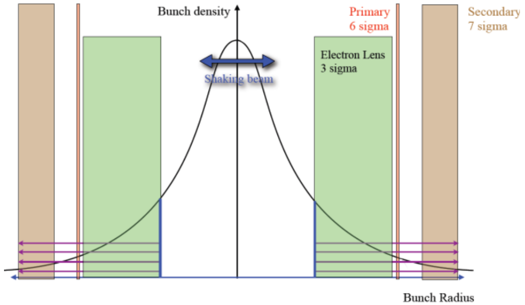
Tevatron experience: ε ~ 99.9%

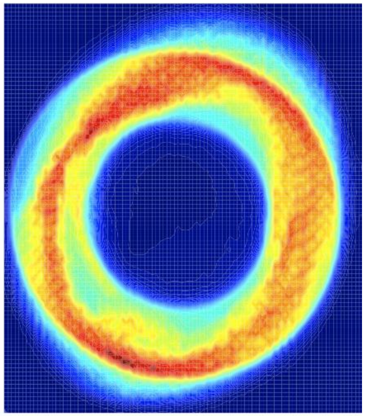
NOVEL COLLIMATION TECHNIQUES

1. Crystal collimation: coherent deflection via channeling and multiple volume reflection of halo particles deep into a secondary collimator. Encouraging results at Tevatron and SPS

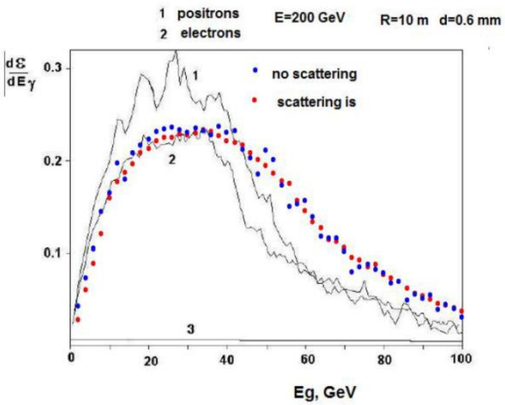


2. Hollow electron beam scraper

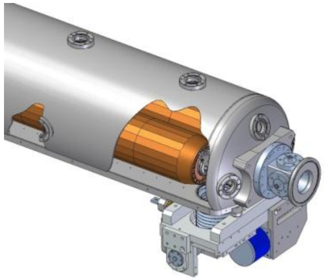




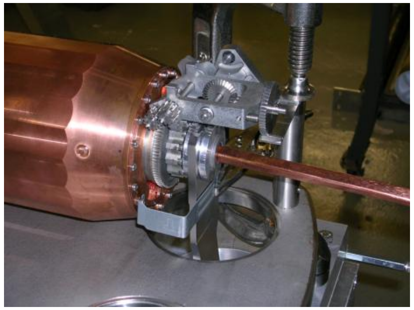
3. Volume reflection radiation

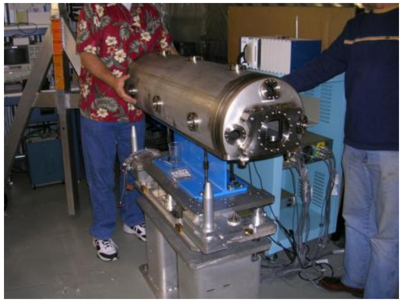


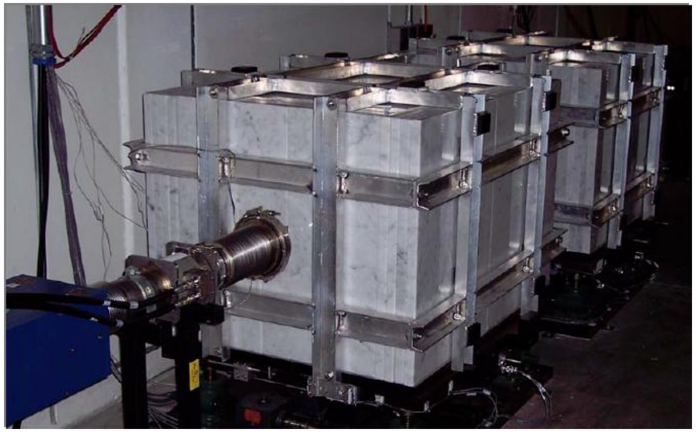
LHC Phase-II and Main Injector Collimators



LHC Phase II Rotatable Collimators







<u>Marble shells</u> of a brand-new collimation system at Fermilab MI

Poly mask

CHALLENGES → REQUIREMENTS

All these put unprecedented requirements on the accuracy of particle production predictions, the capability and reliability of the codes used.

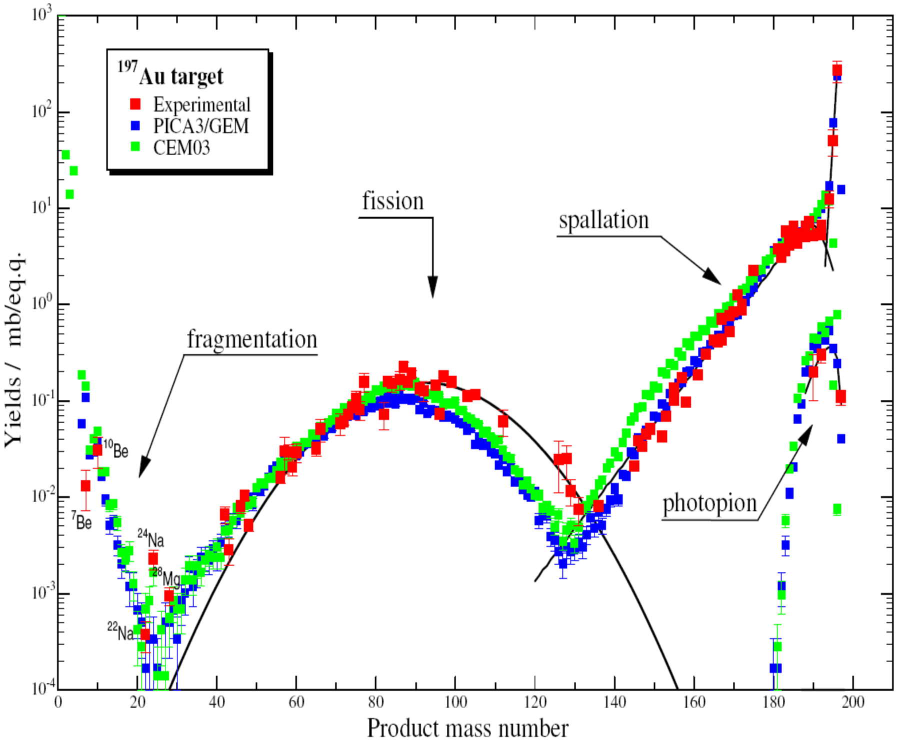
MODELING

Detailed and accurate (to a % level in many cases) modeling of all particle interactions with 3-D system components (kilometers of lattice) in energy region spanning up to 15 decades as a basis of accelerator, detector and shielding designs and their performance evaluation, for both short-term and long term effects.

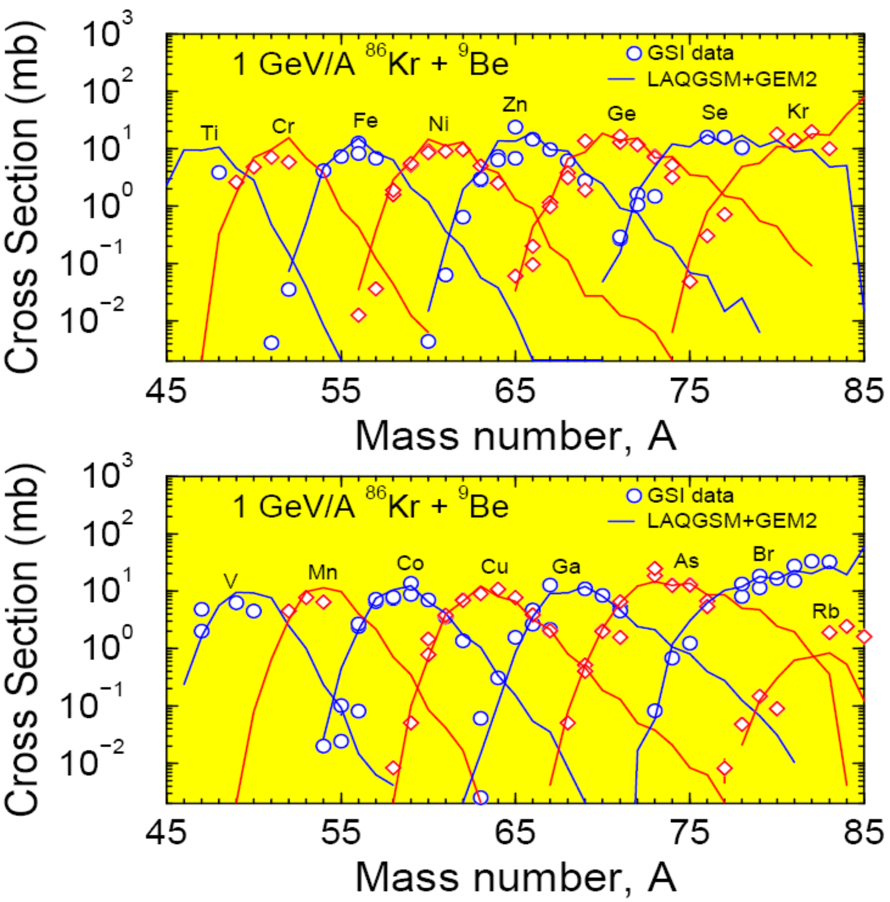
Benchmarking is absolutely crucial!

Benchmarking: NUCLIDE PRODUCTION

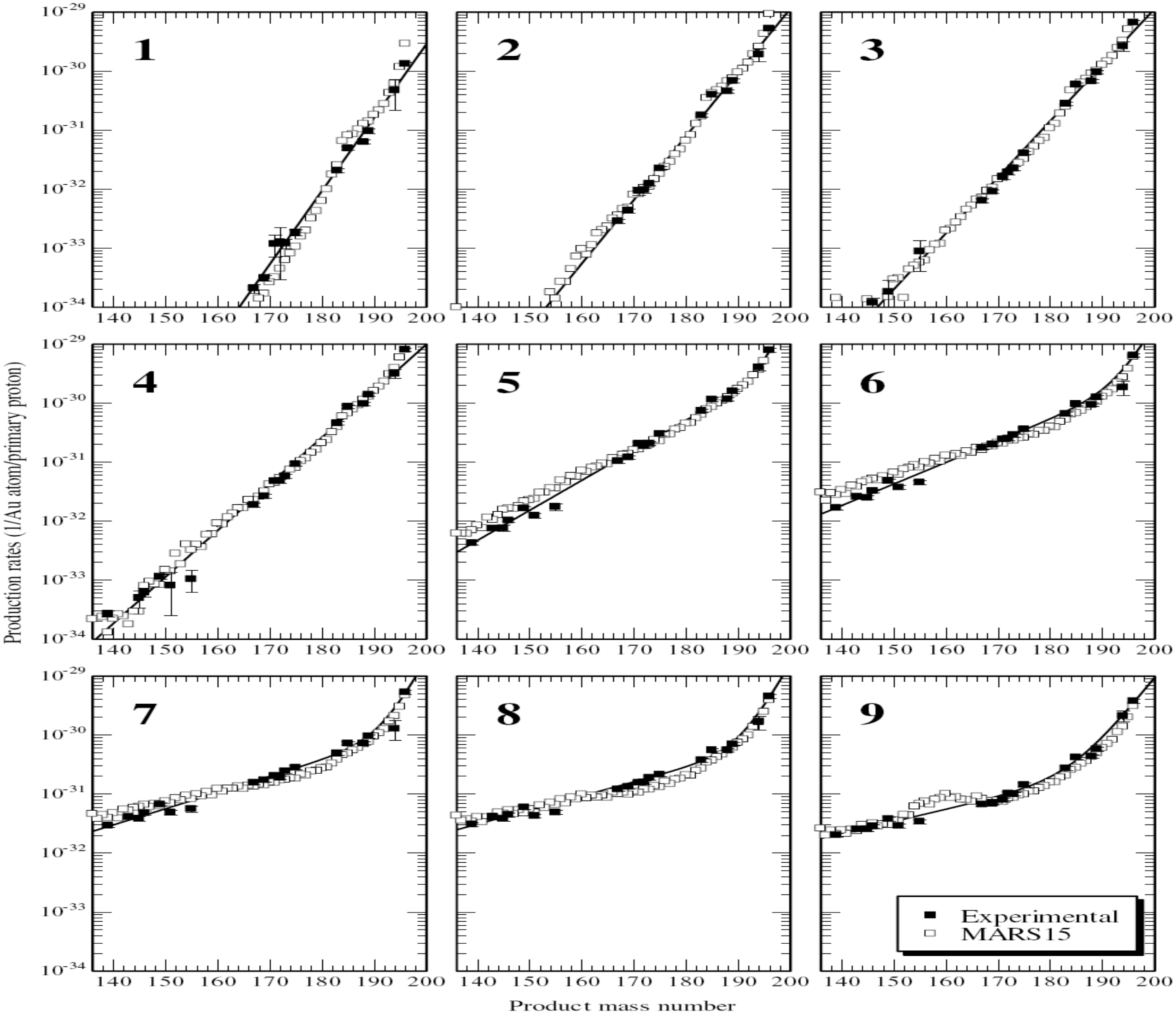
Bremsstrahlung (Emax=1 GeV) on gold

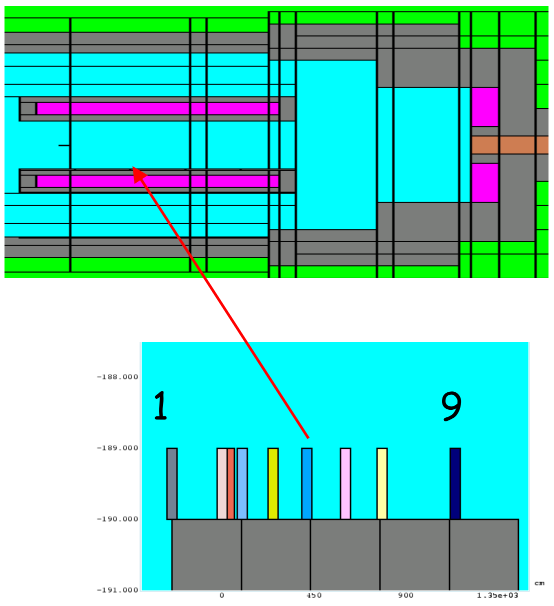


1 GeV/A ^{86}Kr on ^{9}Be



BENCHMARKING: 12-GeV K2K TARGET STATION





Nine gold foil samples over 12 meters

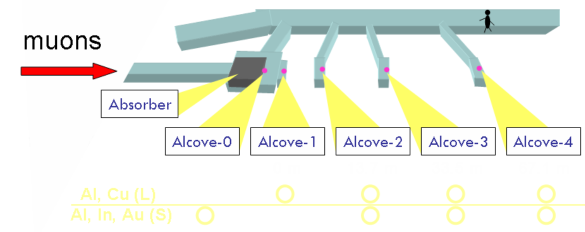
Courtesy: T. Suzuki and H. Matsumura

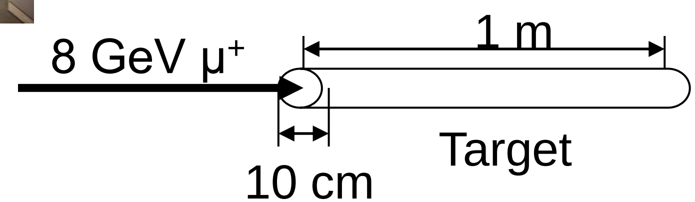
SHIELDING AND RADIATION EFFECT EXPERIMENT

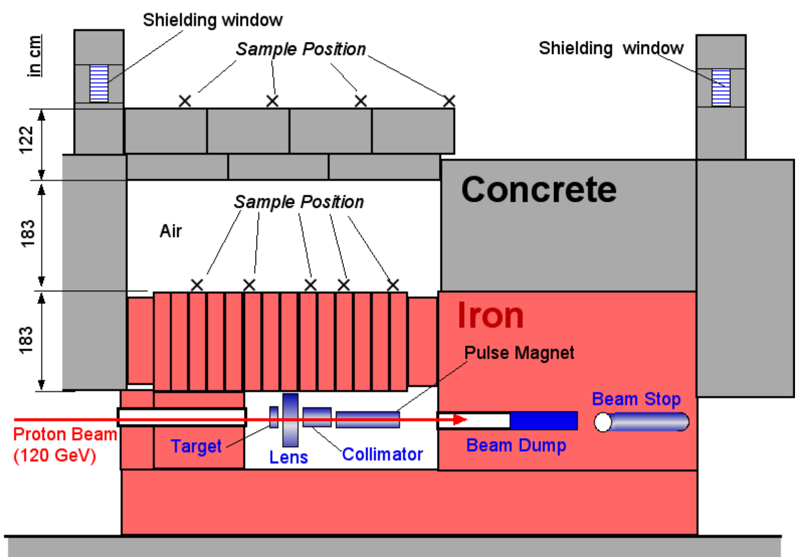
JASMIN Japan-FNAL Collaboration:
Shielding and Radiation Effect Experiments at FNAL
T-972 (2007-2009)
T-993 and T-994 (2009-2012)

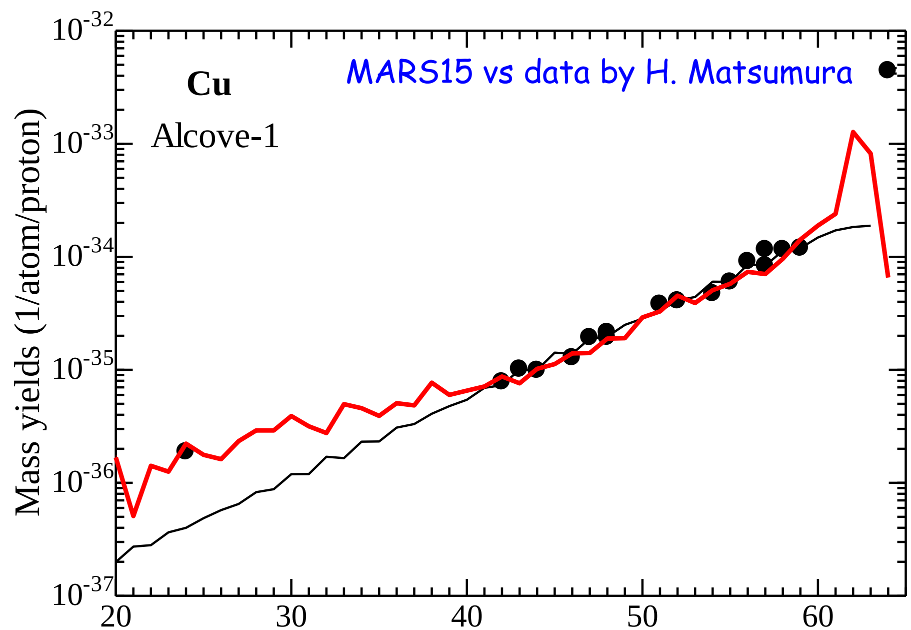
Shielding data and code benchmarking; targets, collimators and thick shields; radiation effects on instruments and materials

Example: Muon-induced nuclide production





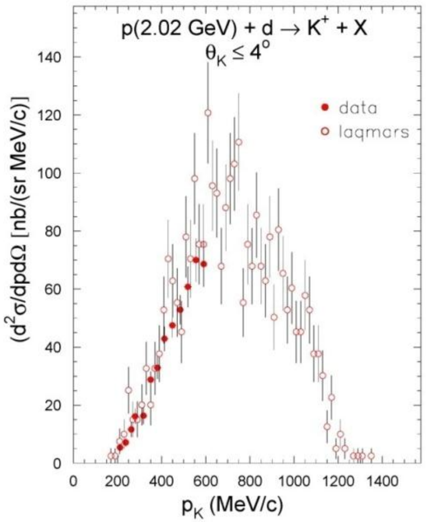


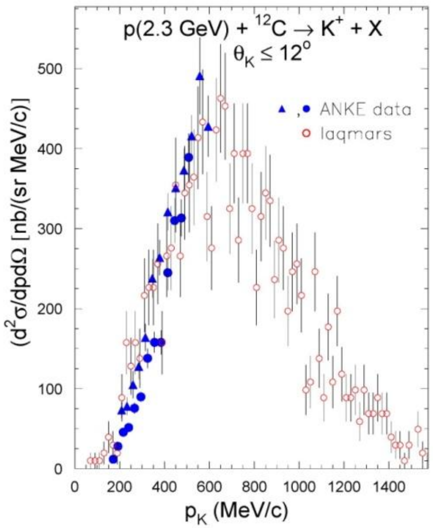


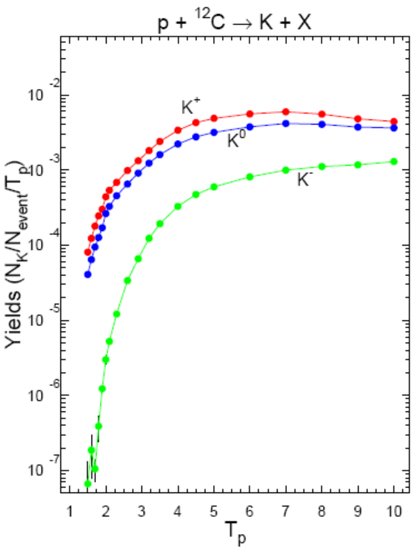
Experiments with High-Power Beams at FNAL

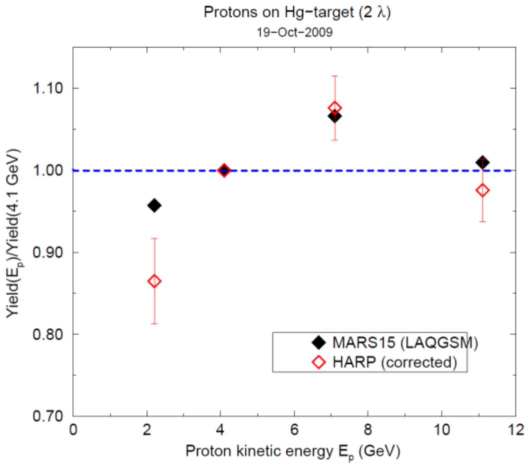
Proton beam energy: 2 to 8 GeV, beam power: 25 kW to 2 MW
Mu2e, New g-2, rare kaon decays, and 4-MW neutrino factory

- MARS/LAQGSM model developments for near-threshold kaon production, low-energy pions and pbars, deuterium targets
- Benchmarking
- Beam energy and beam power choice/justification



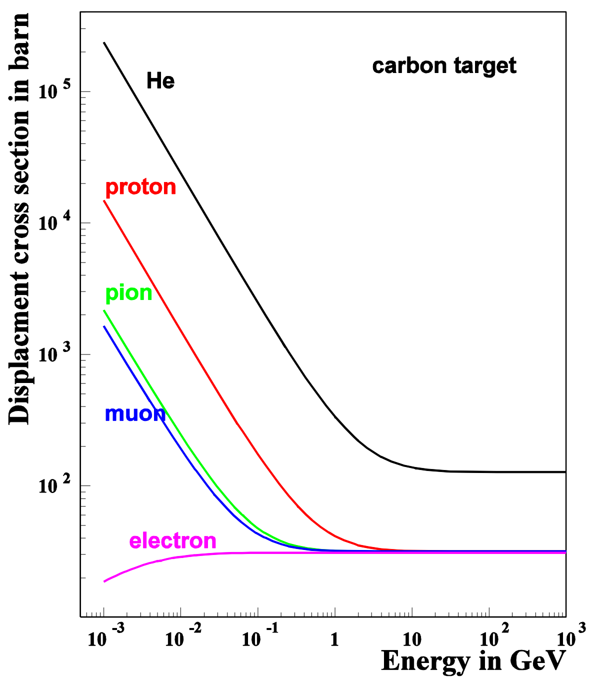


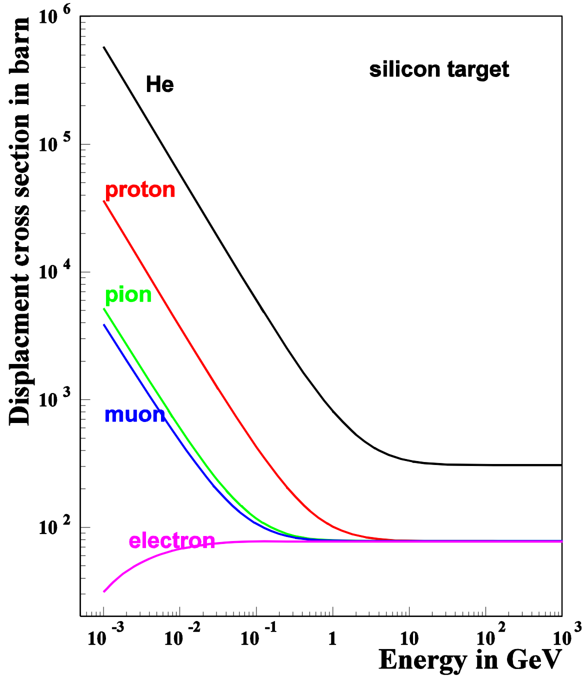




DPA Model in MARS15

Displacement cross section due to Coulomb scatternig





All products of elastic and inelastic nuclear interactions as well as Coulomb elastic scattering (NIEL) of transported charged particles (hadrons, electrons, muons and heavy ions) from 1 keV to 10 TeV contribute to DPA in MARS15 model.

DPA Calculation Comparisons

1-GeV p on 3-mm Fe, 1 cm^2 beam

Code	SRIM	PHITS	MCNPX	MARS15
DPA/pot	1.18e-22	2.96e-21	3.35e-21	8.73e-21

MARS15: Physics process (%)

Nucl. Inel.	Nucl. Elastic	EM elastic	L.E. neutron	$e^{\pm}$
75.5	16	2.75	5.5	0.25

0.32-GeV/u ^{238}U on 1-mm Be, 9 cm^2 beam

Code	SRIM	PHITS	MARS15
DPA/pot	2.97e-20	5.02e-22	2.13e-20

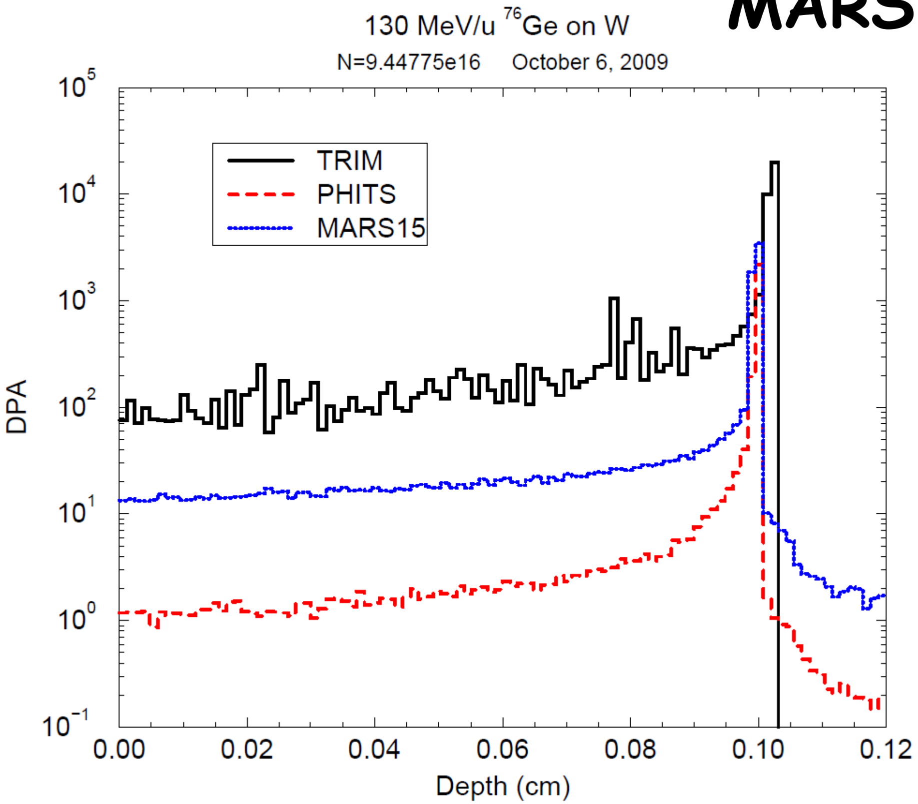
MARS15: Physics process (%)

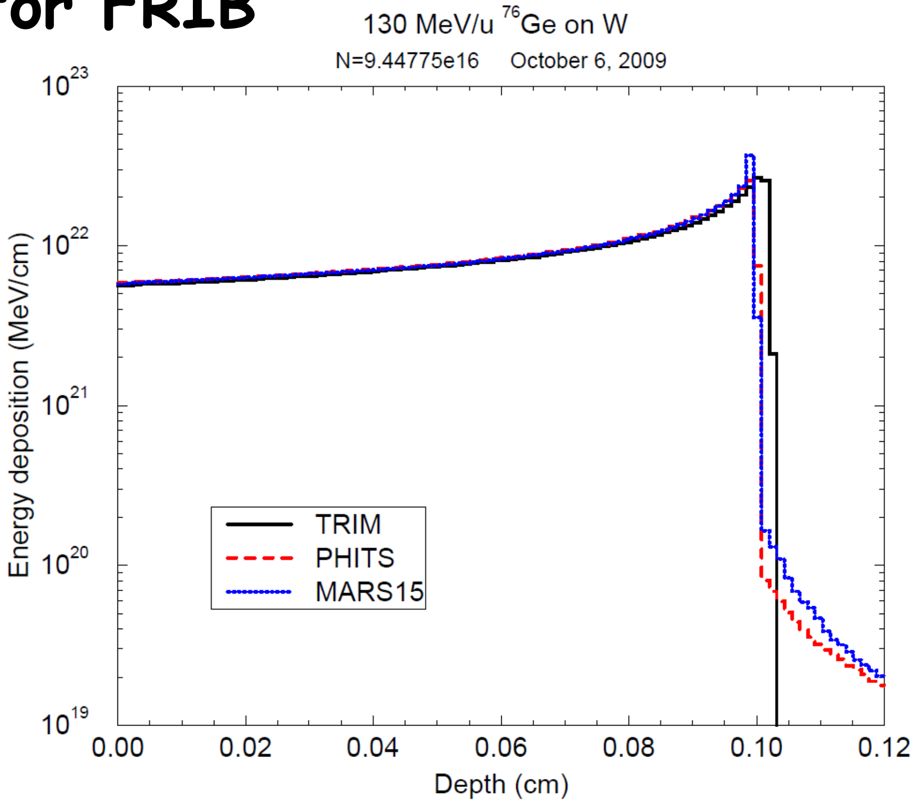
Nucl. Inel.	EM elastic	L.E. neutron	$e^{\pm}$
0.3	99.06	0.02	0.62

SRIM, PHITS and MCNPX results: Courtesy Susana Reyes

DPA & ED Comparison: 130 MeV/u ^{76}Ge on W

MARS for FRIB



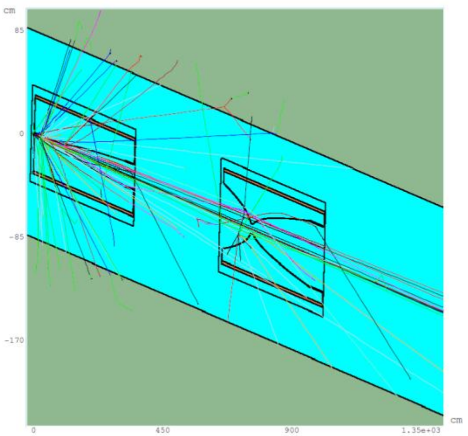


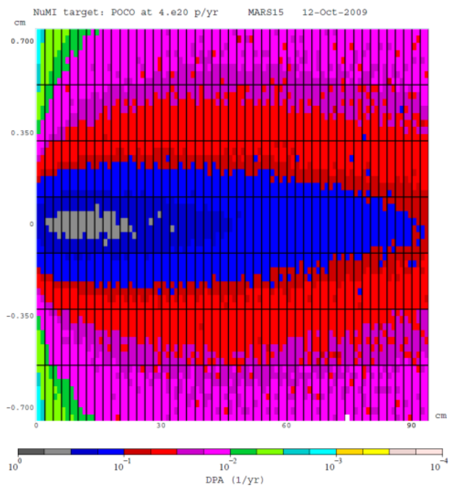
Pencil beam, uniform in R=0.03568 cm disc.
Target W_{nat}, cylinder with R=0.03568 cm, L=0.12 cm

TRIM and PHITS results: Courtesy Yosuke Iwamoto

Neutrino Experiments NOVA and LBNE at 0.7-2.3 MW

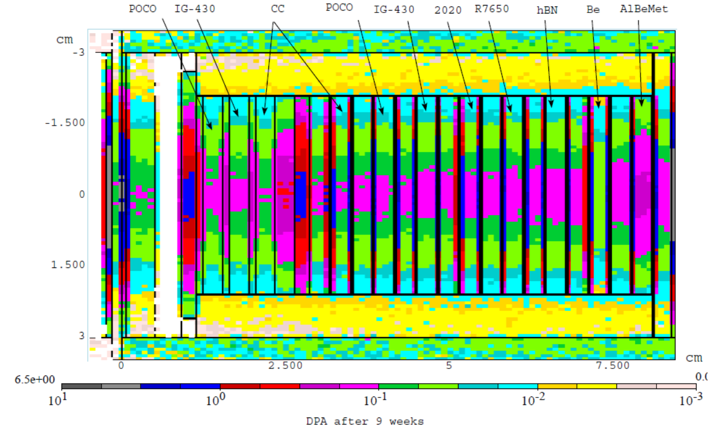
Measured threshold on carbon composites and graphite ~0.2 DPA.
Deterioration of 120-GeV NuMI target (~0.3 MW) at 0.5 DPA.
LBNE: 0.45 DPA/yr at 0.7 MW and 1.5 DPA/yr at 2.3 MW





Emulate for a set of candidate materials in dedicated measurements now underway at BLIP with ~180-MeV proton beam: 96mA, 9 weeks -> 0.2 DPA

As a bonus, possible benchmarking of hydrogen and helium production

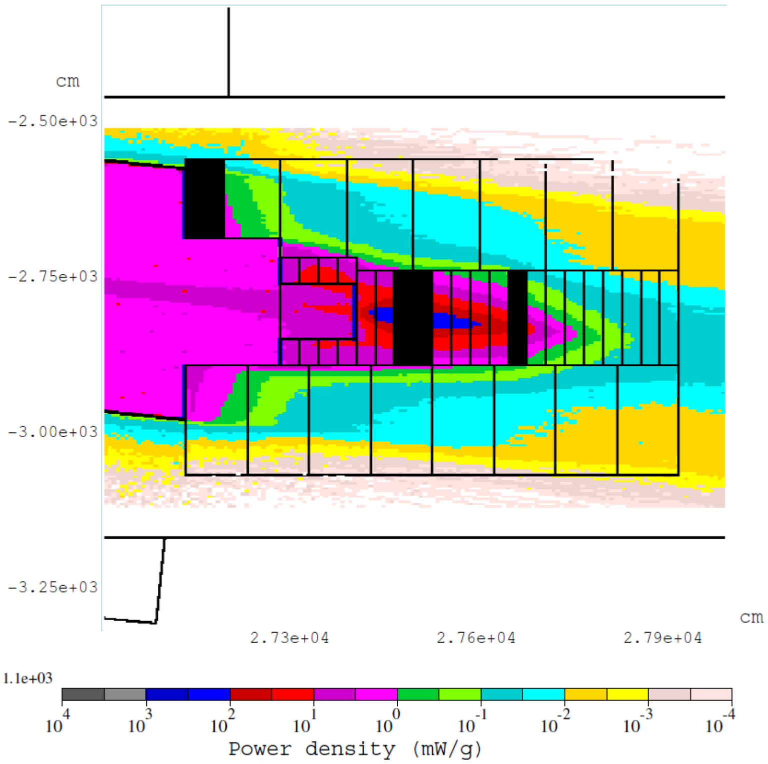


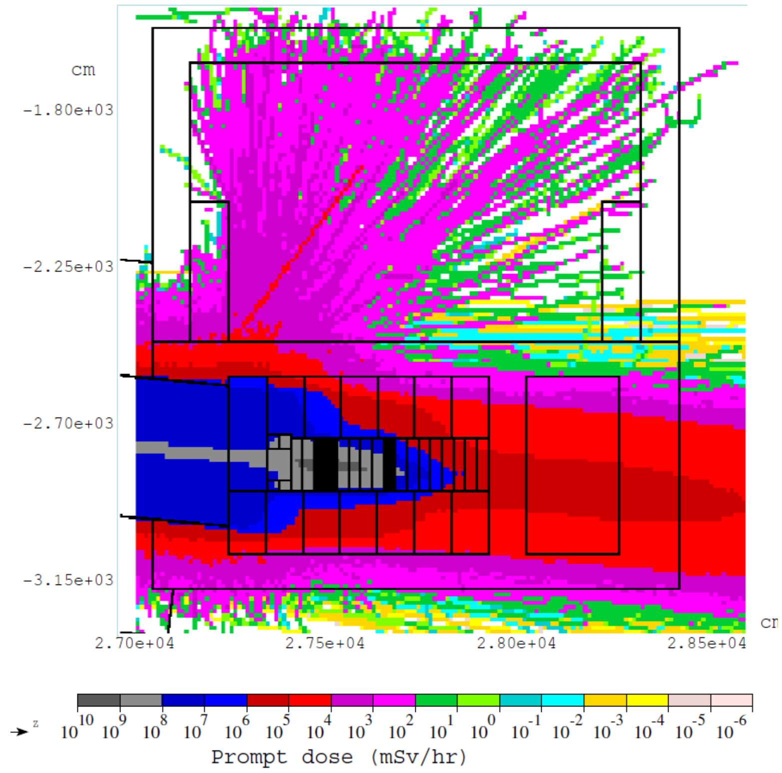
MARS15: DPA process contribution (%)

Target	Nuclear	EM elastic	L.E. neutr	e±
NuMI	50.8	43.3	1.5	4.4
BLIP	43.5	53	3.5	0.02

LBNE at 2.3 MW

All usual **(no show-stoppers, just scale!)** radiation problems in target station, 250-m decay channel and hadron absorber systems: thermal issues, control electronics (soft errors and lifetime), air activation and ground water protection, component activation and hands-on maintenance, cooling system etc.





Summary

- At new generation of accelerators, extremely high peak specific energy (up to ~0.1 MJ/g) and specific power (up to ~1 TW/g) in beam interactions with matter make design of such critical systems as targets, absorbers and collimators very challenging, requiring novel approach.

- This also puts unprecedented requirements on the accuracy, capability and reliability of the simulation codes used in the designs. Particle production, DPA, nuclide inventory, energy deposition and hydrodynamics coupling are the modules of special importance.

- Benchmarking is absolutely crucial. Justified emulation of extreme conditions at existing lower energy and beam power facilities are the way to go. JASMIN (Fermilab/Japan), BLIP (BNL) and HiRadMat (CERN) activities are the excellent examples. More tight efforts with material experts are needed.