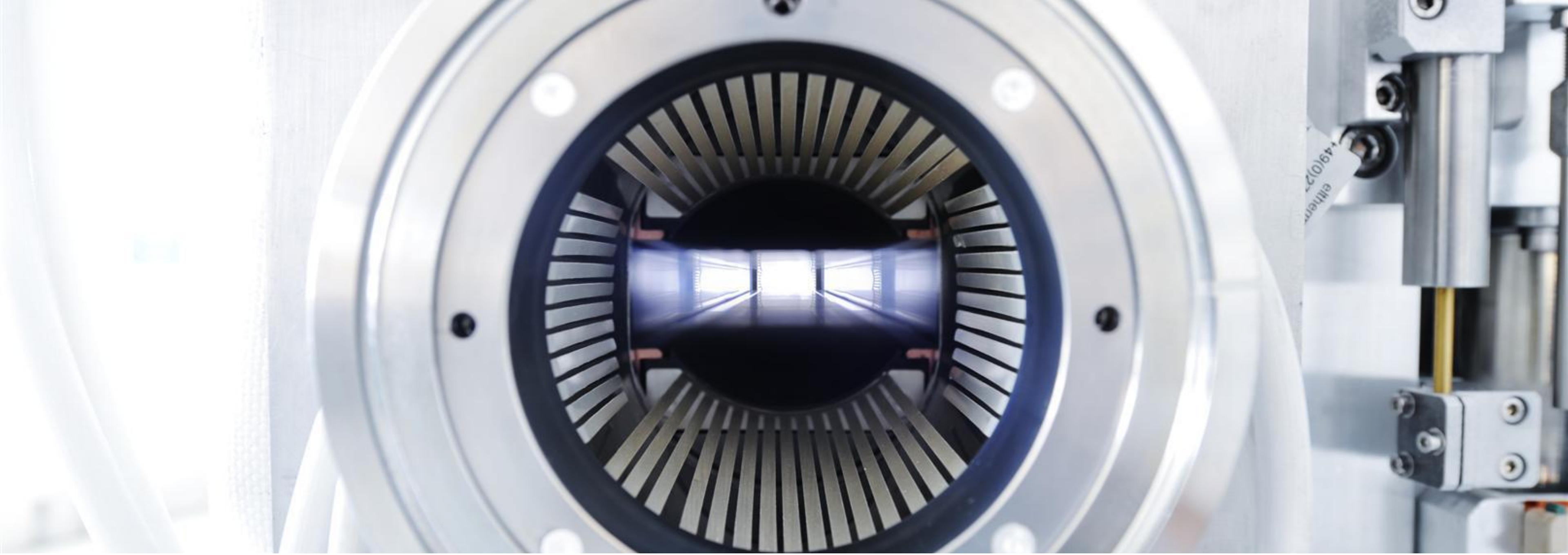


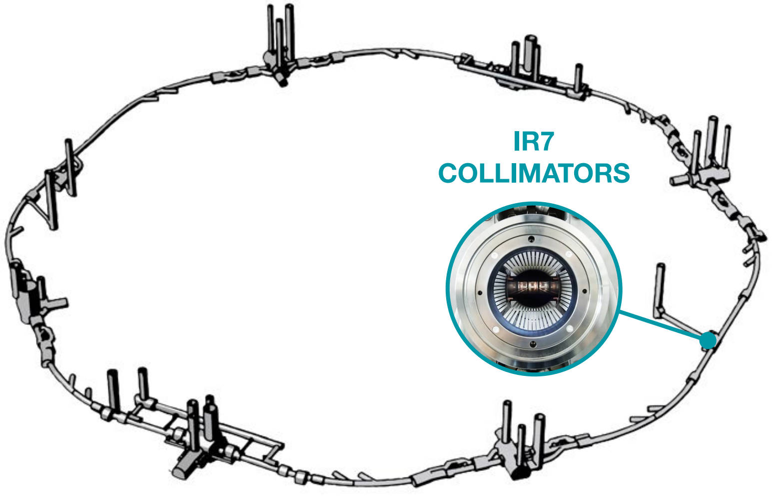
FLUKA simulations on residual gas production in IR7 collimators

9th HiLumi Annual Meeting 16/10/2019

A. Waets, A. Lechner, E. Skordis, J. Espadanal, V. Vlachoudis, A. Mereghetti (EN-STI, BE-ABP)
On behalf of FLUKA and collimation teams

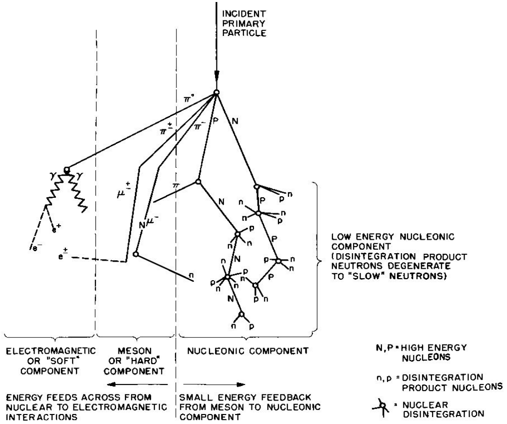
Motivation

- **Radiation damage** incurred by high energy protons and secondary shower particles on beam-intercepting devices like collimators during operation
- Estimate quantities using FLUKA that can be related to **changes in important physical properties** of collimator material:
  - Embrittlement/creep/swelling/corrosion
  - Fracture toughness reduction
  - Fatigue response
  - Thermal/electrical conductivity reduction
- Damage effects are dependent upon irradiation parameters including energy, intensity, material properties, …
- Simulations used to estimate quantities for real accelerator environment which can serve as input for irradiation experiments
  - Displacements in crystal lattice quantified by **DPA**
  - Void formation/embrittlement caused by H, He **residual gas production** inside collimator jaw material, (expressed as atomic parts per million per DPA, appm/DPA)

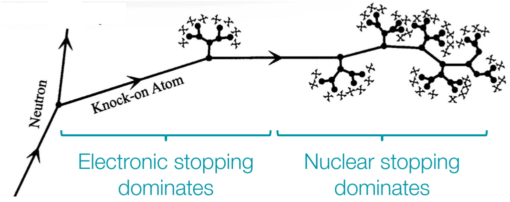


Physics

- Inelastic nuclear interactions of GeV, TeV energy hadrons (primary and secondary) with target nuclei considered as a two-step process:
    - **Fast phase**: nucleon-nucleon collision, primary interacting with single nucleon in target nucleus, production secondary fast nucleons and pions producing a cascade in direction of the beam, further collisions (range cm, m)
    - (Intermediate phase: pre-compound)
    - **Slow phase**: de-excitation of target nuclei in an isotropic fashion (range < 100 µm for charged particles)
        - Evaporation of nucleons/ nucleon clusters, residual H, He nuclei



- Recoils produced by elastic and inelastic interactions, energy loss through:
    - Electronic stopping (inelastic) for high energies
    - **Nuclear stopping** (elastic, NIEL) for lower energies, all shower particles can contribute to DPA, at low energy dominated by heavy recoils
    - Atomic displacement cascade forms, function of target material, threshold energy, primary energy



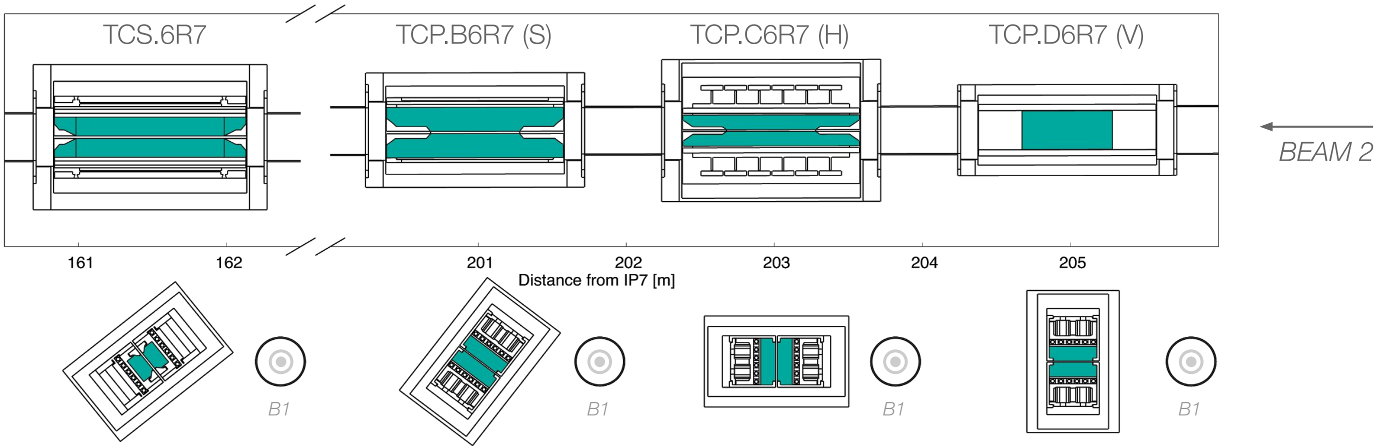
Radiation damage

- The **displacement per atom** (DPA) quantity is a measure of the amount of radiation damage incurred during irradiation, can be used to **relate radiation damage to change of macroscopic material properties**.
- Cannot be measured experimentally, can only be measured indirectly (so far)
- Indirect through study of macroscopic effects (electric and thermal conductivities, radiation hardening, swelling…)
- Quantitative interpretation:
  - 3 dpa means each atom in the material has been displaced from its site within the structural lattice an average of 3 times
  - 0.01 DPA implies 1 out of 100 atoms has been displaced.

	FLUKA material name	Density [g/cm^3]	atoms/cm^3	DPA treshold
CFC	AC150GPH	1.67	8.37E22	35 eV
MoGR	MG6403Fc	2.55	1.13E23	35 eV

Optics and collimator settings

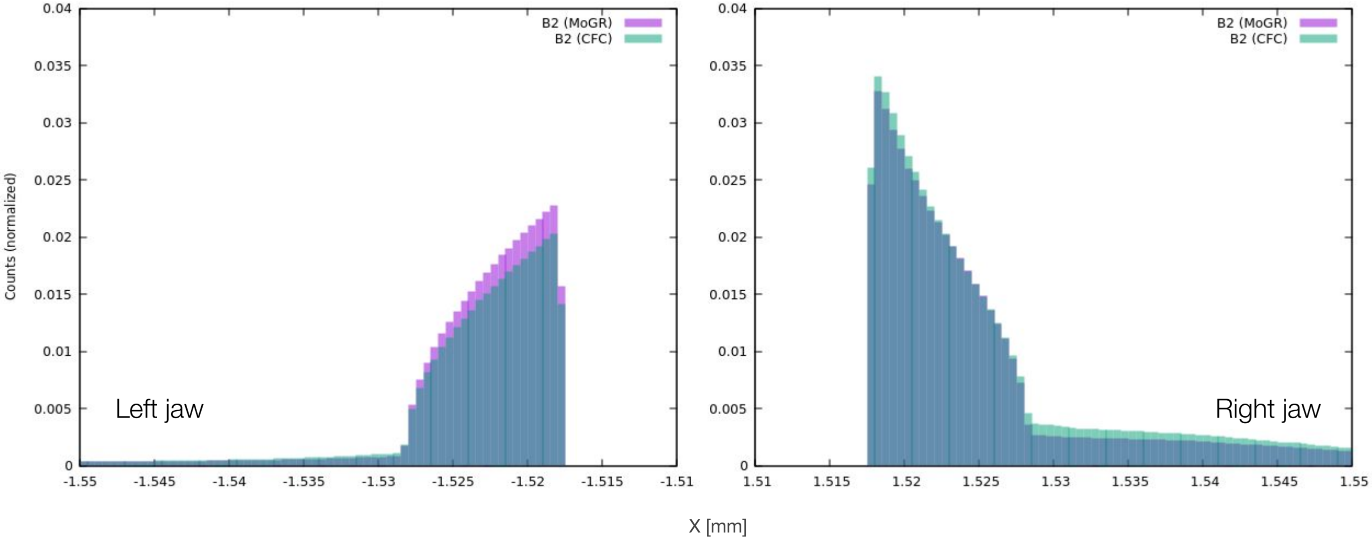
- HL-LHC v1.2
- 2 σ retraction
- 7 TeV proton beam
- Beam 2 only
- No misalignments
- assuming all primary protons are lost on horizontal TCP.C
- ~ 1E17 protons lost during HL-LHC



	TCS.6R7	TCP.B6R7 (S)	TCP.C6R7 (H)	TCP.D6R7 (V)
Half gap [mm]	1.77	1.28	1.52	1.09
σ	7.7	5.7	5.7	5.7
β_x [m]	40.2	143.0	151.1	159.4
β_y [m]	226.9	87.6	82.9	78.4

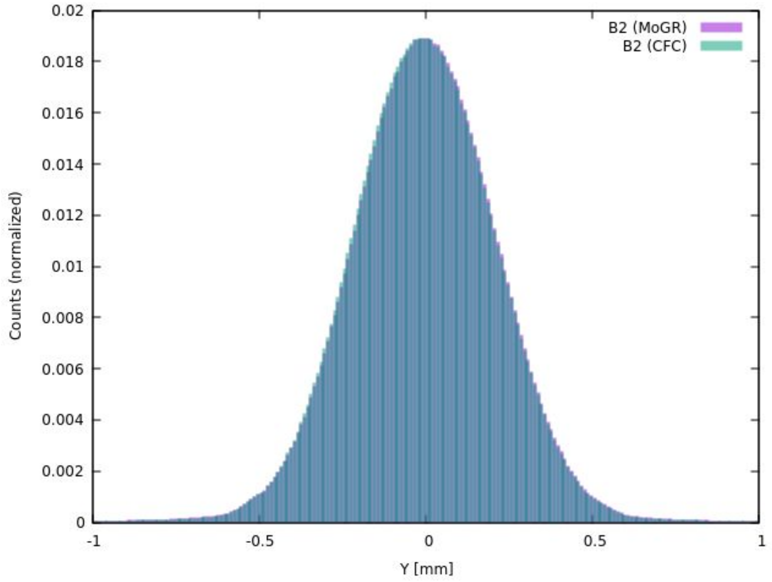
Impact distribution and scoring mesh

- Primary collimators: mesh size determined by impact distribution ("touches") on horizontal collimator (TCP.C)
    - Distribution in X: 5 μm bins between 0 and 0.4 mm.



Scoring

- Primary collimators: mesh size determined by impact distribution (“touches”) on horizontal collimator (TCP.C)
  - assuming all primary protons are lost on TCP.C (~ 1E17 protons lost during HL-LHC lifetime)
  - X: 5 μm bins between 0 and 0.4 mm (in cleaning plane).
  - Y: 50 μm bins between -1 and 1 mm



Scoring

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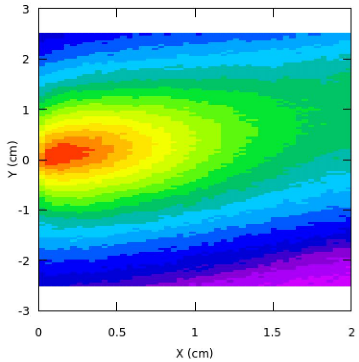
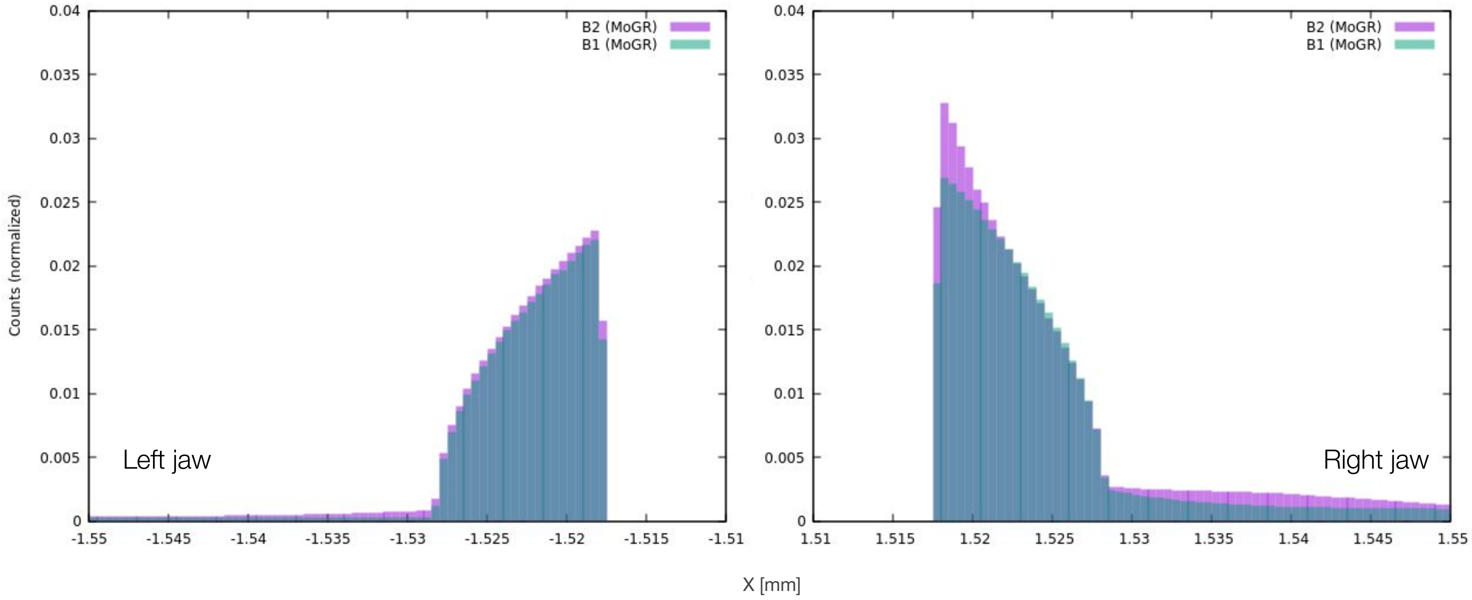
  - assuming all primary protons are lost on TCP.C (~ 1E17 protons lost during HL-LHC lifetime)
  - X: 5 µm bins between 0 and 0.4 mm (in cleaning plane).
  - Y: 50 µm bins between -1 and 1 mm
  - Z (longitudinally): 1 cm bins between -30 and 30 cm
- Secondary collimators: mesh size required to be larger due to shower development, jaws impacted by secondary particles
  - X: 400 µm bins between 0 and 2 cm.
  - Y: 400 µm bins between -2.5 and 2.5 cm
  - Z: 1 cm bins between -50 and 50 cm



- Residual gas production:
  - ^{1}H, ^{2}H, ^{3}H scored separately, summed for analysis
  - ^{3}He, ^{4}He scored separately, summed for analysis

Previous results

- DPA studies on primary and secondary collimators (CFC and MoGR)
- Beam 1 geometry and touches
- v1.2 optics



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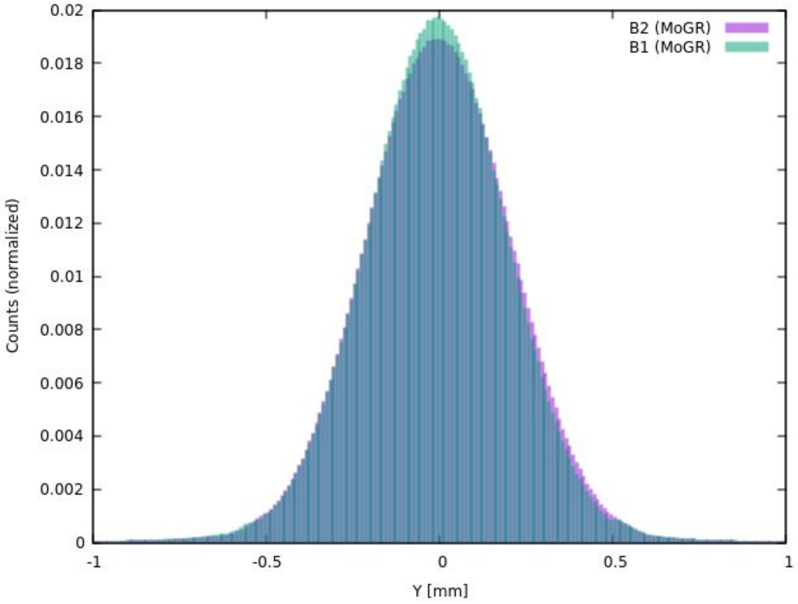
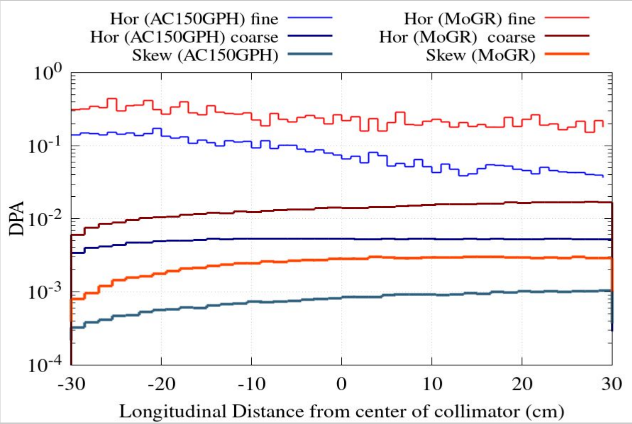
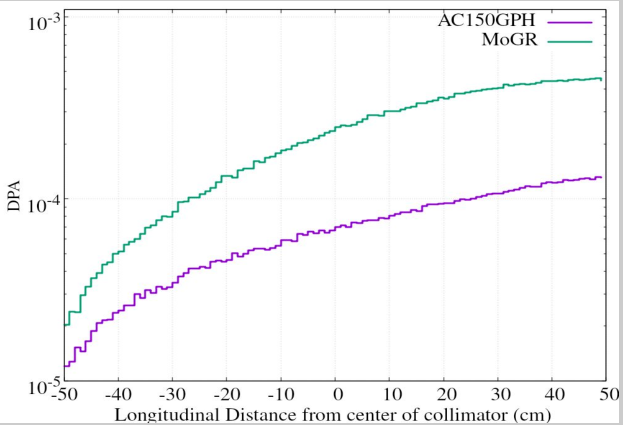


Previous results

Primary



Secondary

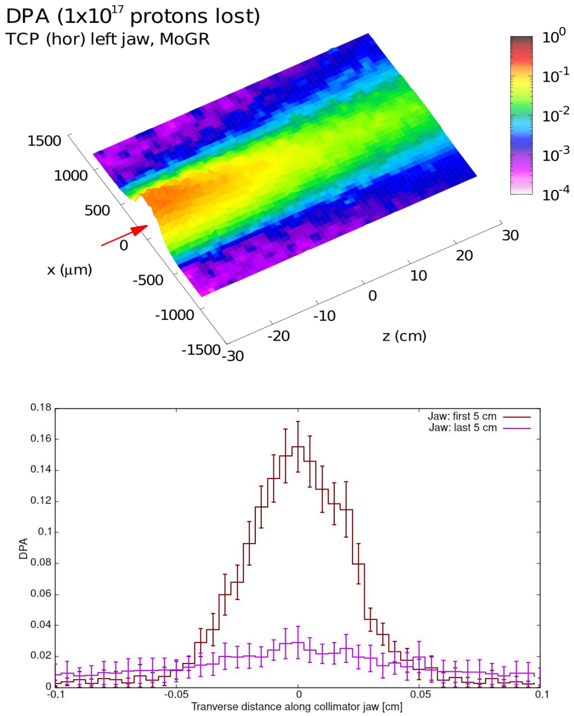


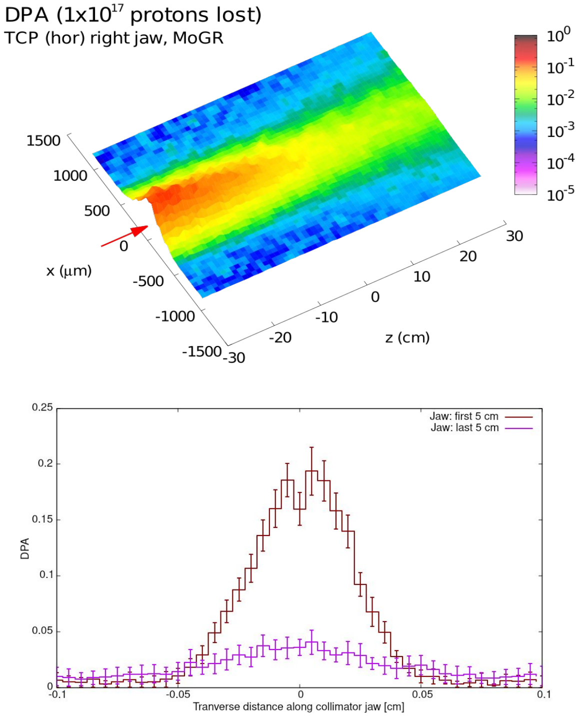
E. Skordis

1E17 protons lost	Primary	Secondary
CFC	0.05 - 0.1	$1 - 2 \cdot 10^{-4}$
MoGR	0.3	$4 - 5 \cdot 10^{-4}$

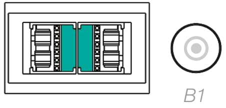
Primary collimators

B1

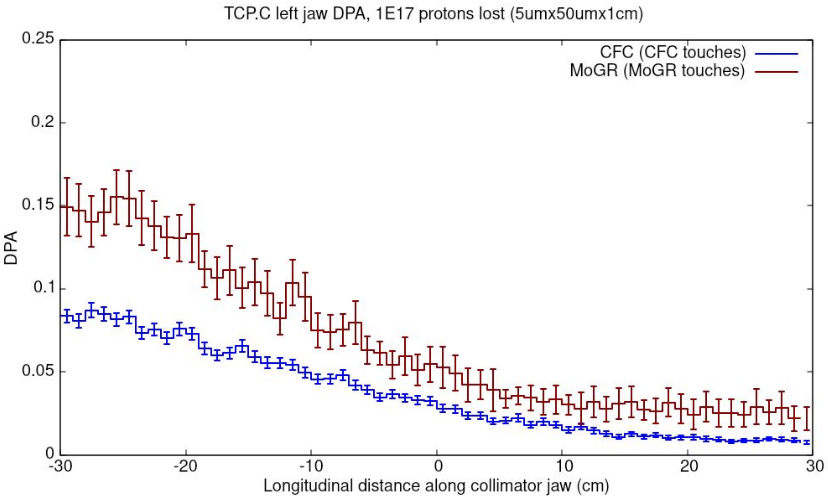


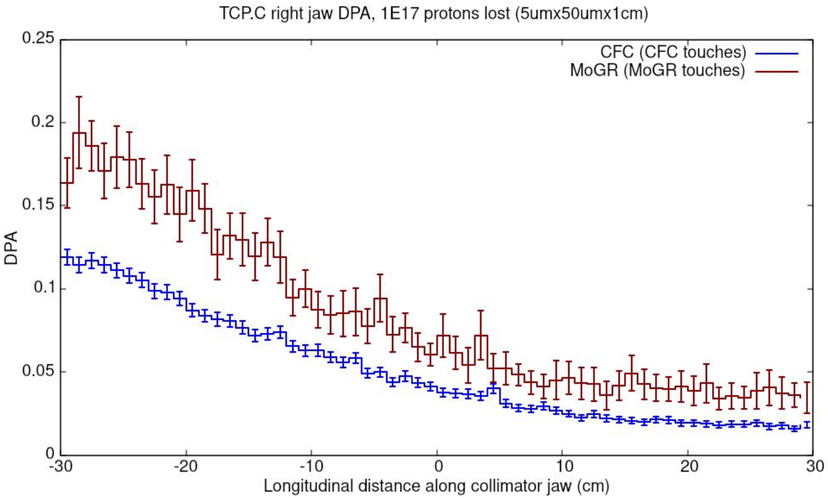


Primary collimators



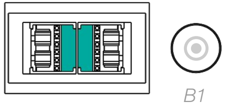
- Assuming 1E17 protons all lost on horizontal TCP.C
  - 5 µm x 50 µm x 1cm mesh





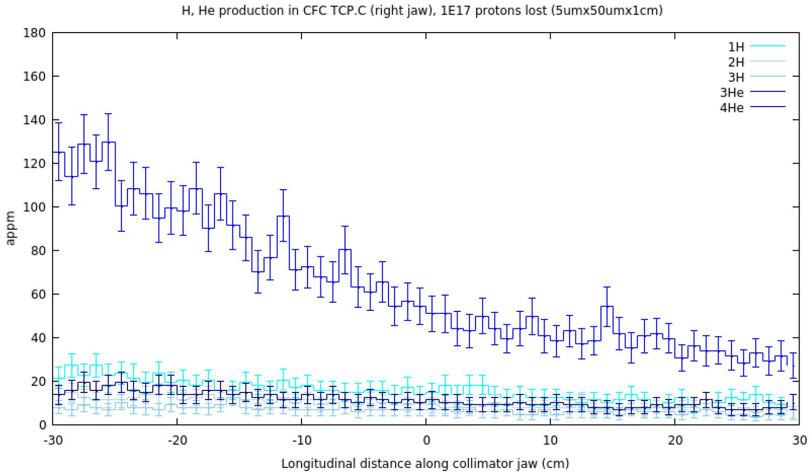
DPA peak values	Left	Right
CFC	~ 0.085	~ 0.12
MoGR	~ 0.15	~ 0.18

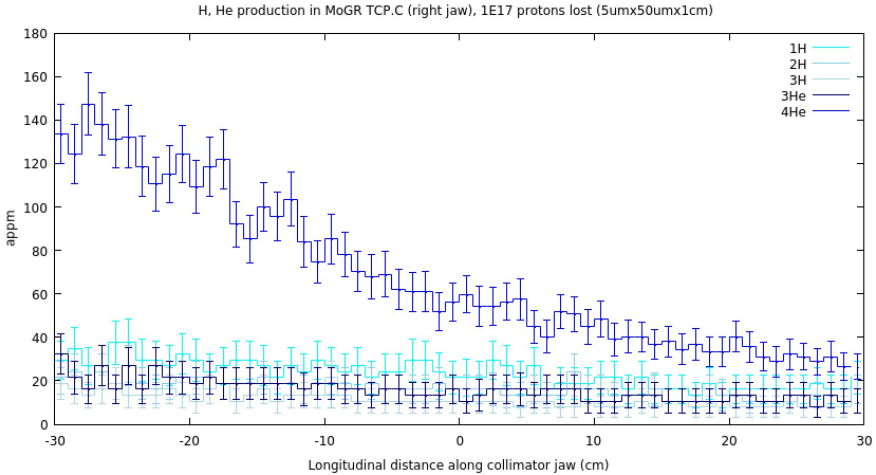
Primary collimators



B1

- Assuming 1E17 protons all lost on horizontal TCP.C
  - 5 µm x 50 µm x 1cm mesh
  - All H, He species scored on most impacted jaw (right) only

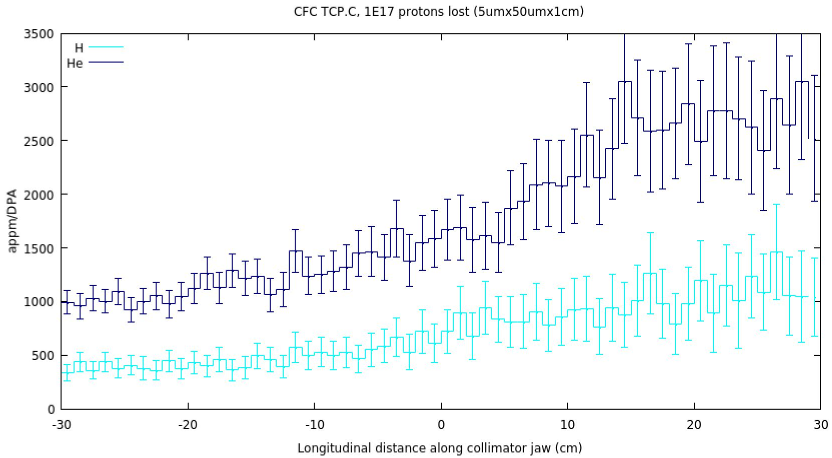


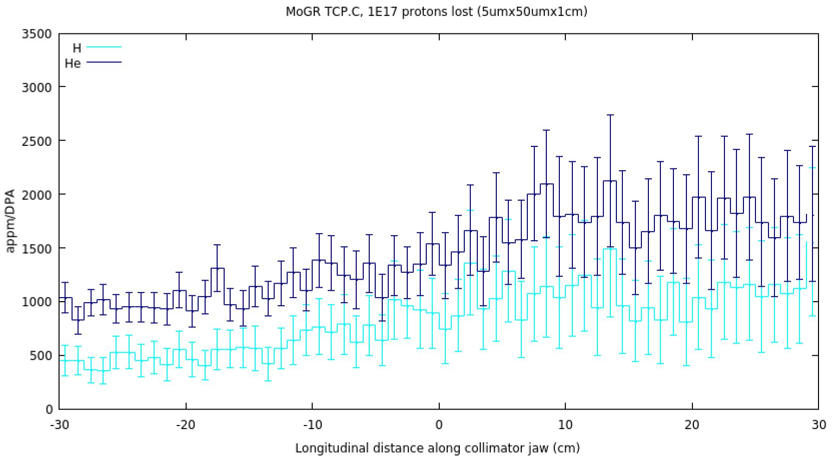


appm peak values	4He	1H
CFC	~ 120	~ 25
MoGR	~ 140	~ 40

Primary collimators

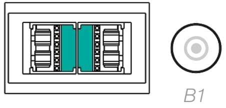
- Assuming 1E17 protons all lost on horizontal TCP.C



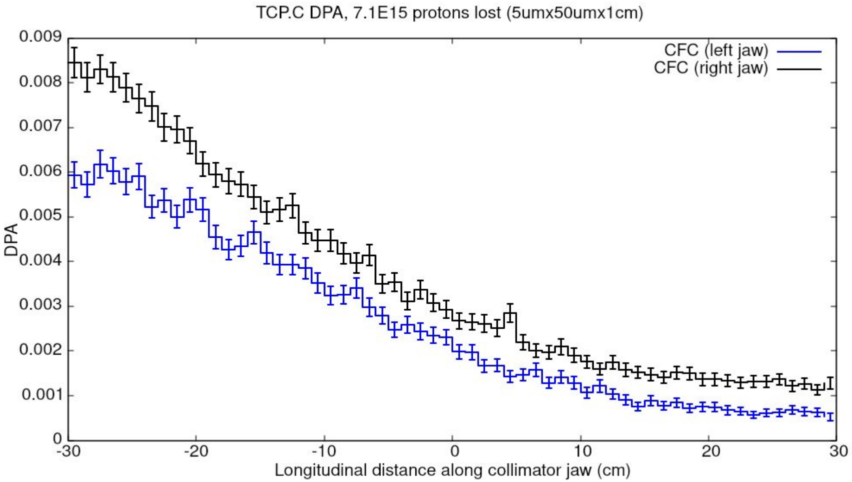


appm/DPA	He	H
CFC	1000 - 3000	400 - 1000
MoGR	1000 - 2000	400 - 1000

Primary collimators: Run 2 results



- Present layout features CFC primary collimators
- Integrated intensity measurements estimate betatron induced proton losses amount to 7.1E15 for Run 2 in Beam 2



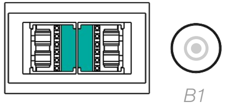
6.5 TeV collimation losses estimation, integrated intensity measurements and scaling factors.

	Year	2015	2016	2017	2018
Beam 1	Estimated # of protons lost	0.4×10^{15}	1.4×10^{15}	1.7×10^{15}	5.1×10^{15}
	Integrated Intensity (ps)	0.254×10^{21}	1.17×10^{21}	1.03×10^{21}	1.36E+21
	Scaling factor (#p lost / ps)	**1.4×10^{-6}**	**1.2×10^{-6}**	**1.6×10^{-6}**	**3.8×10^{-6}**
Beam 2	Estimated # of protons lost	0.5×10^{15}	1.2×10^{15}	1.1×10^{15}	4.3×10^{15}
	Integrated Intensity (ps)	0.250×10^{21}	1.20×10^{21}	1.07×10^{21}	1.36E+21
	Scaling factor (#p lost / ps)	**2.0×10^{-6}**	**1.0×10^{-6}**	**1.0×10^{-6}**	**3.1×10^{-6}**

E. Skordis

- Peak DPA values in CPC.C (CFC) at 0.008 (left jaw) and 0.006 (right jaw).

Primary collimators: Run 2 results



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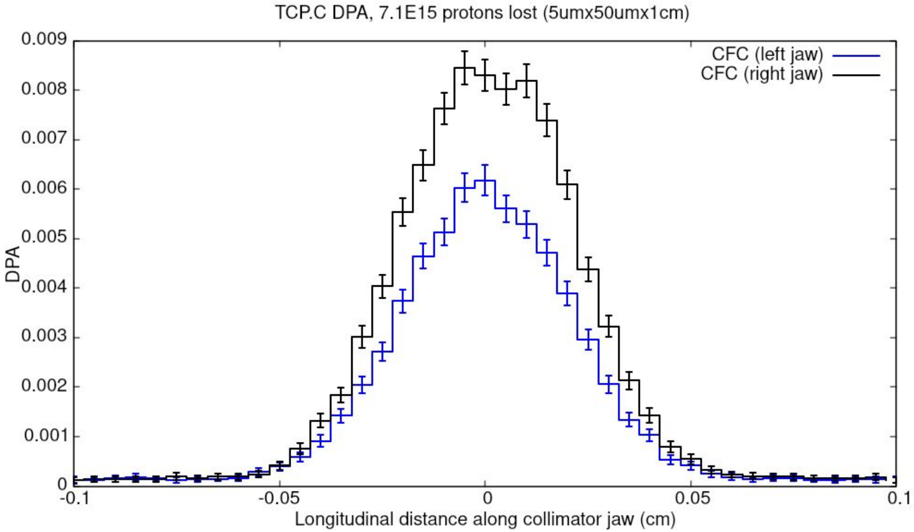

- Orbit jitter on order of 50 µm, applying shift will not change distribution

6.5 TeV collimation losses estimation, integrated intensity measurements and scaling factors.

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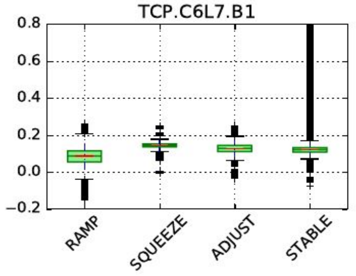

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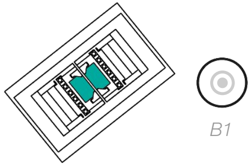
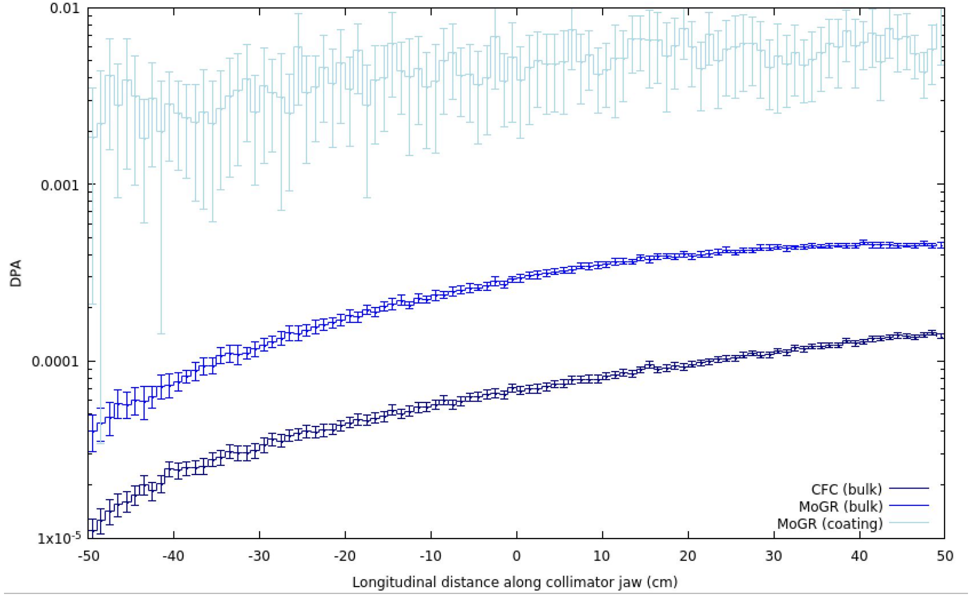
Secondary collimators



- CFC primary/secondary and MoGR (+coating) primary/secondary collimators combination simulated
  - 400 µm x 400 µm x 1cm mesh
  - Consistent with previous results
- Large statistical uncertainties for Mo coating scoring



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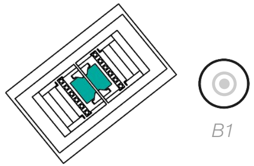
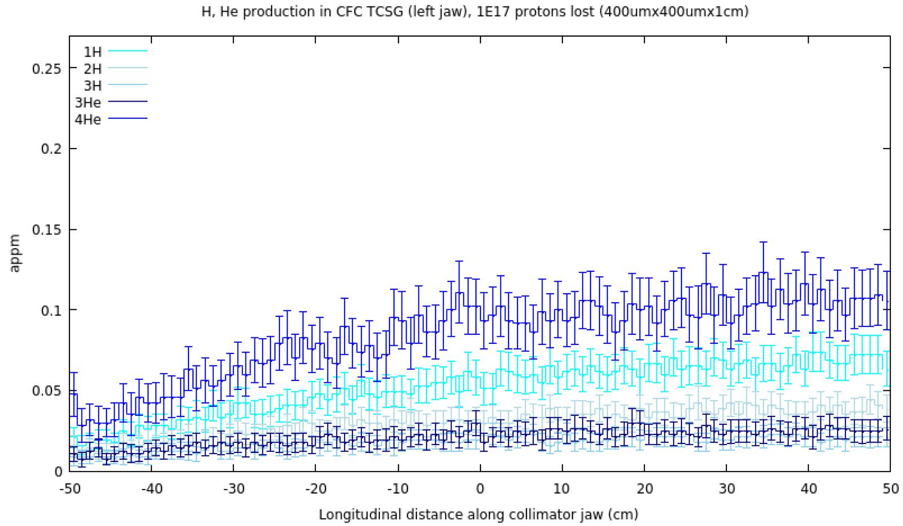
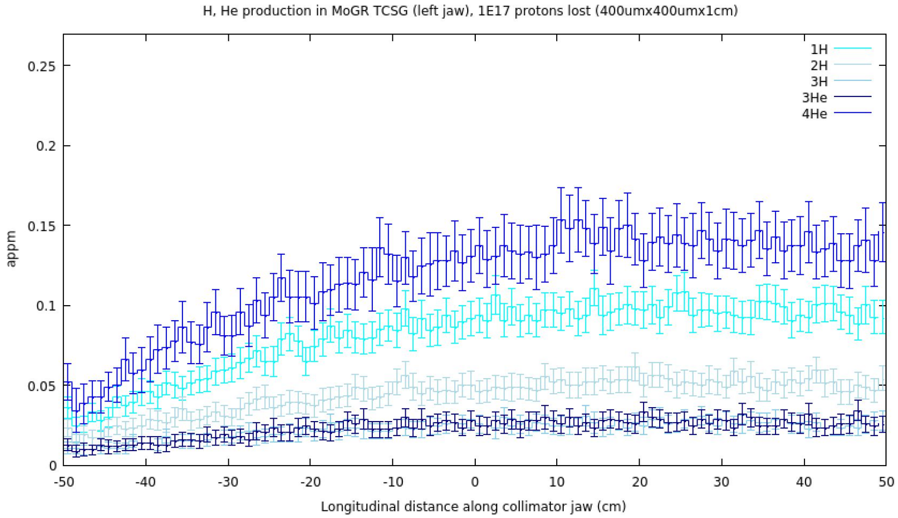
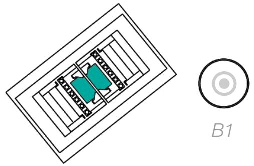


- CFC primary/secondary and MoGR (+coating) primary/secondary collimators combination simulated
  - 400 µm x 400 µm x 1cm mesh
  - Overall higher residual gas production in MoGR bulk jaw material compared to CFC

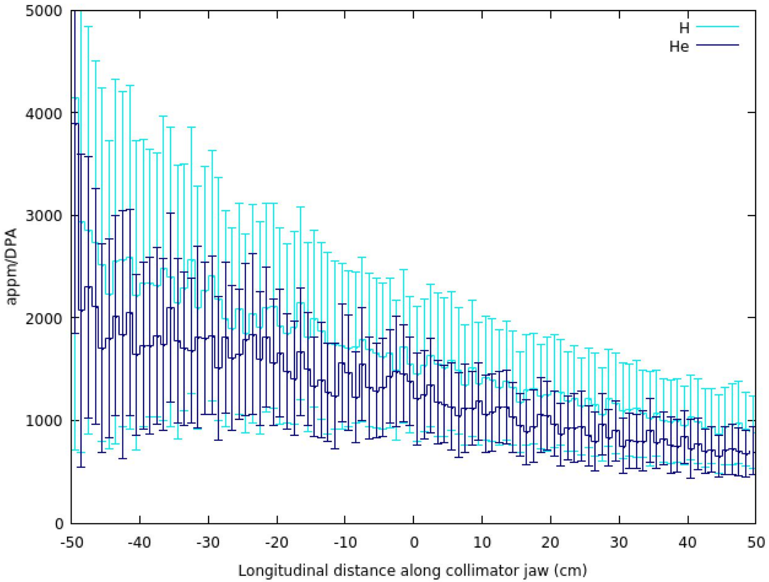


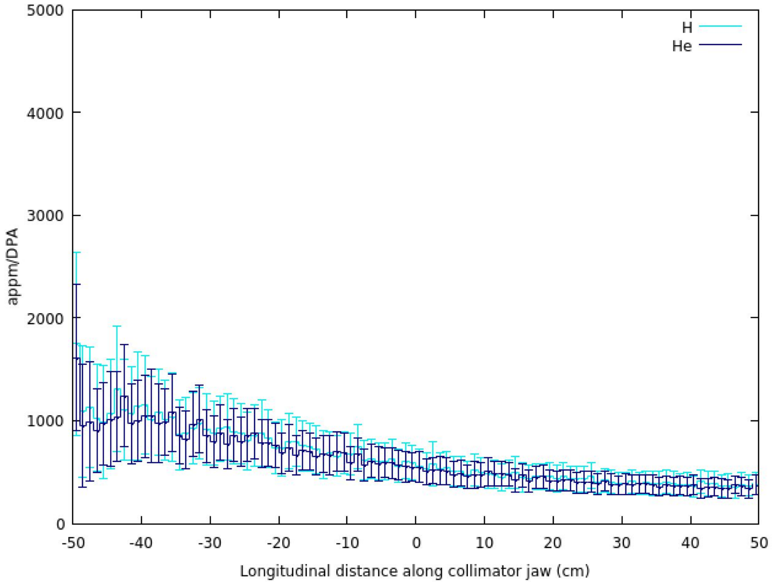


Secondary collimators



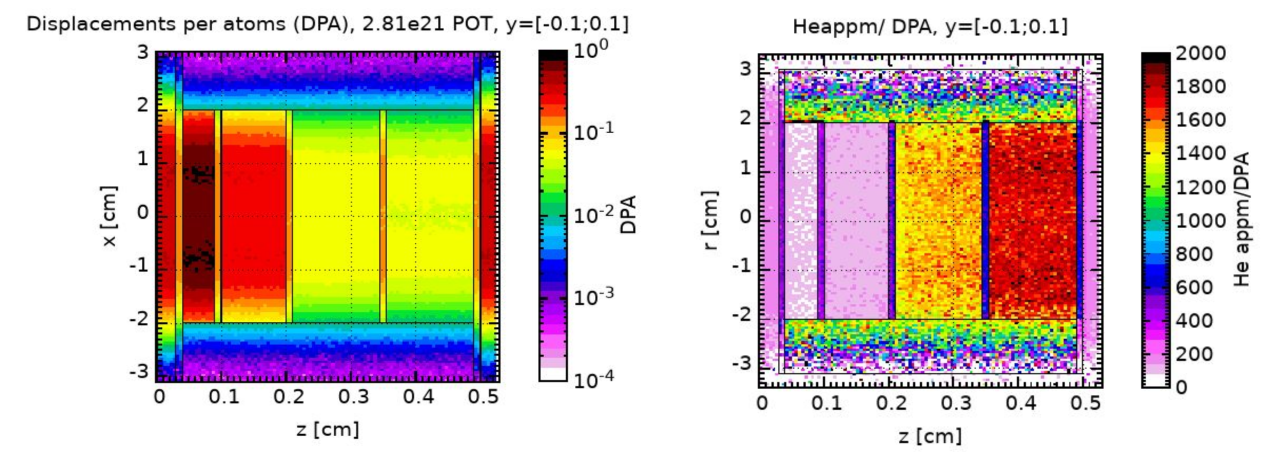
- CFC primary/secondary and MoGR (+coating) primary/secondary collimators combination simulated
  - 400 μm x 400 μm x 1cm mesh
  - appm/DPA result significantly lower for MoGR due to higher overall DPA





BLIP test simulations

- FLUKA simulations performed to estimate BLIP test results
  - DPA and He production for CFC and MoGR capsules
  - Reference calculations of appm/DPA for H (on the same order as He) and ^{3}He (~ 20%)



J. Espadanal, V. Vlachoudis

Summary and outlook

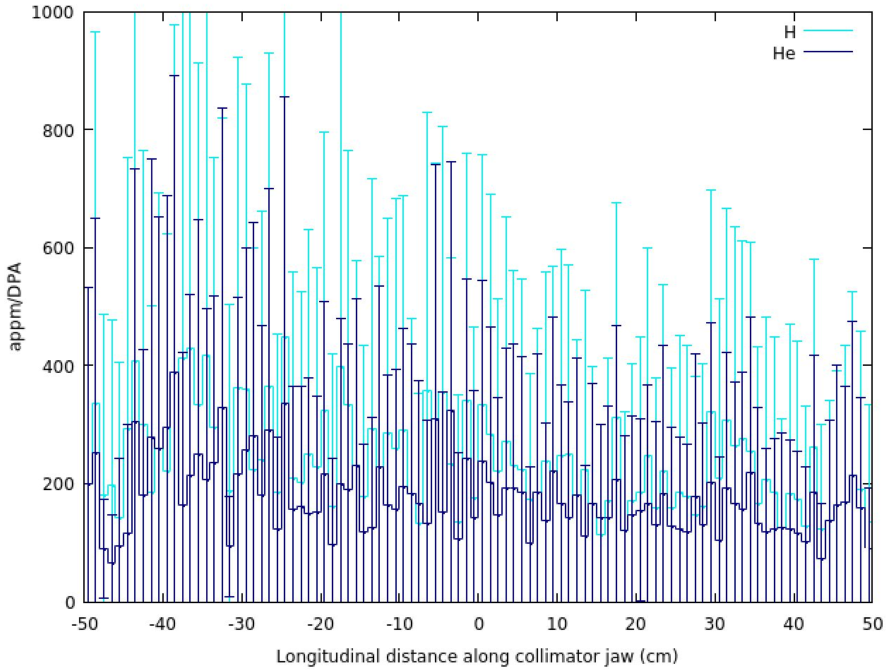
- FLUKA simulations performed to assess DPA and gas production in IR7 primary and secondary collimators
  - B2, v1.2 optics, CFC and (Mo-coated) MoGR
  - Results cross-checked and consistent with previous DPA studies
  - appm/DPA reference calculations from BLIP test and simulations
- Outlook:
  - Improve scoring and statistics (coating)
  - Re-evaluate CFC primary / MoGR secondary configuration
  - Use results for/cross check experimental considerations and expected performance in accelerator

B2H HL-LHC v1.2	Primary CFC		Primary MoGR		Secondary CFC		Secondary MoGR	
	H	He	H	He	H	He	H	He
DPA (peak)	0.12		0.18		0.0001		0.00034	
appm	45	140	65	160	0.075	0.12	0.01	0.15
appm/DPA	400 - 1000	1000 -3000	400 - 1000	1000 - 2000	1200 - 3000	1000 - 2000	600 - 1500	500 - 1000

Backup slides

Backup slides

- appm/DPA in Mo coating on MoGR secondary collimators



H, He production quantity calculation

- H, He production expressed as *appm* or atomic parts per million
- Results in FLUKA normalized per cm^3, appm is then expressed with respect to amount of atoms in 1 cm^3 of jaw material
- Collimator jaw materials:
  - **CFC**, Fluka material AC150GPH, density $\rho = 1.67\ g/cm^3$
    - $M(C) = 12.0107$ g/mol

$$M(C) \cdot N_A \cdot \rho_{CFC} = \mathbf{8.37E22\ atoms / cm^3}$$

  - **MoGR**, Fluka (compound) material MG6403Fc, $\rho = 2.55\ g/cm^3$
    - $M(Mo) = 95.95$ g/mol, 1.84%
    - $M(C) = 12.0107$ g/mol, 98.09%
    - $M(Ti) = 47.867$ g/mol, 0.07%

$$= (95.95 \cdot 0.0184 + 12.0107 \cdot 0.9809 + 47.867 \cdot 0.0007)\ g/mol = 13.58\ g/mol$$

$$M(MoGR) \cdot N_A \cdot \rho_{MoGR} = \mathbf{1.13E23\ atoms / cm^3}$$

Avogadro constant N_A: $6.022 \cdot 10^{23}\ mol^{-1}$