Dilution requirements for the FCC-hh dump

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FCC Week 2018

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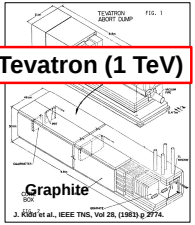
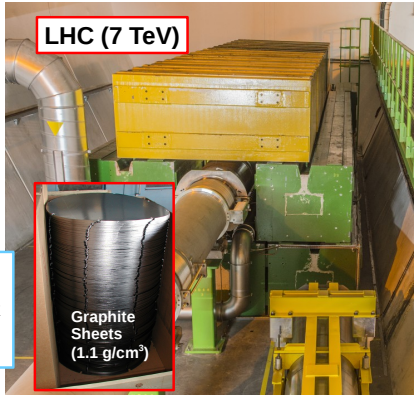
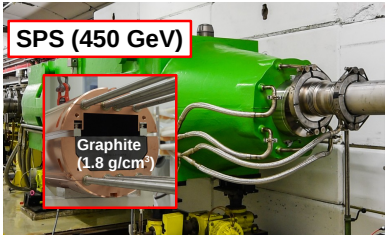
Introduction

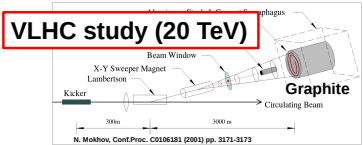
- **Graphite - the natural choice for high-energy proton dumps**







Graphite:
+ low Z and density
+ high thermal shock resistance
+ high melting point

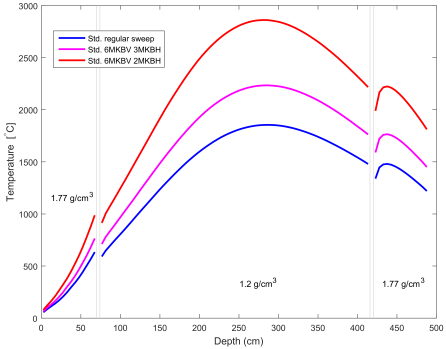


- **This talk:**
  - **Dilution requirements** for safely absorbing FCC beams in a **LHC-like Graphite dump**
  - Brief outlook: achievable dose reduction by using **lower-density Graphite/C foam grades**

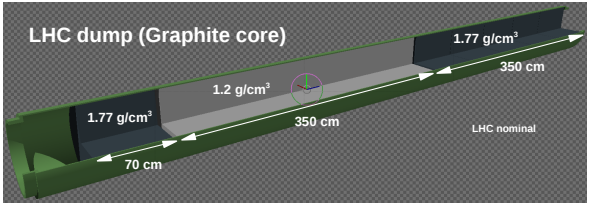
HL-LHC beams: already challenging

→ LHC: **6 V + 4 H dilution kickers**

Longitudinal peak temperature profile for standard HL-LHC 25 sec beams:

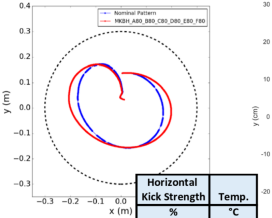


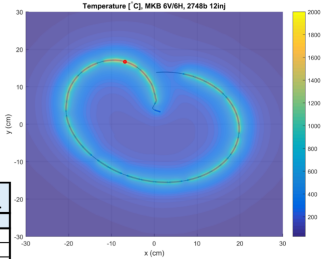
Figures by M.I. Frankl, bunch patterns by C. Wiesner



→ **HL-LHC: additional dilution kickers under study:**

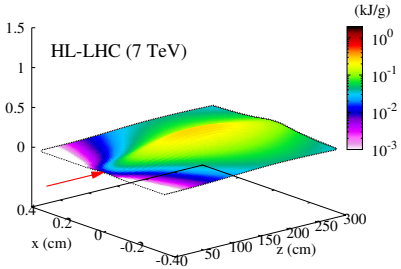
120 %

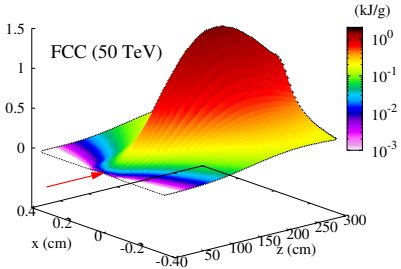




Horizontal Kick Strength	Temp.
%	°C
100	1860
110	1760
120	1660

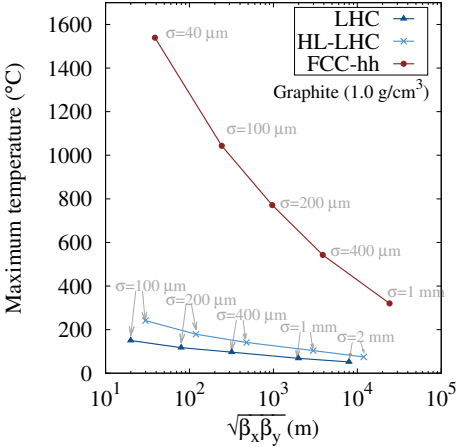
(HL-)LHC vs FCC-hh: single proton bunch on Graphite





Max. energy density/temp. by single bunch → spot size

	LHC	HL-LHC	FCC
E (TeV)	7	7	50
ϵ_n (μm·rad)	3.75	2.5	2.2
ppb ($\times 10^{11}$)	1.15	2.2	1.0



1 proton bunch,
Graphite (1.0 g/cm^3)

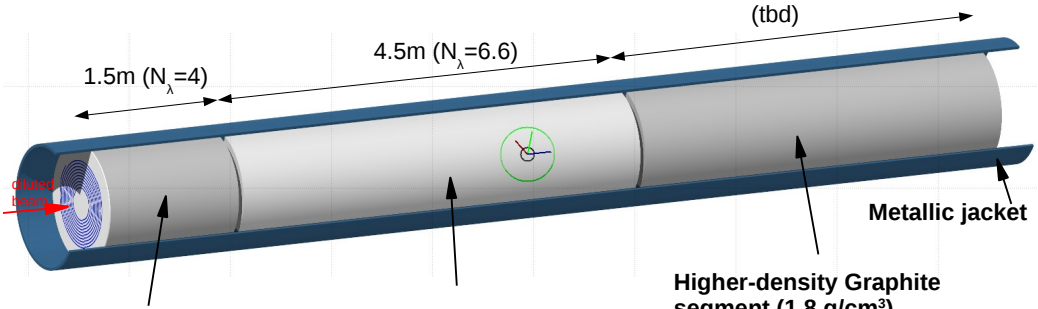
Even with large β:

- **O(few) FCC bunches** can induce **critical stresses**
- **O(tens) FCC bunches** can provoke **phase transition**

(if all on the same spot)

Figures on the left: dose in 3 m long Graphite (1.83 g/cm3) for one nominal proton bunch (σ =400μm) - HL-LHC (top) and FCC (bottom).

FCC-hh dump concept (LHC-like Graphite dump)



Higher-density Graphite segment (1.8 g/cm^3)

Higher material density at upstream end gives rise to a steeper shower build-up and hence reduces the overall dump length
Note: the presence of the higher-density graphite has only a small effect on the maximum energy density in the low-density segment if the beam is diluted across the dump face

Low-density Graphite segment (1.0 g/cm^3)

Lower material density in the region of the shower maximum reduces the max. energy density and temperature

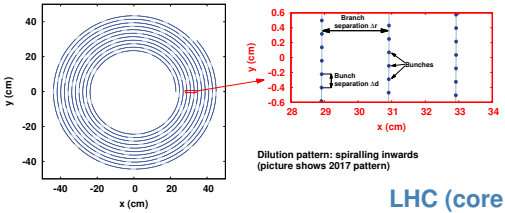
Higher-density Graphite segment (1.8 g/cm^3)
+ possibly other materials (tbd)

Higher material density gives rise to better attenuation of the longitudinal shower tails and hence reduces the dump length

Total core length expected < 10-12m

Core radius depends on sweep pattern (+ a certain margin to jacket)

Spiral dilution pattern



Dilution pattern: spiralling inwards (picture shows 2017 pattern)

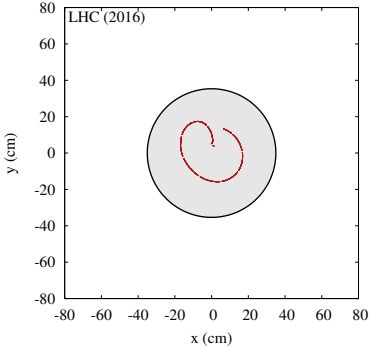
	FCC Week 2017	FCC Week 2018
Frequency	modulated ($\leq$50 kHz)	const. (50 kHz)
Bunch separation Δd	1.8 mm	1.8–4.3 mm
Branch separation Δr	2 cm	2 cm
Total sweep length	24 m	39 m
Outer spiral radius	45 cm	55 cm
β_x/β_y	45 km/240 km	170 km/170 km

New sweep pattern 2018:

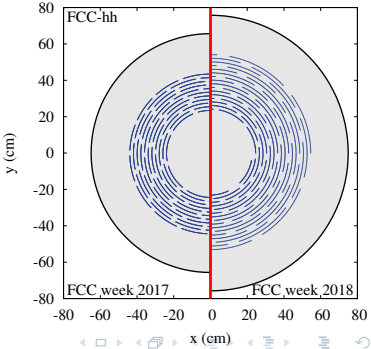
→ larger spiral footprint (requires larger dump radius of min. 70-80 cm)

→ reduced temperature in dump and less challenging for kickers

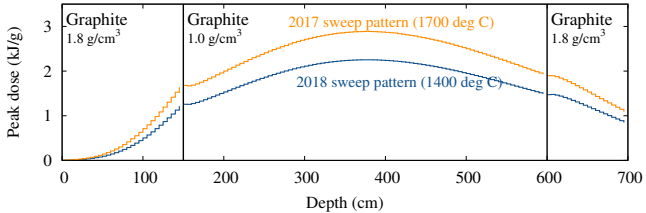
LHC (core radius = 35 cm):



FCC-hh (min. core radius 70-80 cm):



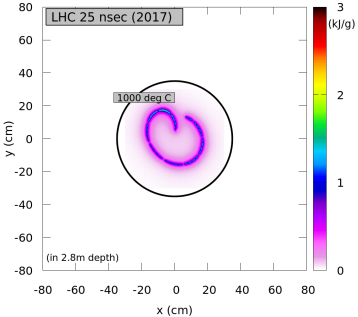
LHC vs FCC-hh: transverse dose distribution



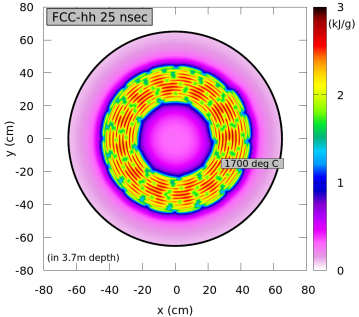
- **Updated sweep pattern**
  FCC week 2017 → FCC week 2018:
  Max. temp: 1700°C → 1400°C
  leaves more margin for failure cases

Dilution patterns by E. Renner and F. Burkart

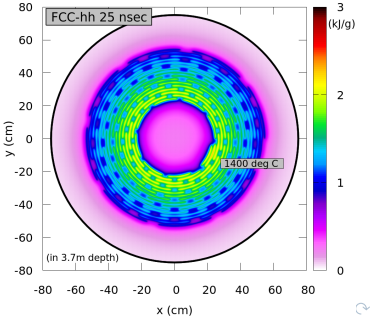
LHC (25 nsec, 2017):



FCC-hh (2017 sweep pattern):



FCC-hh (2018 sweep pattern):



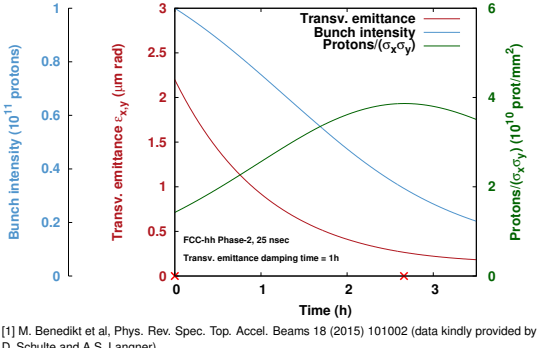
FCC-hh: effect of bunch brightness on energy deposition in dump

- *Beginning of a fill (largest bunch intensity):*

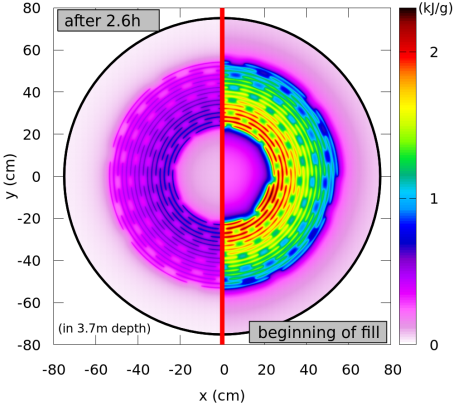
$\varepsilon_{x,y}$	I_b	$\sigma_x = \sigma_y$	$I_b/(\sigma_x\sigma_y)$
2.2 μm·rad	1×10^{11}	2.6 mm	1.5×10^{10}p/mm^2

- *After about 2.6h (with collisions) [1] (highest proton density):*

$\varepsilon_{x,y}$	I_b	$\sigma_x = \sigma_y$	$I_b/(\sigma_x\sigma_y)$
0.26 μm·rad	0.33×10^{11}	0.9 mm	4.0×10^{10}p/mm^2



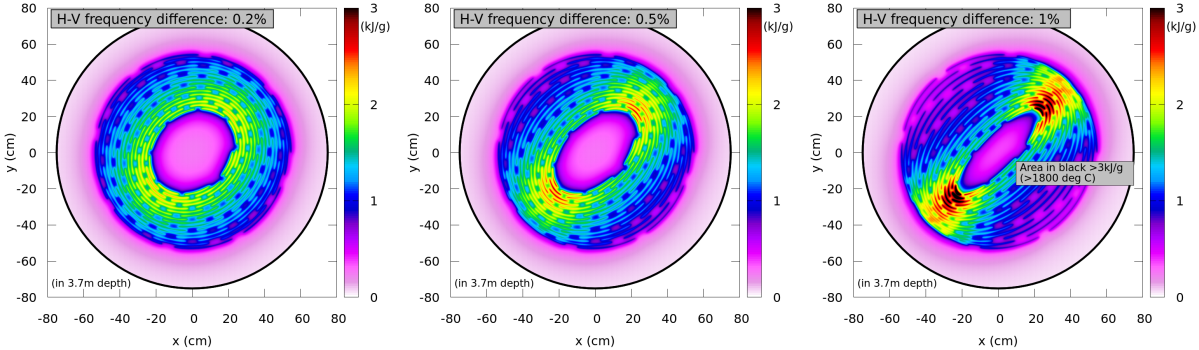
[1] M. Benedikt et al, Phys. Rev. Spec. Top. Accel. Beams 18 (2015) 101002 (data kindly provided by D. Schulte and A.S. Langner)

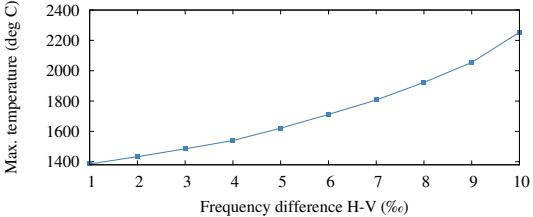


- Synchrotron radiation damping: **bunch brightness increases with time** (by more than a factor of two)
- Because of dilution, peak temperature depends **much stronger on bunch intensity than brightness**

→ **transv. emittance damping not harmful for dump**

FCC-hh: impact of H-V frequency mismatch on energy deposition

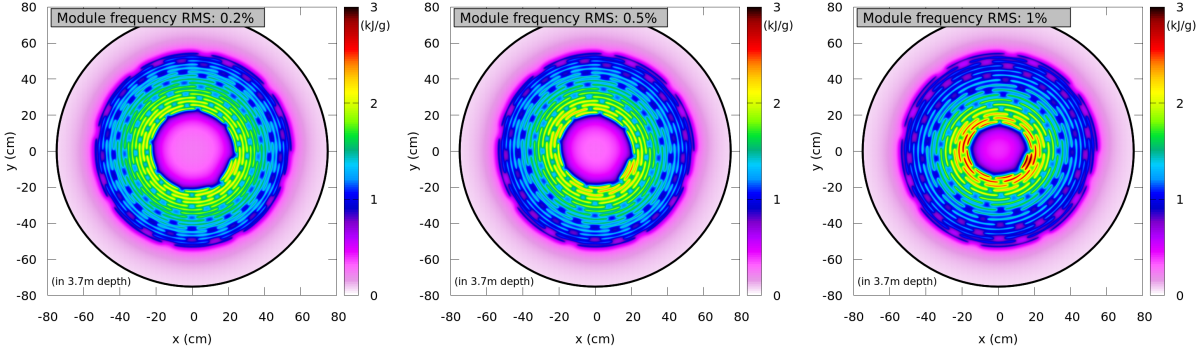


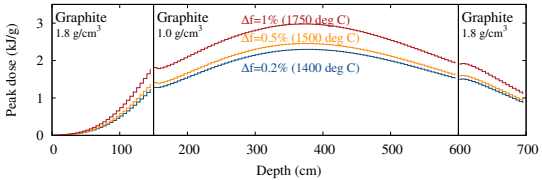


- A frequency mismatch between H and V dilution kickers distorts the sweep pattern → higher temperatures in dump
- **A mismatch of a few permille acceptable**

Sweep patterns by E. Renner

FCC-hh: impact of frequency offsets of individual kicker modules



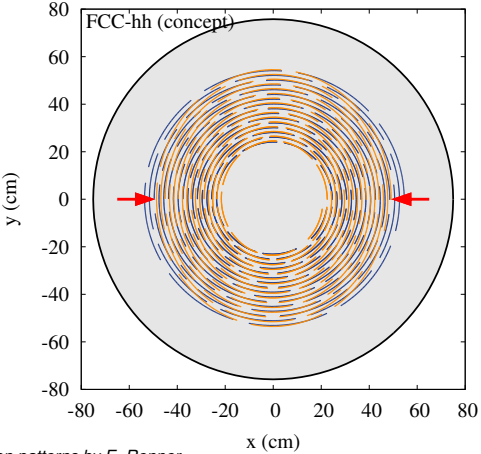


- Assumed random frequency offsets on individual kicker modules (Gaussian distributed, with RMS as specified in the figures)
- Affects mainly inner part of the sweep pattern
- **Random offsets of a few permille acceptable**

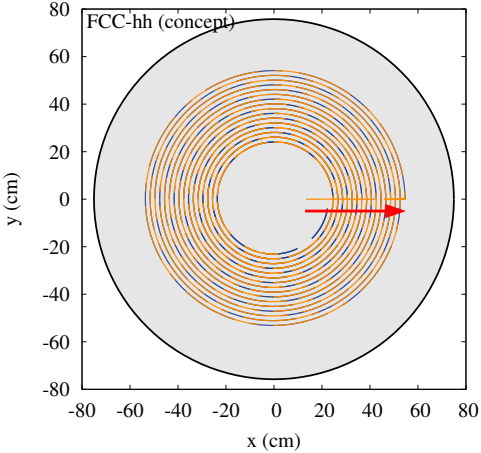
Sweep patterns by E. Renner

Failure cases: distortion of dilution pattern

- **Dilution failure:**
  - **10% less dilution** in horiz. plane (dilution system highly segmented)

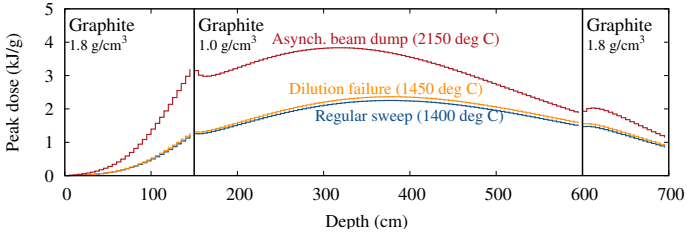


- **Asynchronous beam dump:**
  - Beam extracted while **dilution kickers still raising**



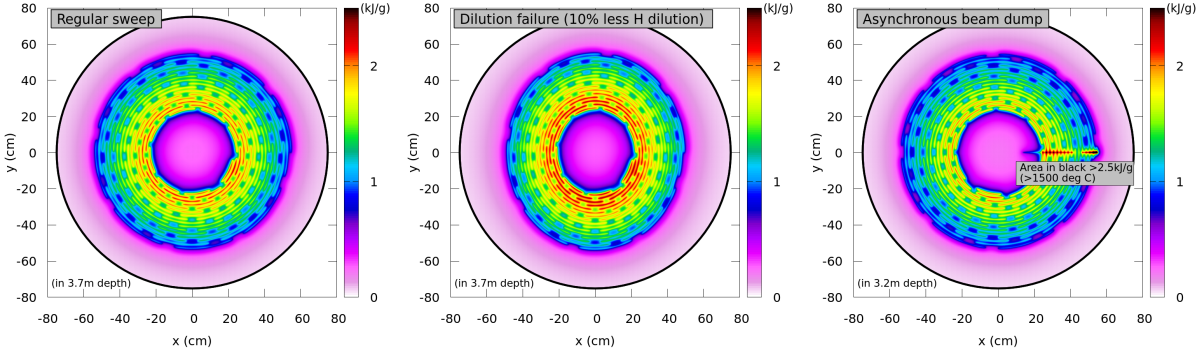
Dilution patterns by E. Renner.

FCC-hh: impact of extraction/dilution failures on energy deposition

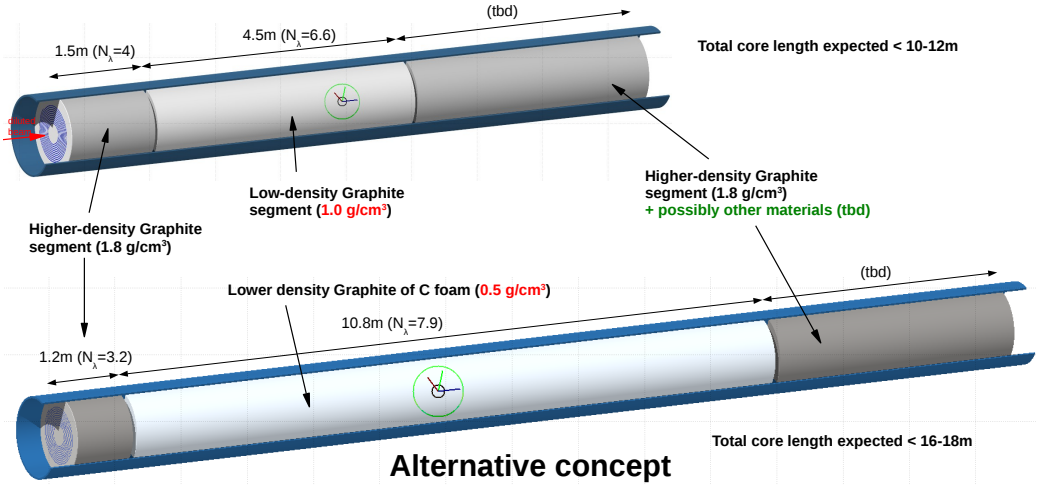


- **Asynchronous beam dump:**
  - → **Old sweep pattern FCC week 2017:** >8 kJ/g (local damage expected)
  - → **New sweep pattern FCC week 2018: dump core functionality should not be compromised***

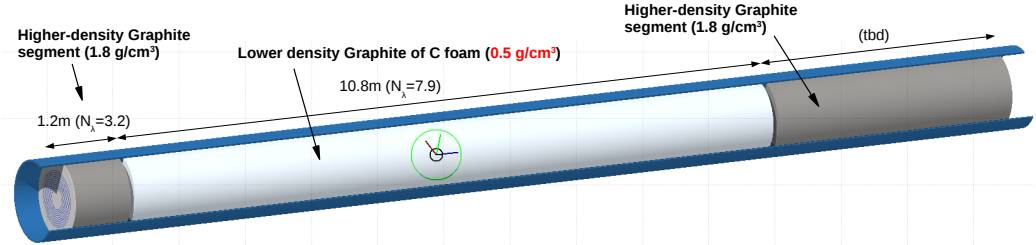
* *The properties of the low-density Graphite sheets are being better characterised within HL-LHC.*

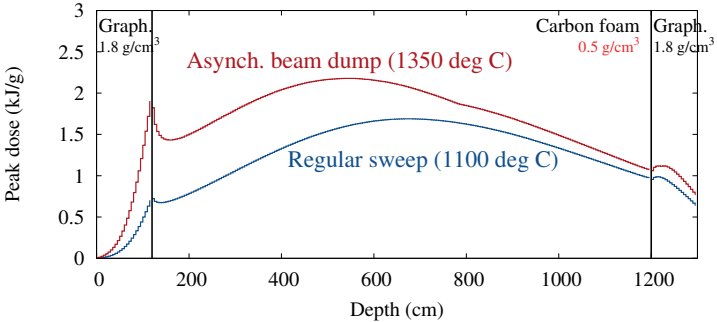


FCC-hh alternative dump concept: lower material density



FCC-hh alternative dump concept: energy deposition





- Peak dose reduction wrt baseline concept:
  - Regular sweep: **-25%**
  - Asynch. dump: **-43%**
- **Further material testing & characterisation required** (needed to assess stresses etc.)

Conclusion and outlook

- **Baseline Graphite dump for FCC-hh (LHC-like flexible Graphite with 1g/cm^3):**
  - Approximate dimensions:
    - $\Rightarrow$ **min. radius of 70-80 cm** $\rightarrow$ shower load on containment jacket to be checked, Graphite radius challenging for manufacturing
    - $\Rightarrow$ **length of 10–12 m**
  - With present sweep pattern, dump functionality expected not to be compromised **in case of asynchronous beam dumps**
  - **Dilution system remains challenging** (see previous talk of E. Renner)
  - Dilution frequency must be well matched between H and V planes (within a few permille), large frequency offsets of individual kicker modules (of more than a percent) must be avoided
- **Alternative directions to reduce to some extent the dilution requirements:**
  - Employ lower-density **Graphite variants or C foams** with densities $\leq$0.5 g/cm^3 (or even lower)
    - $\Rightarrow$ reduces shower-induced peak dose (few 10%)
    - $\Rightarrow$ dump length still expected to stay below 20 m
  - Materials already exist but **material characterisation and testing** required to assess their response to beam impact - they have never been used in high-energy proton BIDs or dumps