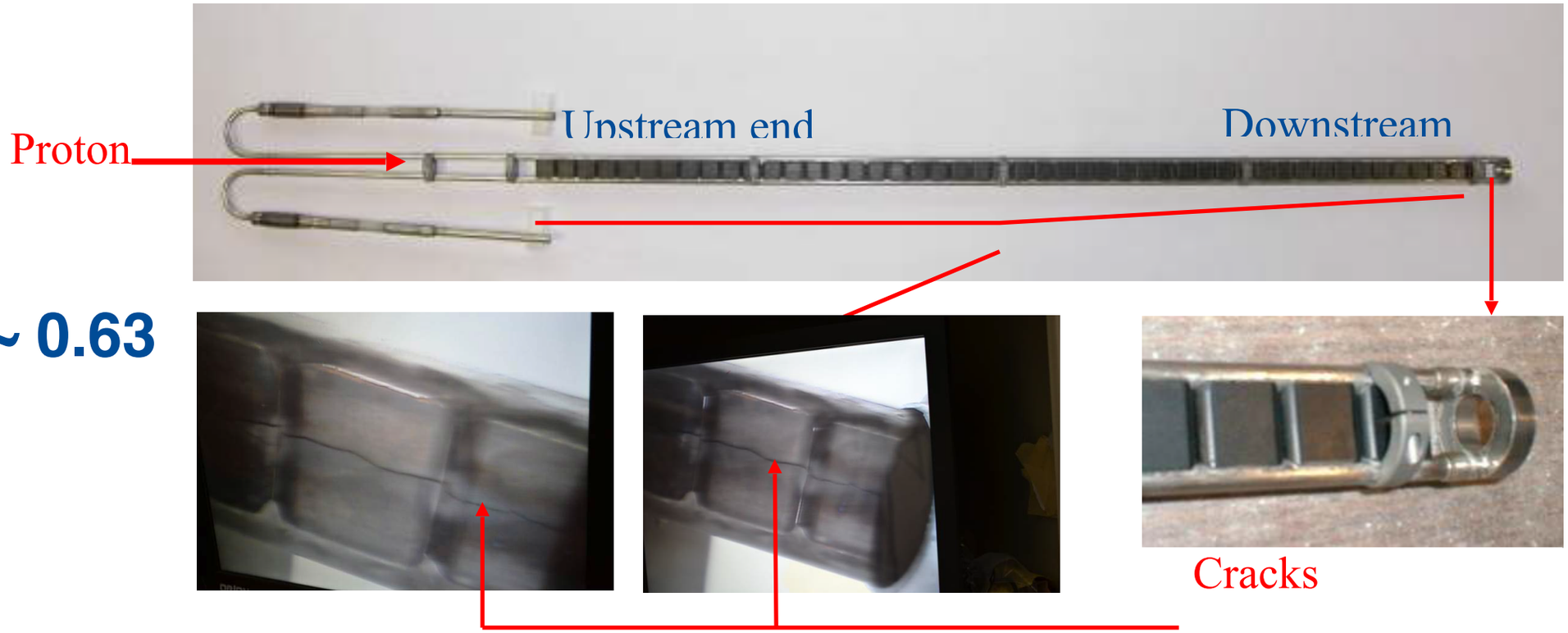
FNAL Graphite Target Operating Conditions

PhD Accelerator Program: Low Energy Ion Research Motivation

- Determination of the effects of increasing beam power and fluence on target materials is essential to avoid component failure.
- High energy proton irradiation presents many difficulties: sample activation, high costs, long irradiation times, rigorous planning and sample preparation.
- Low-energy ion irradiations suggest a method of testing new beam designs without the costly and time consuming high-energy irradiations commonly undertaken while also allowing for faster experiment iteration without sample activation.

NT-02 Target:
Estimated DPA ~ 0.63



HE vs LE irradiations

HE protons

- Very long irradiation times (months).
- BLIP 2010: 0.11 DPA/ ~11 weeks
- Rigorous sample preparation and testing: many people/resources required
- Sample activation requires special shipping & handling
- Hot cell PIE work

LE ions

- Short irradiations (days)
- MIBL trial: 1DPA/95hrs
- Simple and fast sample preparation
- Transport samples in my backpack on Amtrak
- PIE work at standard laboratories (no sample activation)

FNAL Graphite Target Synopsis

Experiment	MINOS	NoVA	AIP	DUNE (120 GeV)	DUNE (60 GeV)	BLIP 2010
Targets	NT-01 - NT-08	MET-01 - MET-04	MET-05 - MET-09	TBD	TBD	Capsule 1-9
Energy (GeV)	120	120	120	120	60	0.181
p/pulse	3.37E+13	4.90E+13	6.50E+13	7.50E+13	7.50E+13	Continuous
Beam Pulse	10 μs, 0.53 Hz	10 μs, 0.75 Hz	10 μs, 0.83 Hz	10 μs, 0.83 Hz	10 μs, 1.43 Hz	Continuous
p/s	1.79E+13	3.68E+13	5.40E+13	6.23E+13	1.07E+14	5.87E+14
σ (mm)	1.1	1.3	1.5	2.67	2.67	σx =8.92, σy=6.79
Power (kW)	340	700	1000	1200, 2400	1200, 2400	17
Peak Temp. (C)	330	670	1000	580 (1.2 MW)	--------	120-180
QS. Temp. (C)	60	390	890	440 (1.2 MW)	--------	--------
Peak Stress (MPa)	32	4.7	--------	2.9	--------	--------
POT	6.55E+20 (NT-02)	1.10E+21 (MET-01)	1.28E+21 (9-months)	1.47E+21 (9-months)	2.54E+21 (9-months)	8.25E+20
Peak Fluence (p/cm2)	8.62E+19 (NT-02)	1.04E+20 (MET-01)	9.03E+19 (9-months)	3.28E+19 (9-months)	5.67E+19 (9-months)	2.17E+18
Peak DPA	0.63 (NT-02)	1.10 (MET-01)	0.96 (9-months)	0.52 (9-months)	0.73 (9-months)	0.11
Peak He APPM	2270	5580	360	388	400	34
Peak He APPM/DPA	10900	18200	--------	1050	1070	1151

[1],[2],[3],[4],[5],[6]

Radiation Damage Measure: Displacements per atom (DPA)

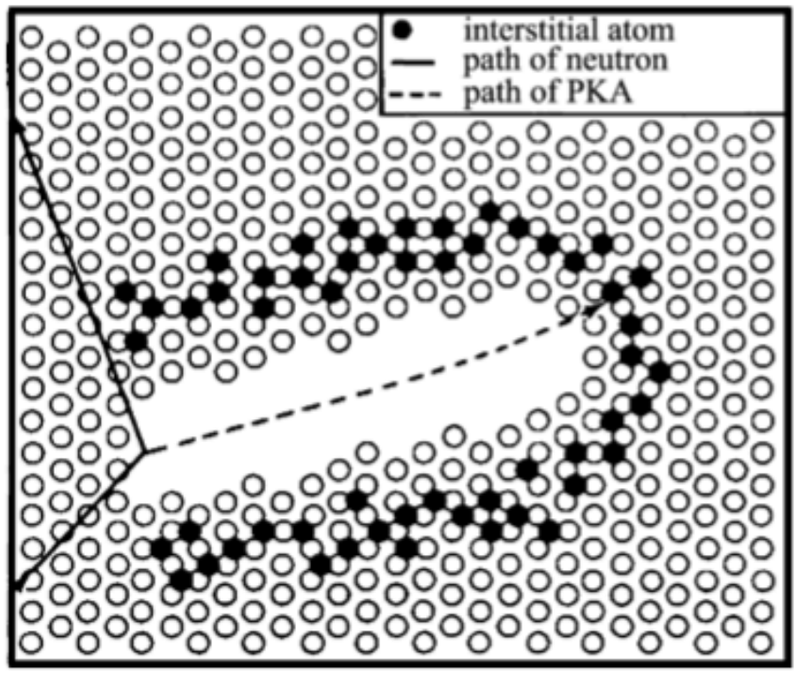


Fig. 3.3. Original version of the displacement spike as drawn by Brinkman (after [3])

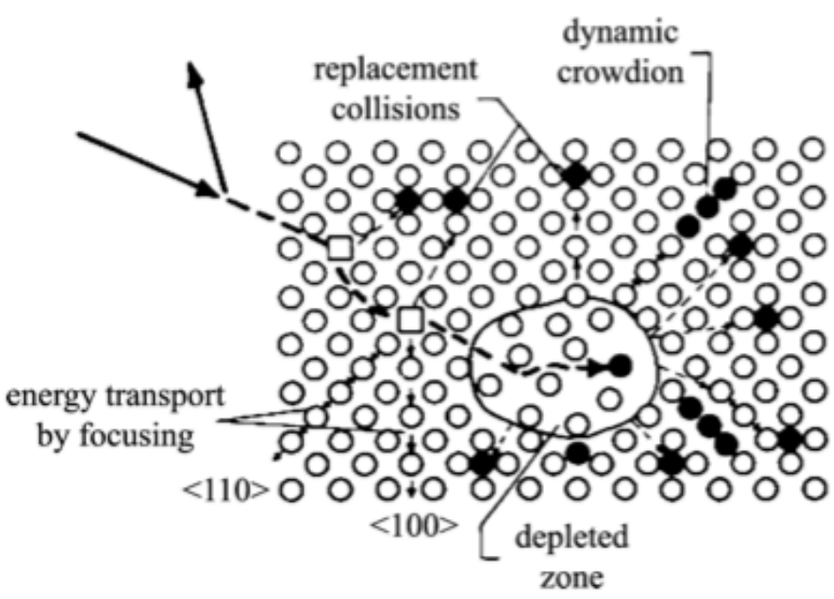
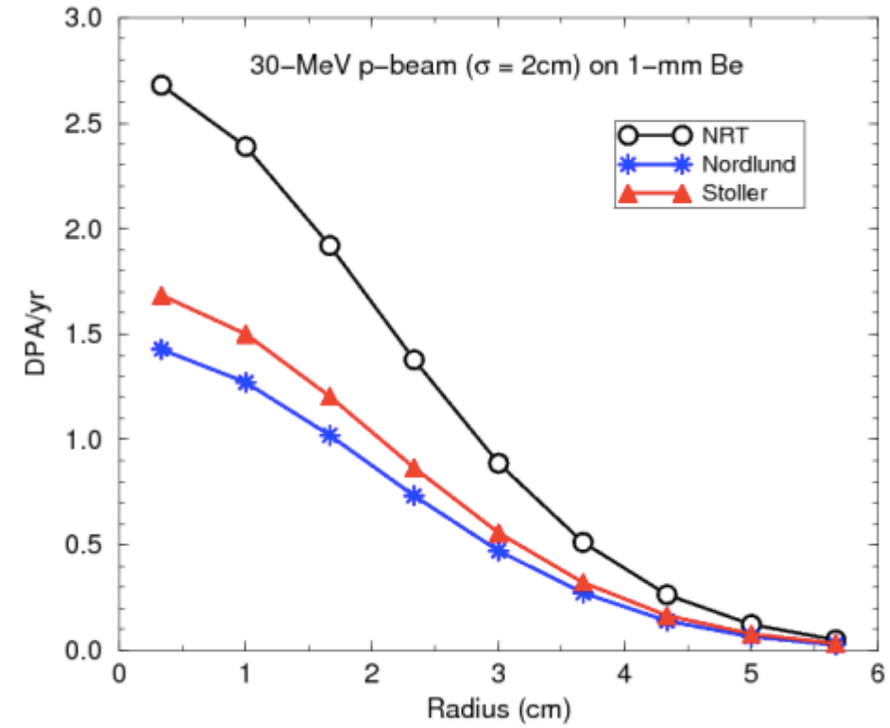
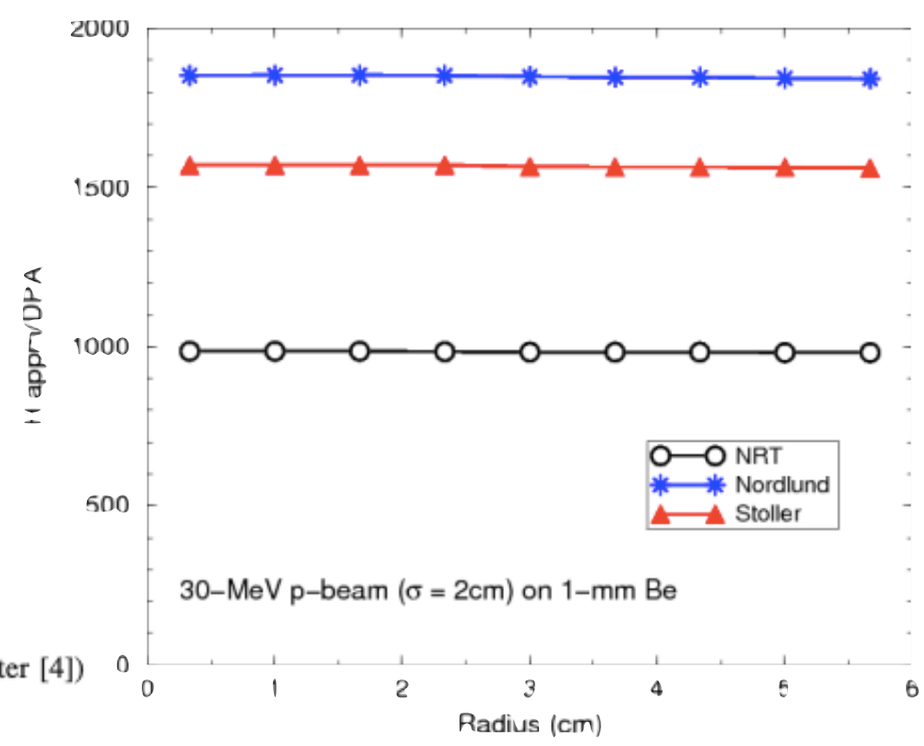


Fig. 3.4. Revised version of Brinkman's displacement spike as drawn by Seger (after [4]) accounting for crystallinity in the damage cascade

[6] Was



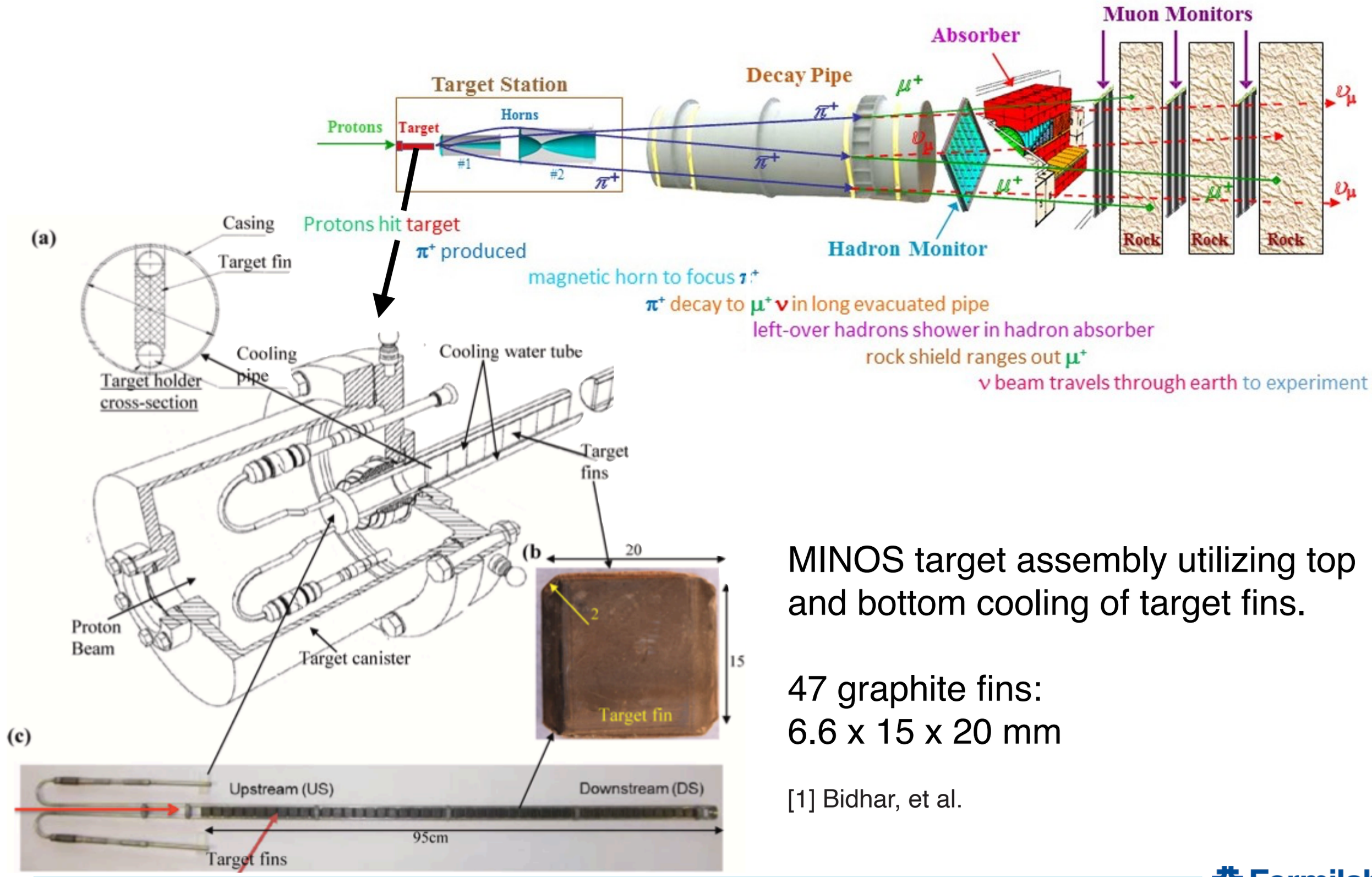


DPA

- 3 prevalent methods to calculate
- NRT
- NRT w/ Stoller corr.
- Nordlund (this work)
- Decreasing DPA value is the result of including "athermal" recombination due to kinetic energy introduced by incident particle

[7] Mokhov

NuMI Beamline: MINOS



MINOS target assembly utilizing top and bottom cooling of target fins.

47 graphite fins:
6.6 x 15 x 20 mm

[1] Bidhar, et al.

NuMI MINOS (NT-02): Target temperature

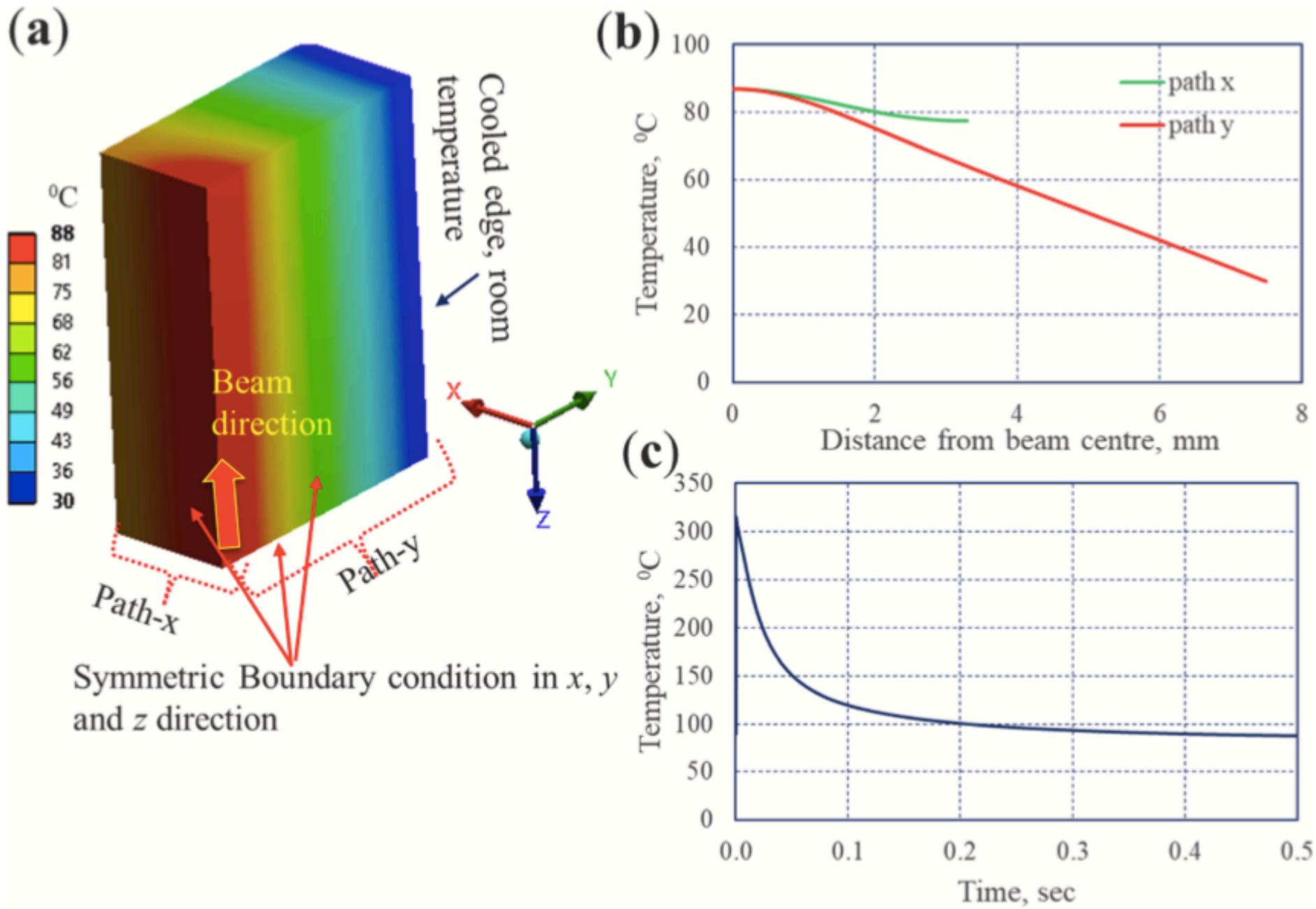
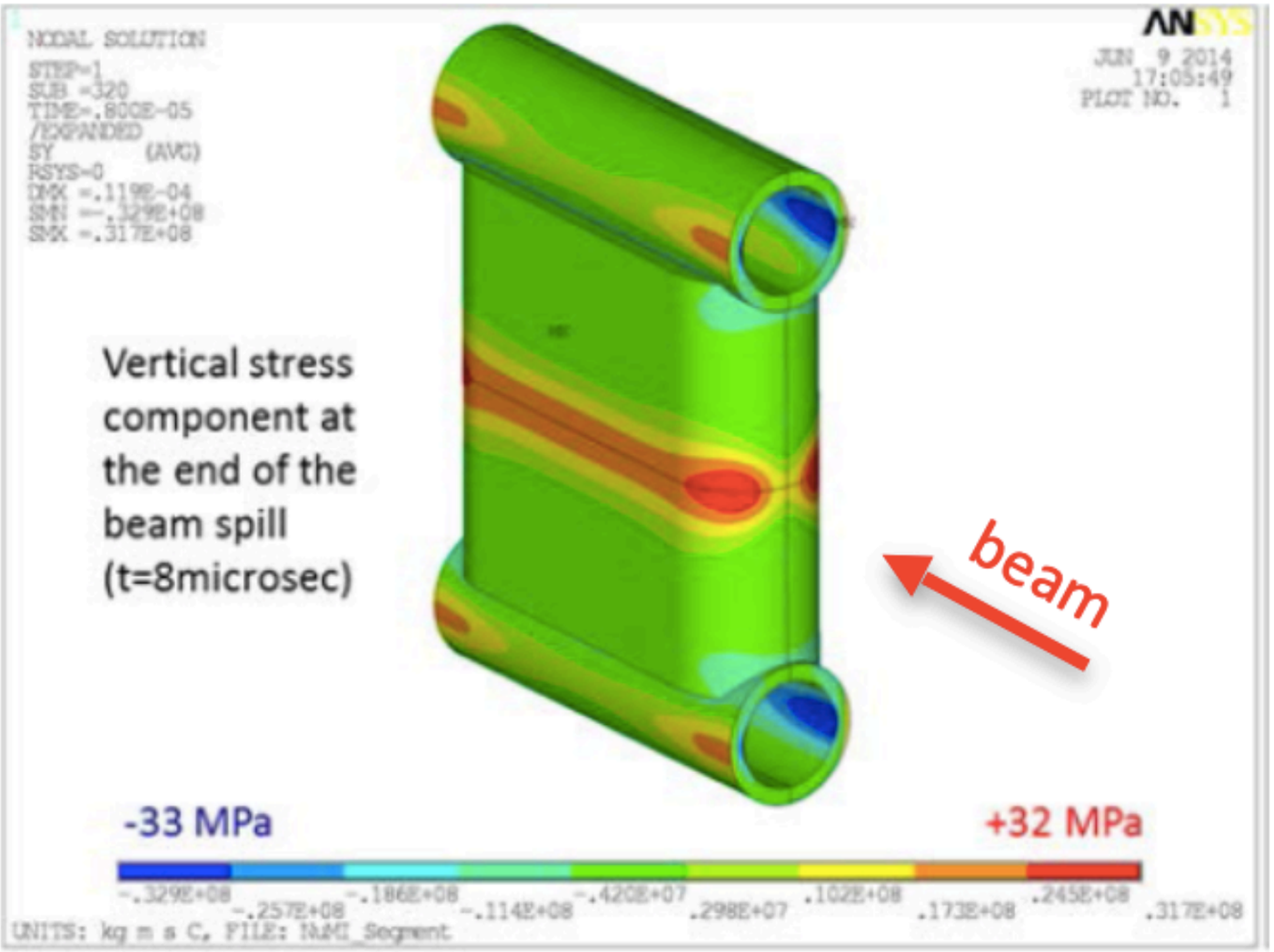


Fig. 4. a) steady state temperature distribution, 1/8th symmetry model, b) along a path from beam center along thickness and width direction, c) transient temperature response of target center.

[1] Bidhar, et al.

NuMI MINOS (NT-02): Target stress

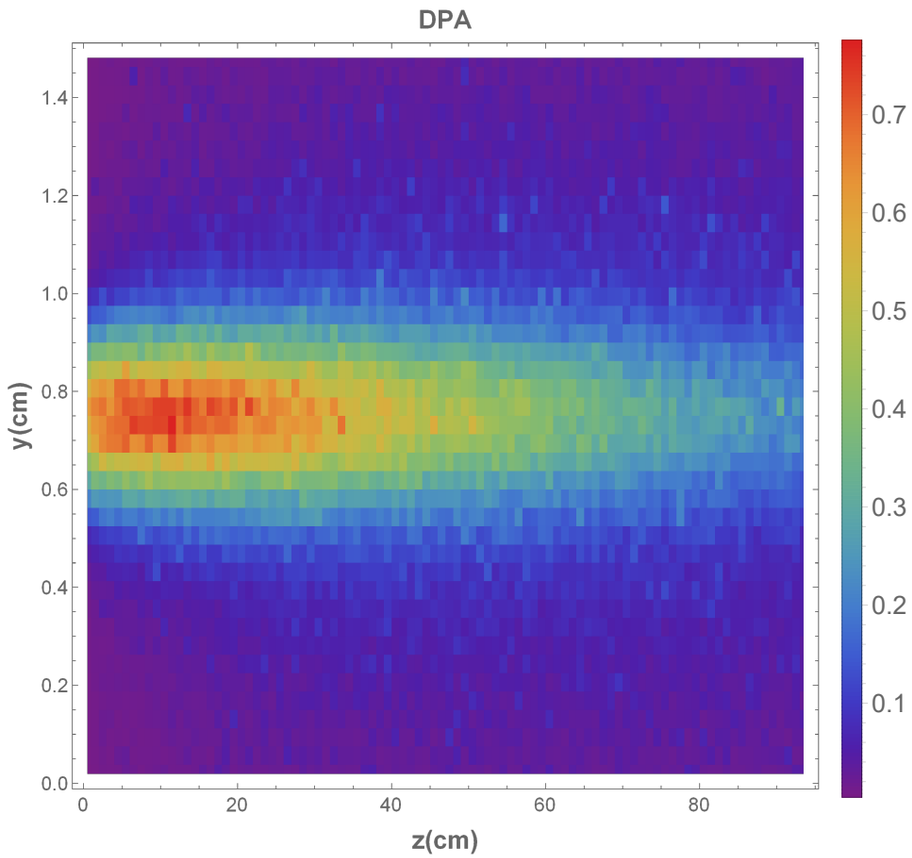


Peak tensile stress:
~32 MPa along beam center

Peak compressive stress:
~19 MPa along cooling interface

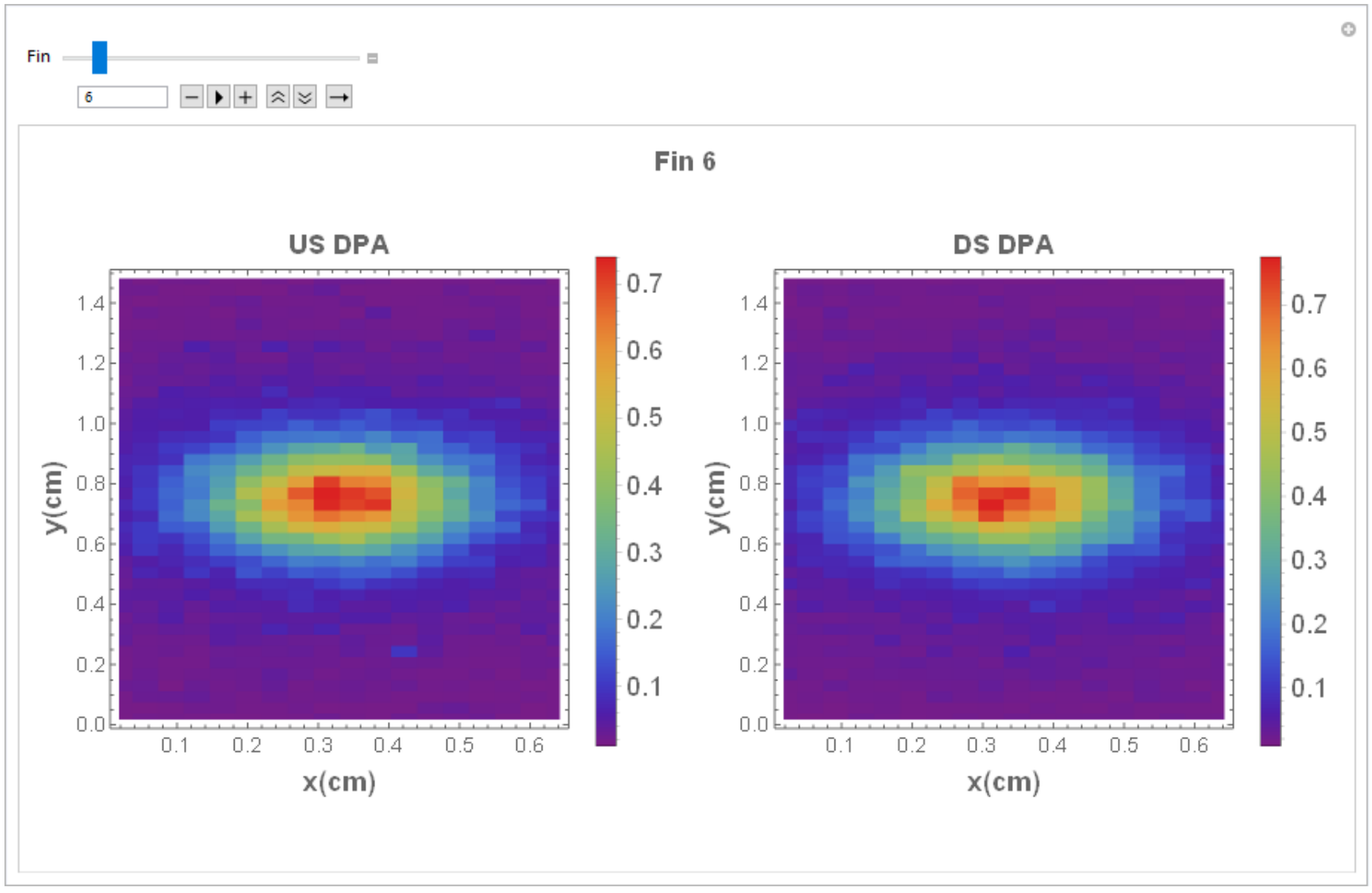
[2] Calculation by RAL

MINOS NT-02: DPA calculations, NRT w/ Nordlund corr.



Max total DPA = 0.78
at z = 11.5 cm
Fin 6

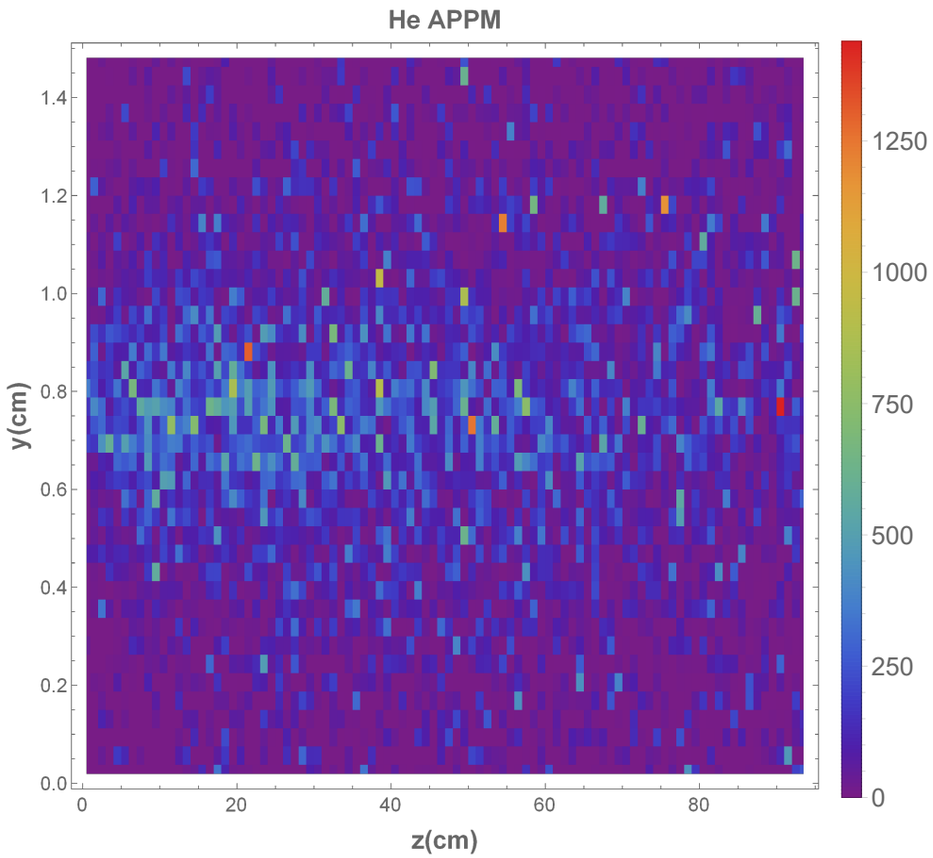
Literature: Max total DPA = 0.63



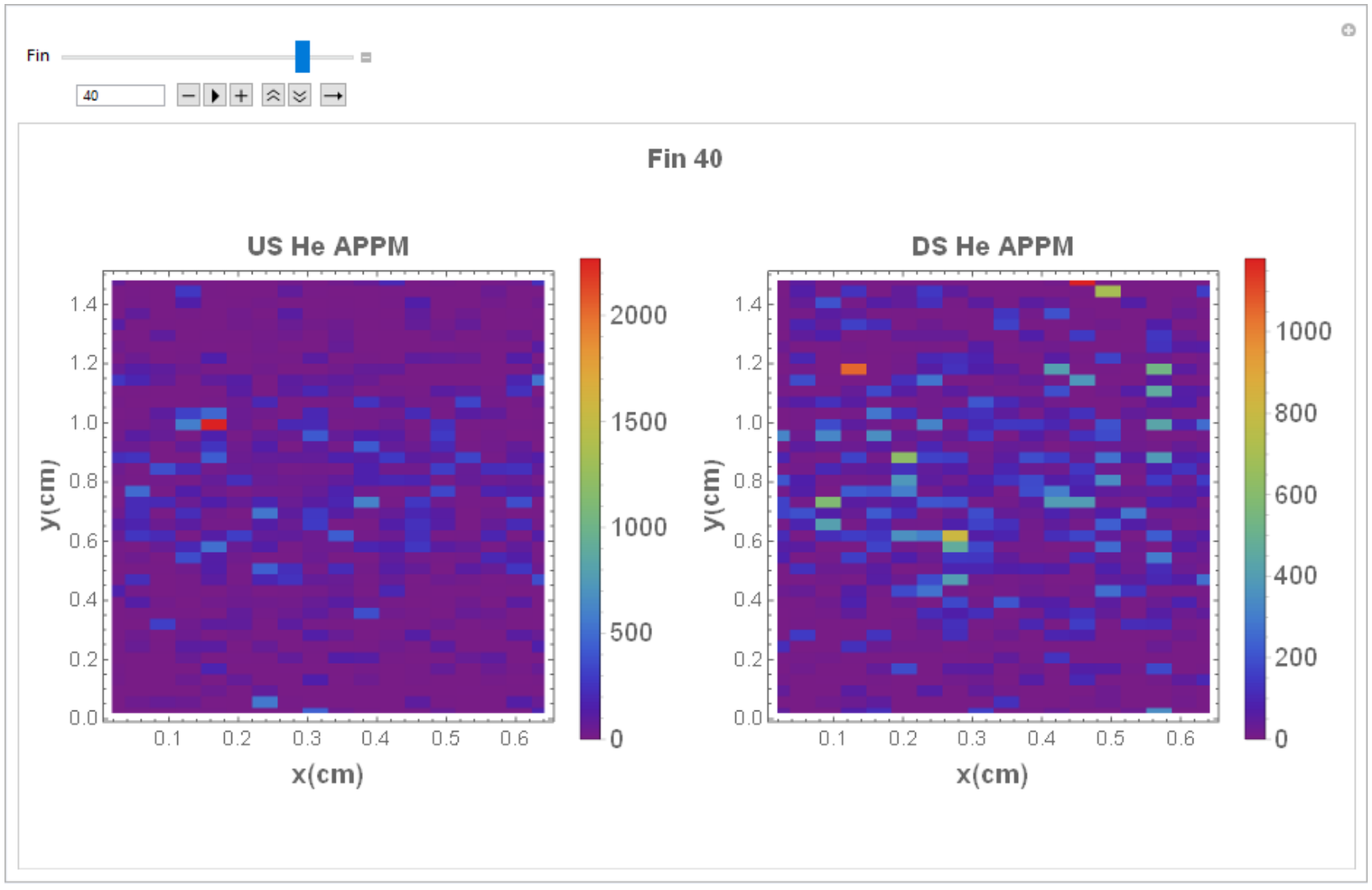
Above: NT-02 Target through beam center, along length.

Right: Damage in US and DS individual fin.

MINOS NT-02: Helium transmutation



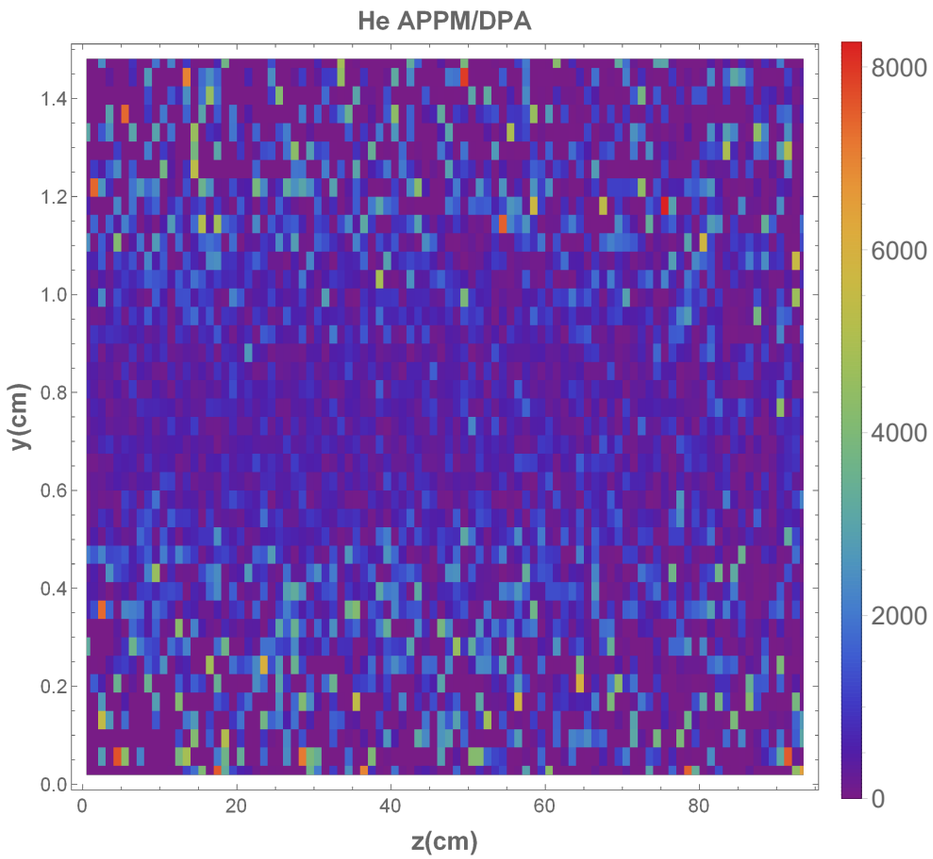
Max total He = 2270 APPM
at z = 78.5 cm
Fin 40 US
Beam Center ~800-900 APPM



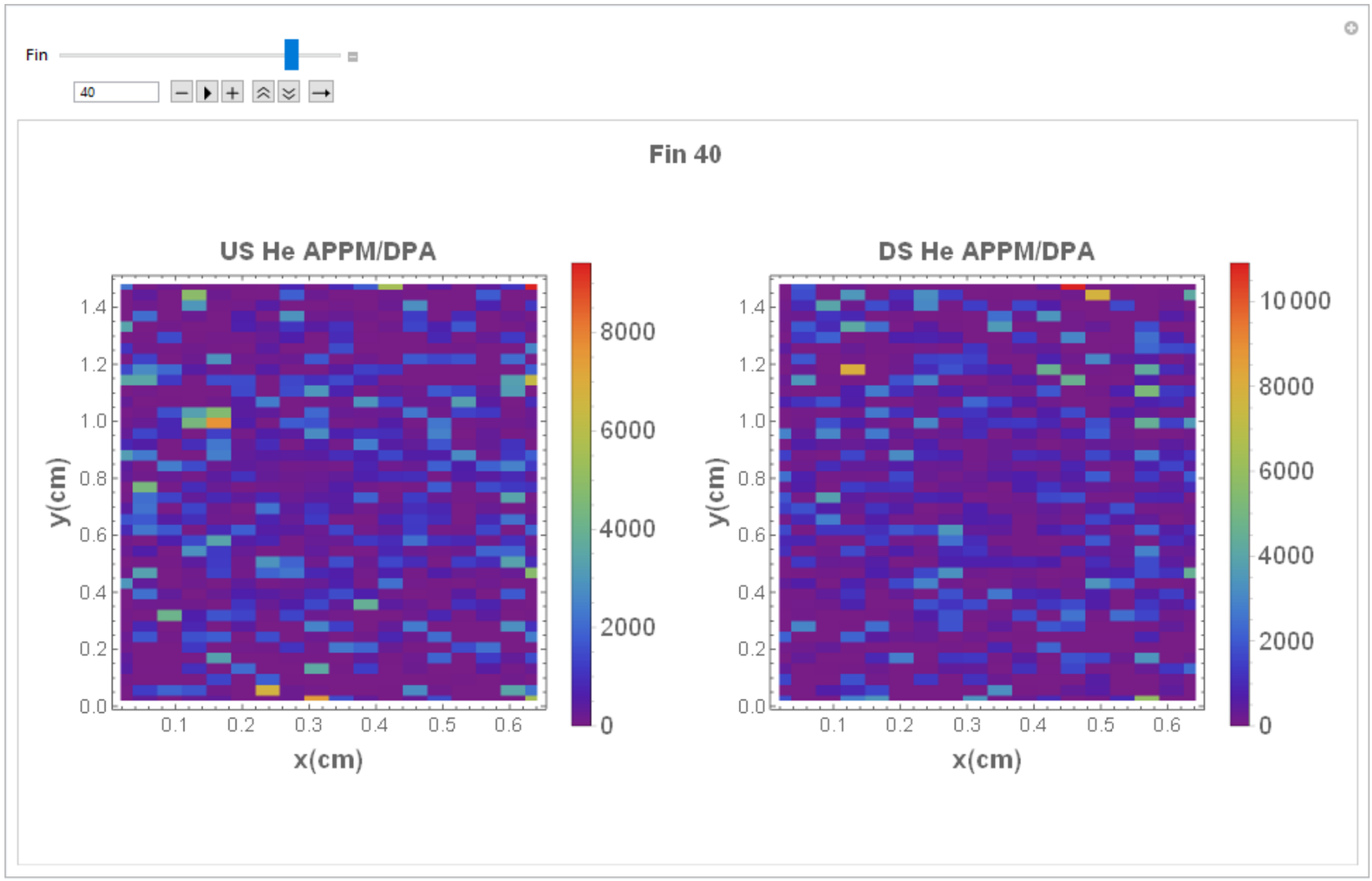
Above: NT-02 Target through beam center, along length.

Right: He APPM in US and DS individual fin.

MINOS NT-02: Helium APPM/DPA



Max total HE APPM/DPA = 10900
at z= 79.5 cm
Fin 40 DS
Beam Center ~1000-2000 APPM/DPA



Above: NT-02 Target through beam center, along length.

Right: Damage in US and DS individual fin.

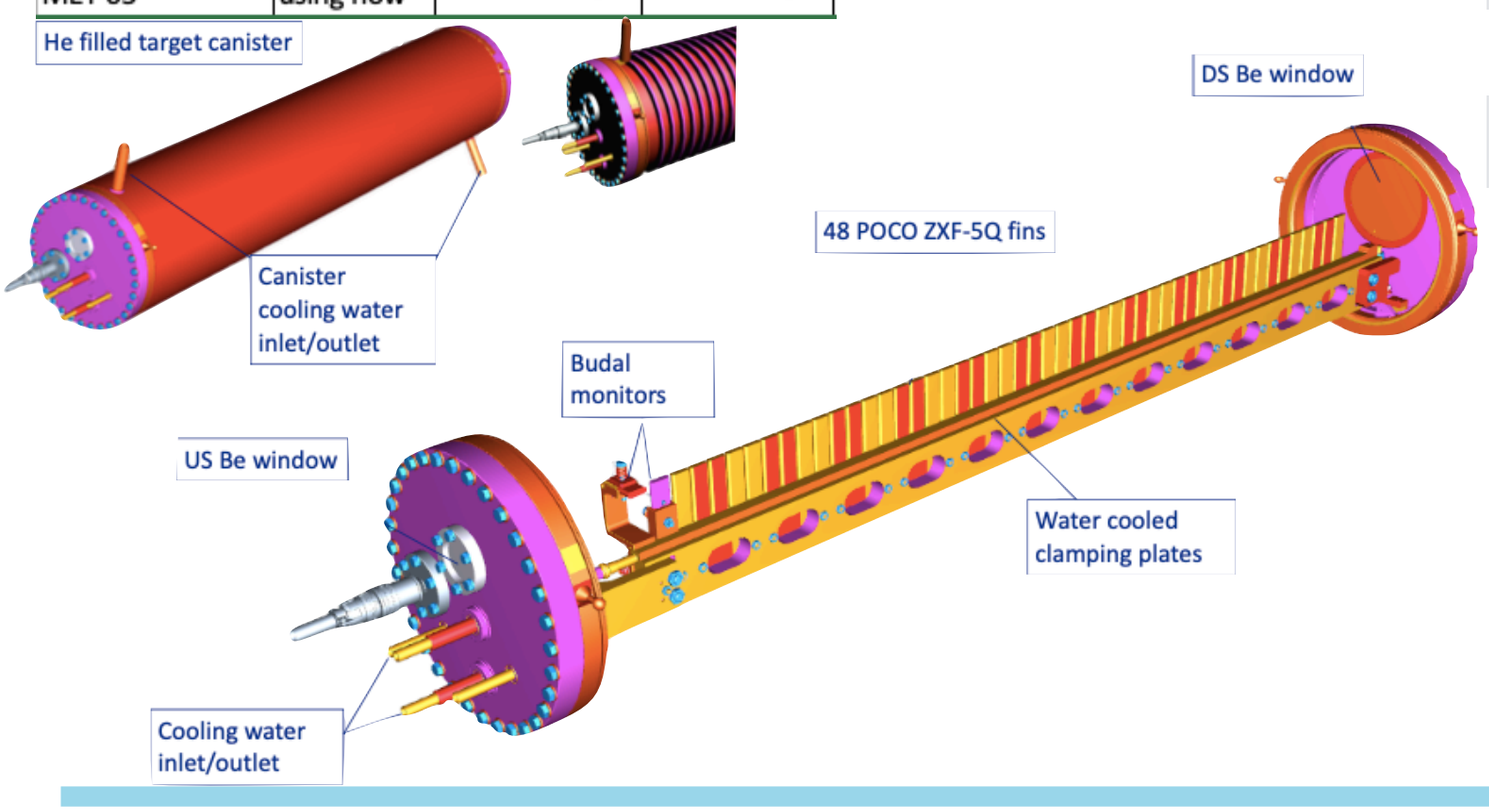
NuMI Beamline: NOvA/AIP

NuMI target lifetimes

Item	Status	When Removed from Service	POT While in Service
NuMI/Nova Targets			
NT-01	dead	1st: Aug-06 2nd: Jul-11	1st: 1.60E+20 2nd: 2.10E+19
NT-02	degraded	1st: Jun-09 2nd: Sep-11	1st: 6.10E+20 2nd: 4.50E+19
NT-03	dead	Jul-10	3.10E+20
NT-04	dead	Sep-10	2.00E+19
NT-05	dead	Feb-11	1.30E+20
NT-06	dead	May-11	2.00E+19
NT-07	used	Apr-12	2.60E+20
NT-08	new	-	-
MET-01	dead	Jul-16	1.10E+21
MET-02	dead	Jul-18	1.08E+21
MET-03	used	Nov-19	5.65E+20
MET-04	new	-	-
MET-05	using now	-	-

1.81E+20 total

6.55E+20 total



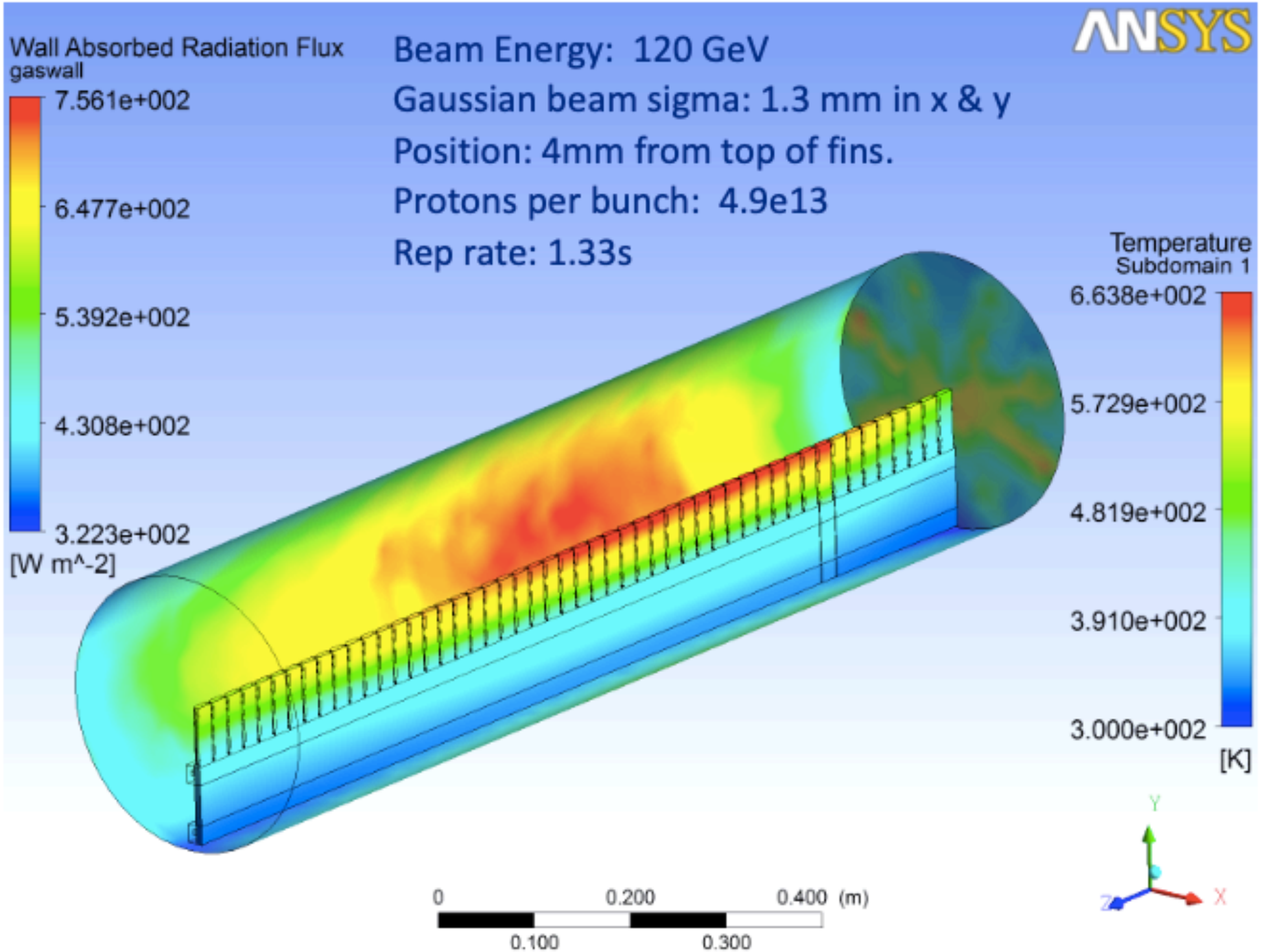
Experiment	MINOS	NoVA	AIP
Targets	NT-01 - NT-08	MET-01 - MET-04	MET-05 - MET-09
Energy (GeV)	120	120	120
p/pulse	3.37E+13	4.90E+13	6.50E+13
Beam Pulse	10 μs, 0.53 Hz	10 μs, 0.75 Hz	10 μs, 0.83 Hz
p/s	1.79E+13	3.68E+13	5.40E+13
σ (mm)	1.1	1.3	1.5
Power (kW)	340	700	1000
Peak Temp. (C)	330	670	1000
QS. Temp. (C)	60	390	890
POT	6.55E+20 (NT-02)	1.10E+21 (MET-01)	1.28E+21 (9-months)
Peak Fluence (p/cm2)	8.62E+19 (NT-02)	1.04E+20 (MET-01)	9.03E+19 (9-months)
Peak DPA	0.63 (NT-02)	1.10 (MET-01)	0.96 (9-months)

NOvA target assembly utilizing single ended cooling of target fins.

50 graphite fins: 7.4 x 15 x 24 mm

For 1MW AIP operation the target fins will be widened and canister cooling increased to compensate for increased heat deposition.

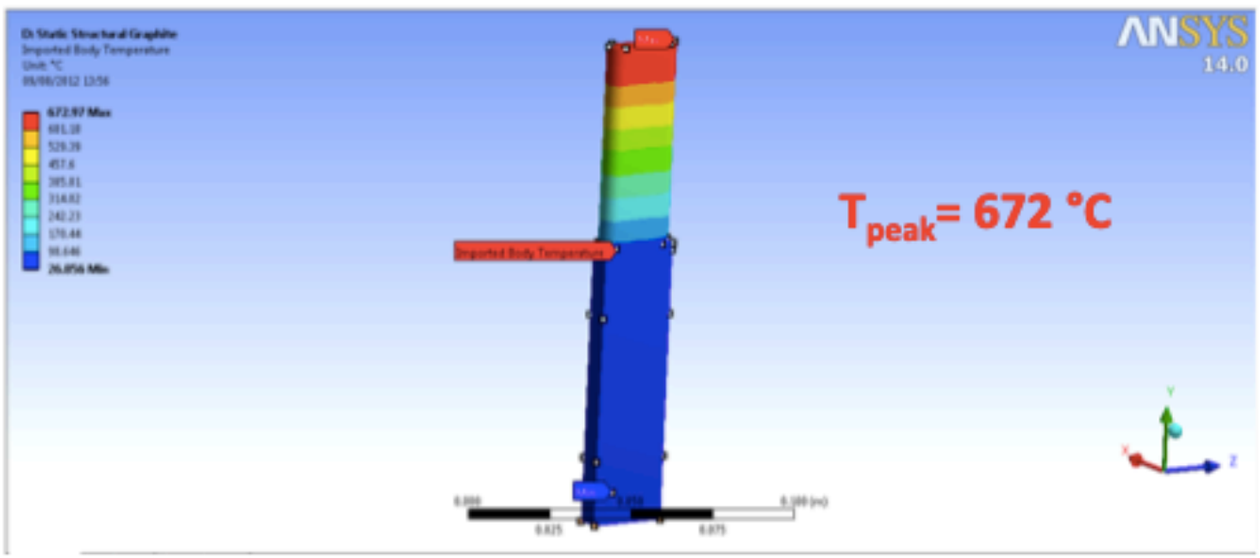
NuMI NoVA: Target temperature

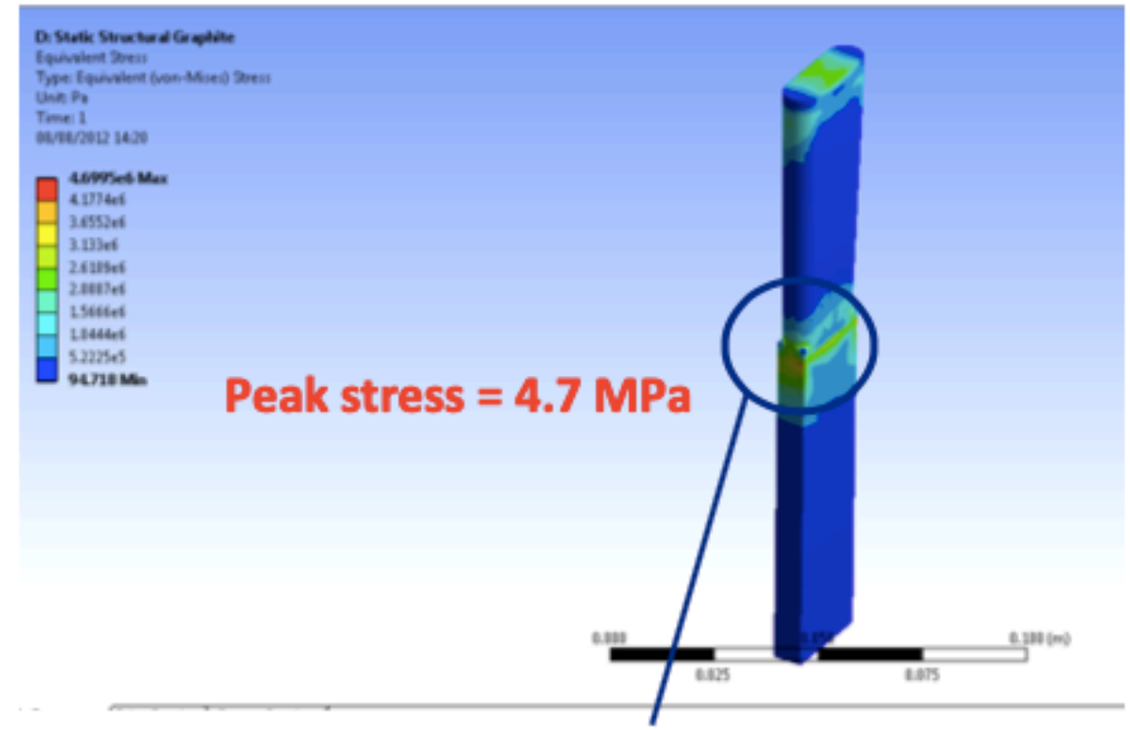


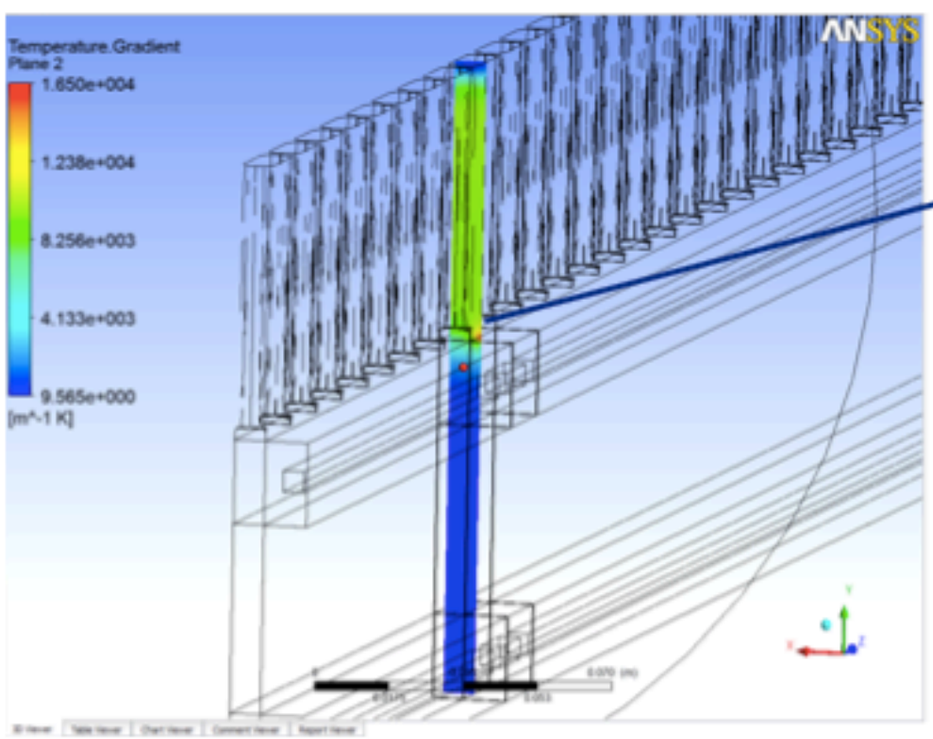
Quasi-static radiation flux and target temperature.
[2] Calculation: T. Davenne (STFC/RAL)

NuMI NoVA: Target stress

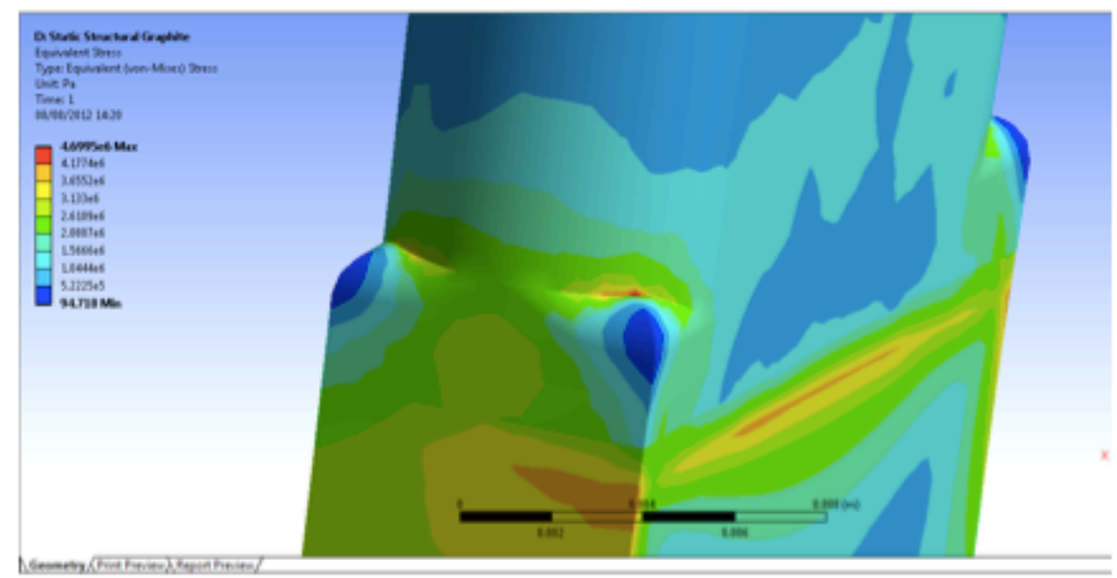
POCO ZXF-5Q steady state temperature and stress







Largest temperature gradient near cooling block

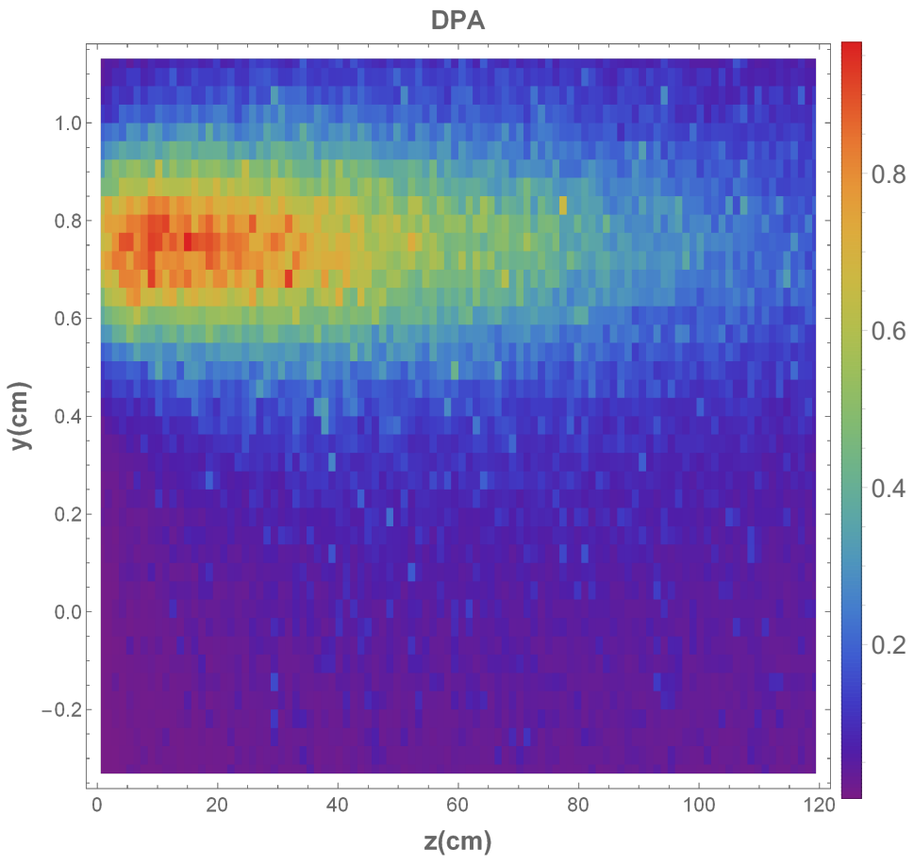


Peak dynamic stress during beam pulse: ~26 MPa

ZXF-5Q tensile strength: 79 MPa

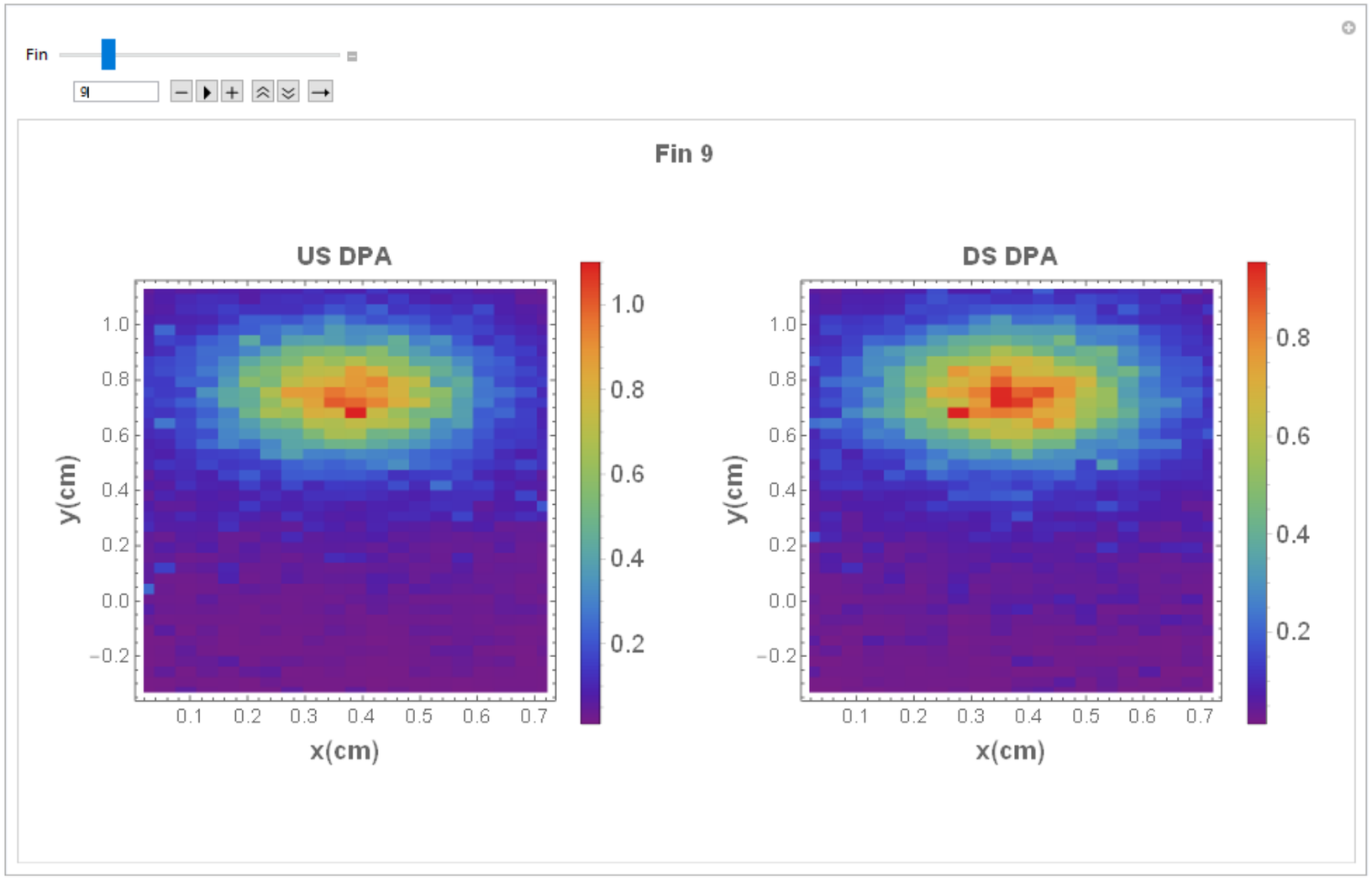
[2] Calculation: T. Davenne (STFC/RAL)

NOvA MET-01: DPA calculations, NRT w/ Nordlund corr.



Max total DPA = 1.10
at z = 19.8 cm
Fin 9

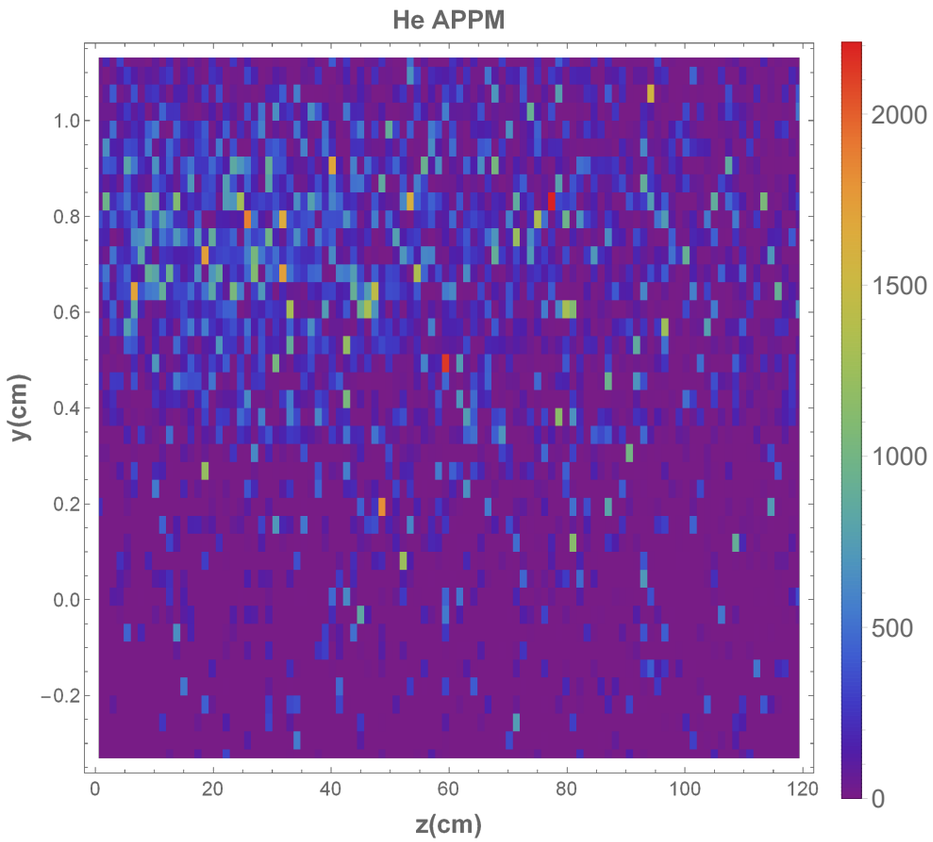
Max DPA AIP (9 months) = 0.96



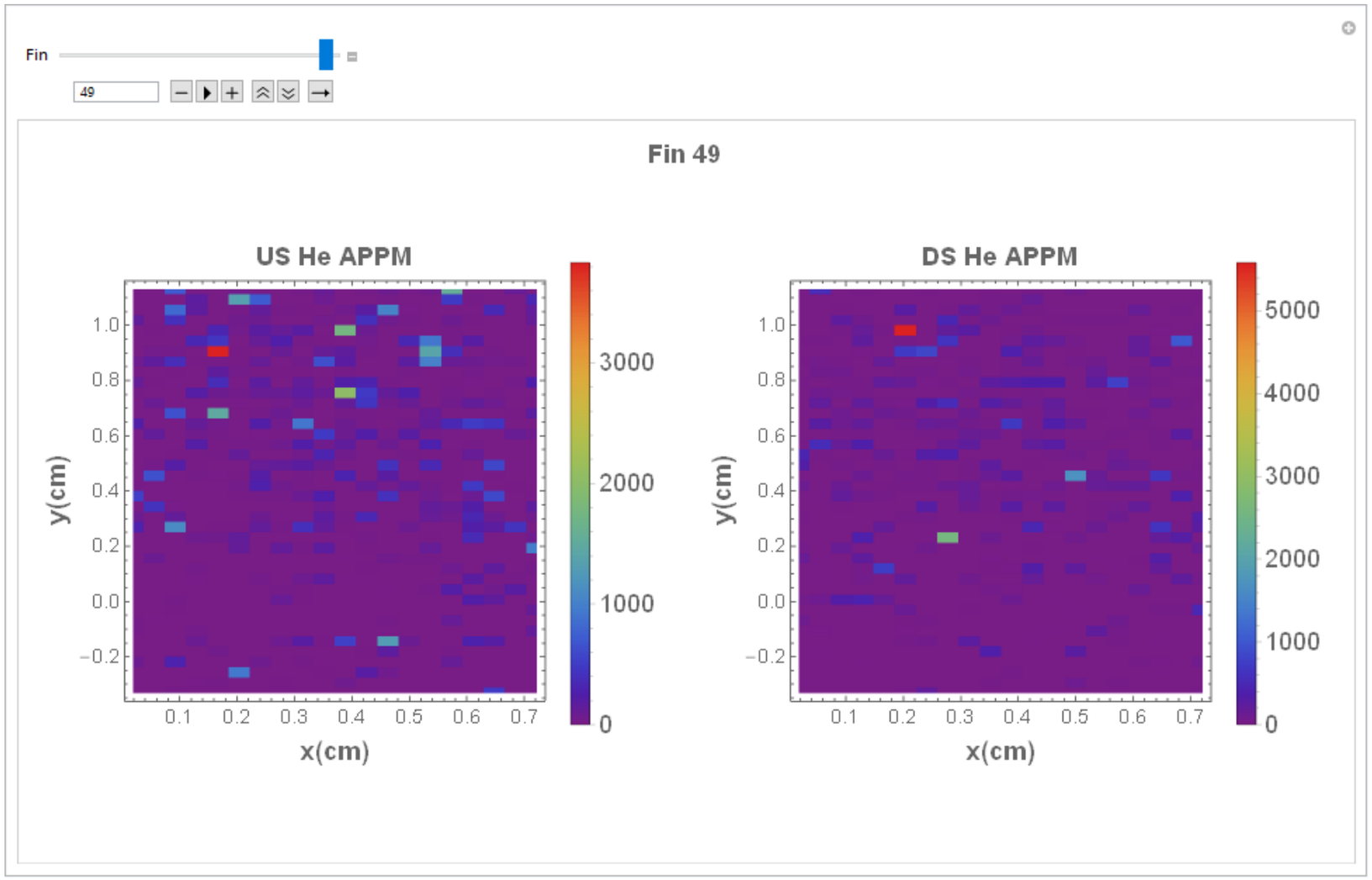
Above: MET-01 Target through beam center, along length.

Right: Damage in US and DS individual fin.

NOvA MET-01: Helium transmutation



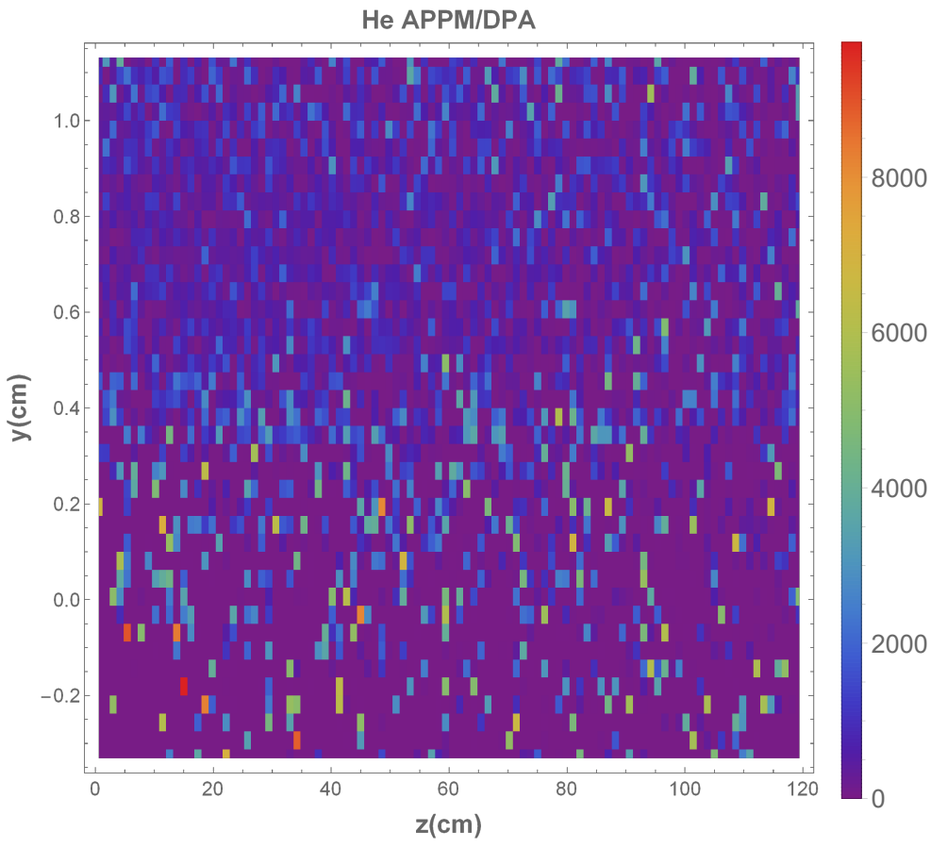
Max total He = 5580 APPM
at z = 117 cm
Fin 49 DS
Beam Center ~500-1500 APPM



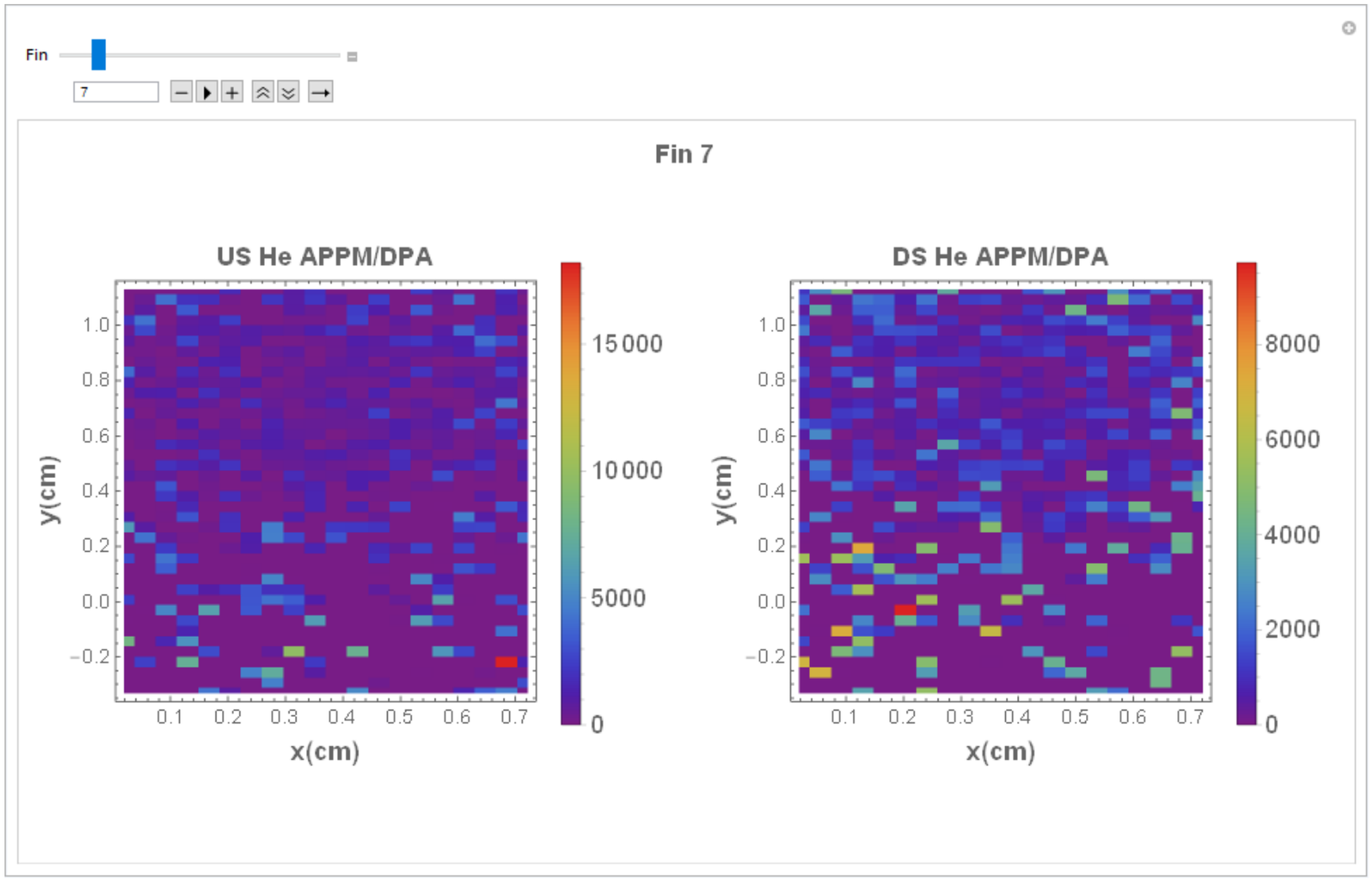
Above: MET-01 Target through beam center, along length.

Right: He APPM in US and DS individual fin.

NOvA MET-01: Helium APPM/DPA



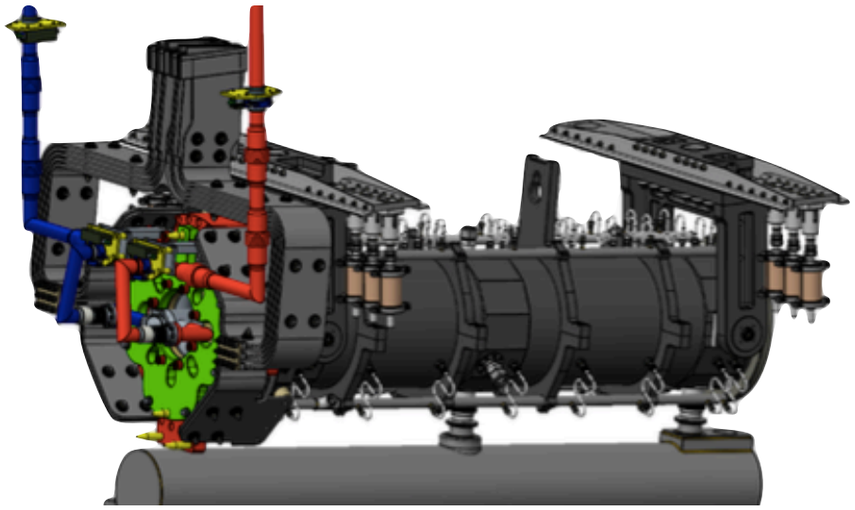
Max total HE APPM/DPA = 10900
at z= 79.5 cm
Fin 40 DS
Beam Center ~1000-2000 APPM/DPA

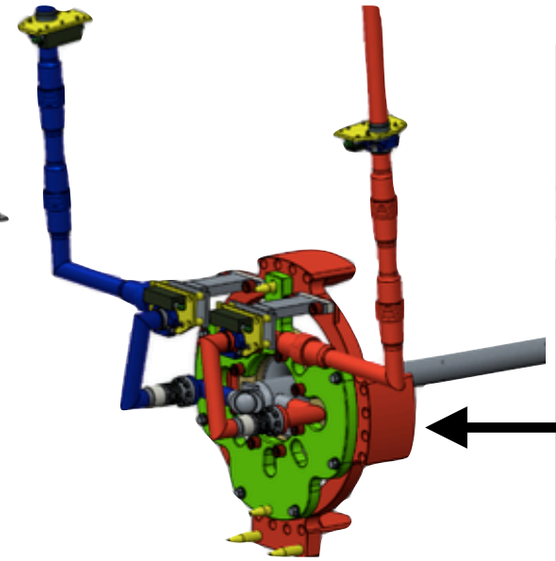


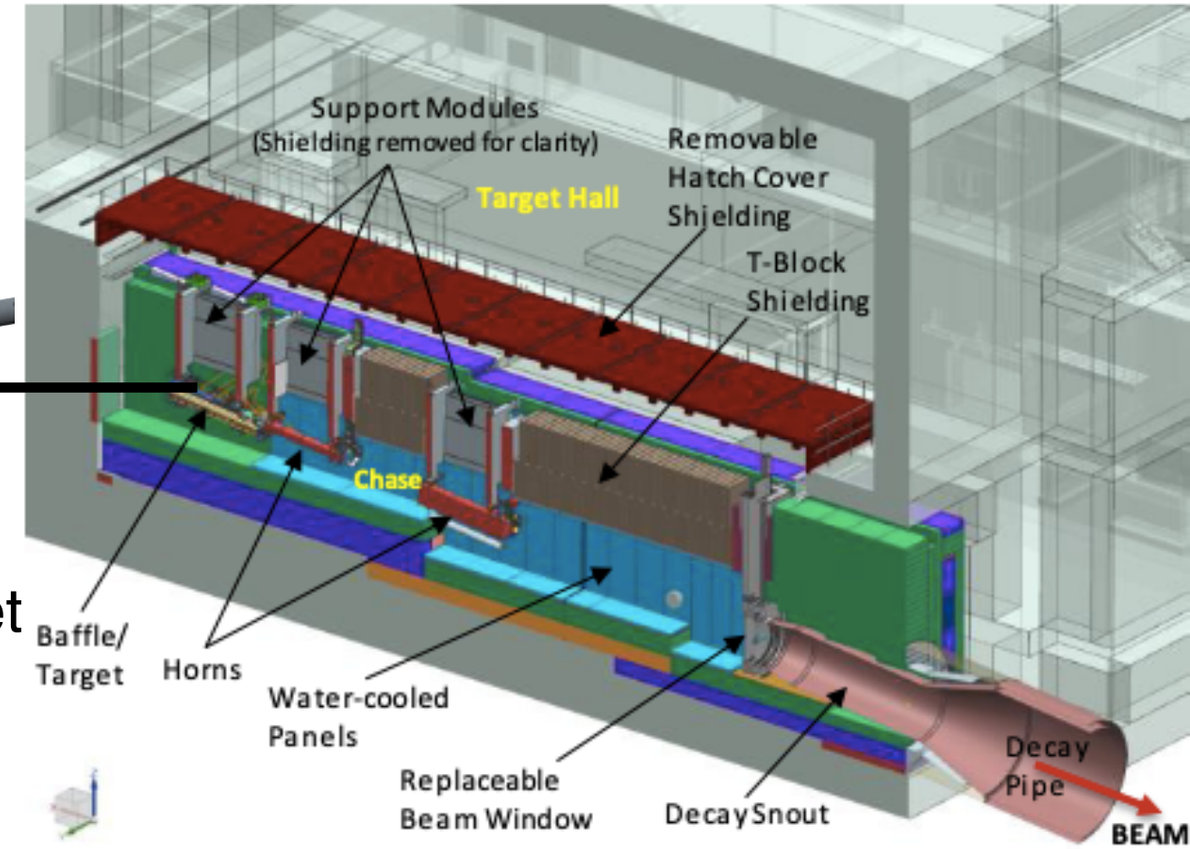
Above: MET-01 Target through beam center, along length.

Right: HE APPM/DPA in US and DS individual fin.

LBNF Beamline







Experiment	DUNE (120 GeV)	DUNE (60 GeV)
Targets	TBD	TBD
Energy (GeV)	120	60
p/pulse	7.50E+13	7.50E+13
Beam Pulse	~10 μs, 0.83 Hz	~10 μs, 1.43 Hz
p/s	6.23E+13	1.07E+14
σ (mm)	2.67	2.67
Power (kW)	1200, 2400	1200, 2400
Peak Temp. (C)	580 (1.2 MW)	--------
QS. Temp. (C)	440 (1.2 MW)	--------
POT	1.47E+21 (9-months)	2.54E+21 (9-months)
Peak Fluence (p/cm2)	3.28E+19 (9-months)	5.67E+19 (9-months)
Peak DPA	0.52 (9-months)	0.73 (9-months)

Proposed LBNF target assembly

4 graphite cylinders:
r = 8 mm, total length 1.5 m

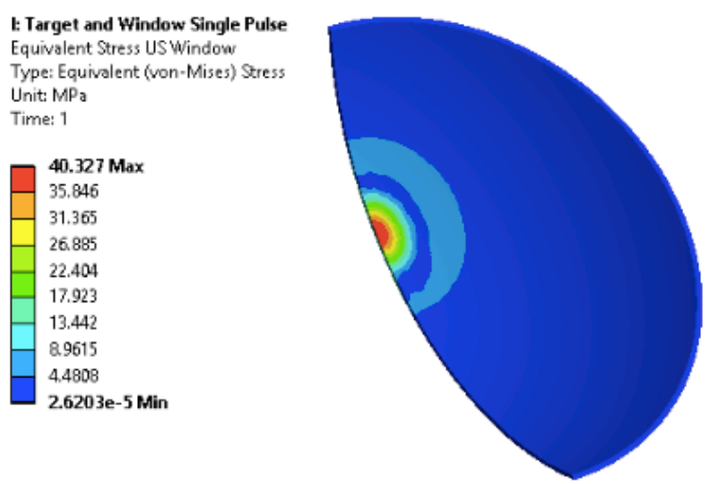
	LBNF	NuMI
	1x1.5m	
Integrated Power (kW)	24	4.9
Peak Energy Density (J/g/pulse)	100	282
Peak ΔT per pulse in graphite (°C)	142	400

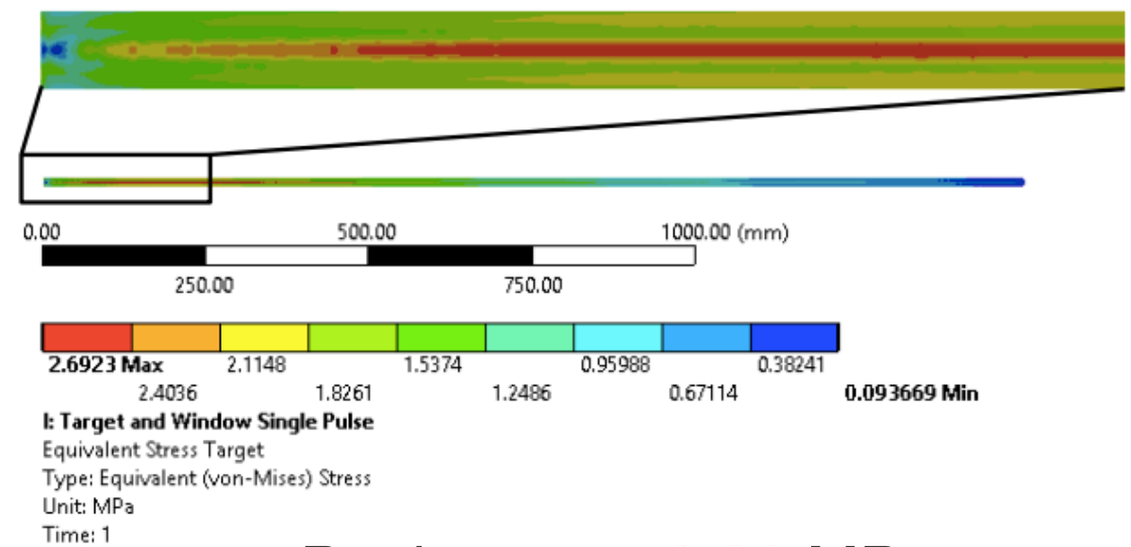
LBNF: Candidate target temperature and stress

	LBNF 1x1.5m
Flowrate (g/s)	26
Target Core	580
Outer Can	247
DS Window	264
Helium Outlet	199

[5] Wilcox

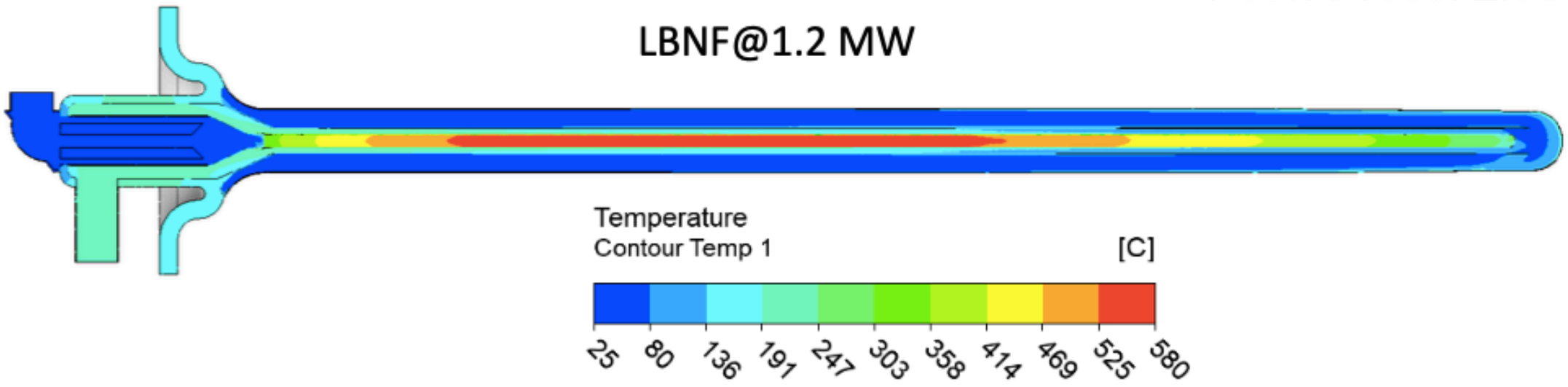
Beam induced stress distributions after a single pulse:





Peak stress: 2.90 MPa

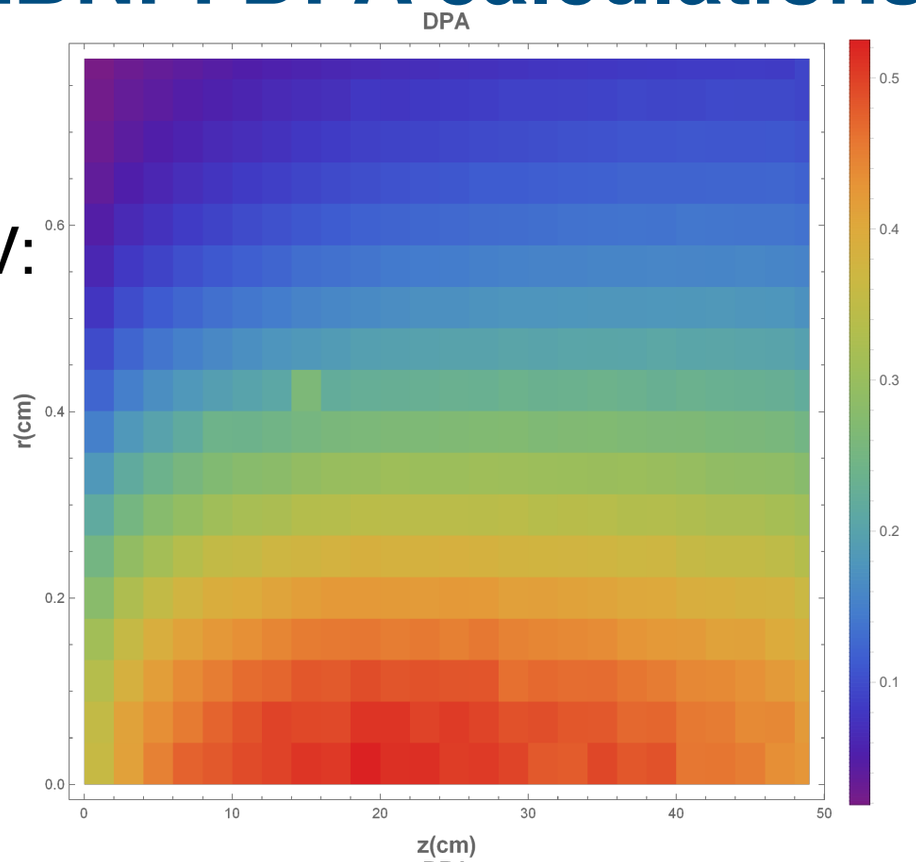
LBNF@1.2 MW

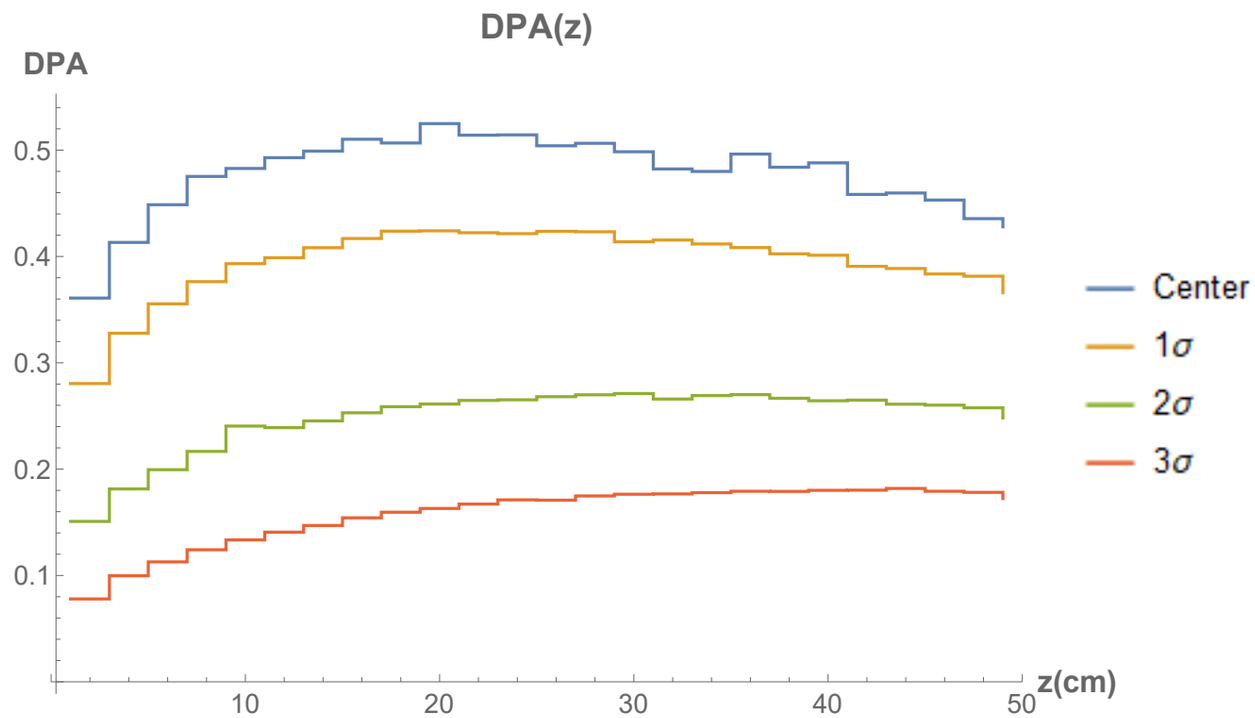


LBNF candidate design. The temperature is simulated for an outlet temperature of 200C; this constraint may be relaxed to allow for higher operating temperatures.

LBNF: DPA calculations, NRT w/ Nordlund correction

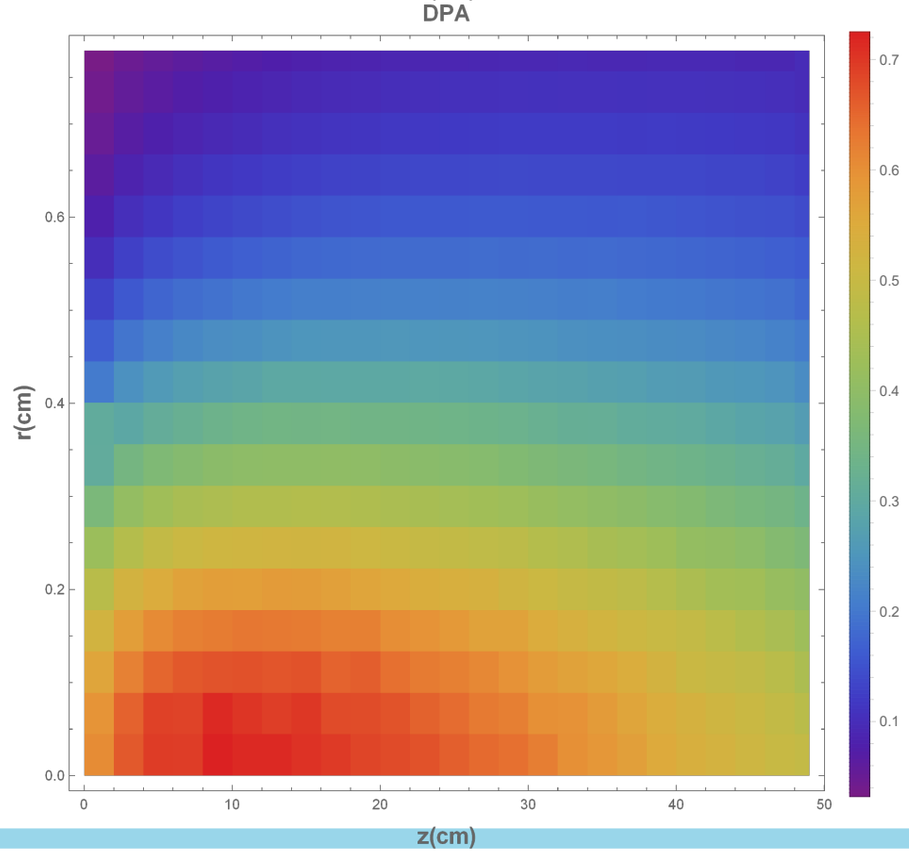
120 GeV:

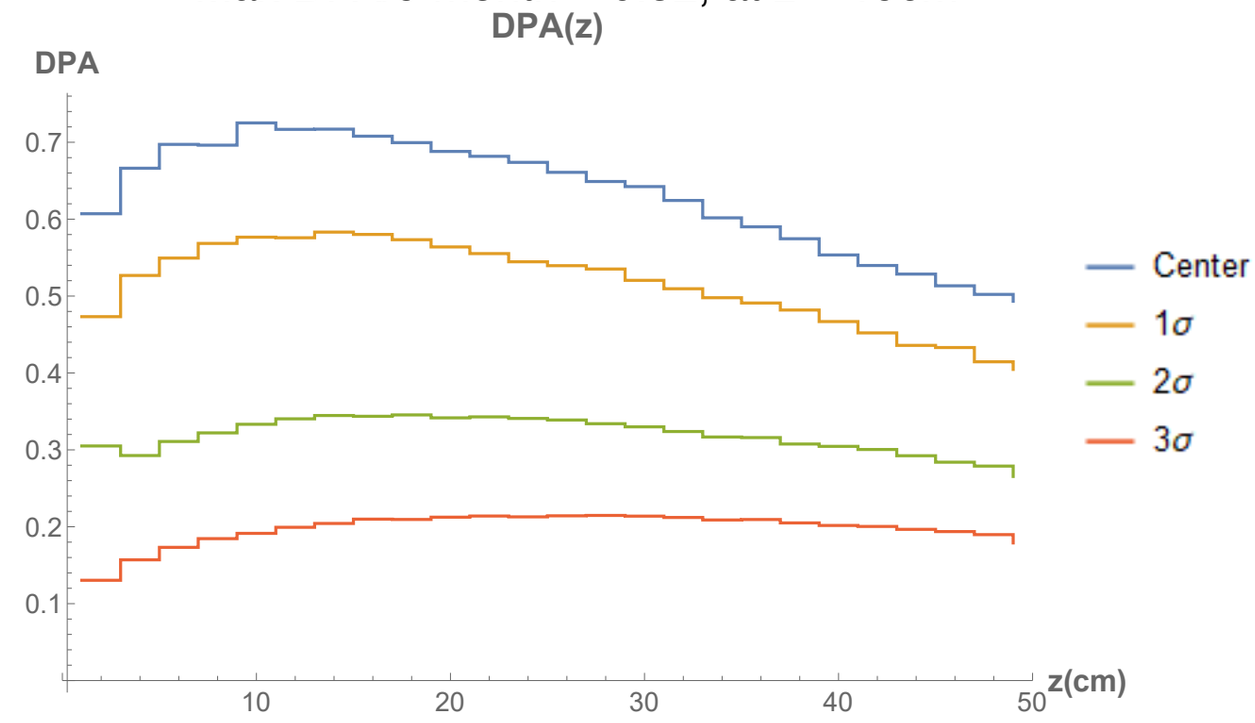




Max DPA/9 month = 0.52, at z = 19cm

60 GeV:

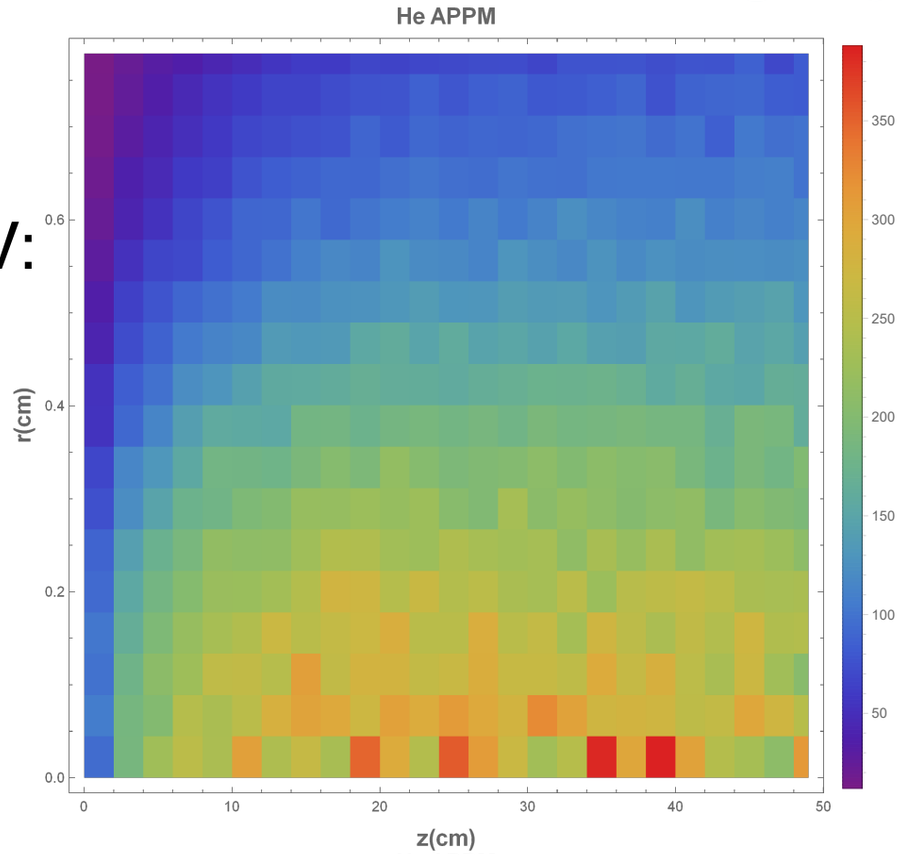


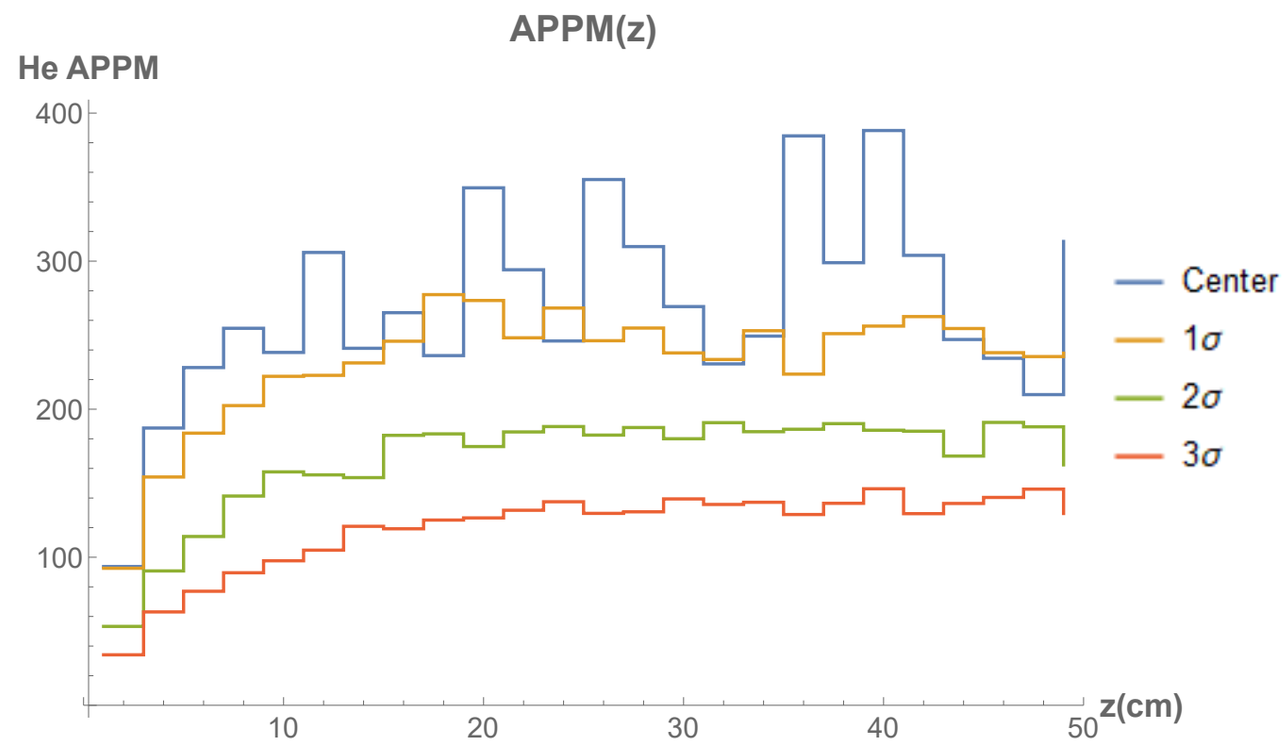


Max DPA/9 month = 0.73, at z = 19cm

LBNF: Helium transmutation

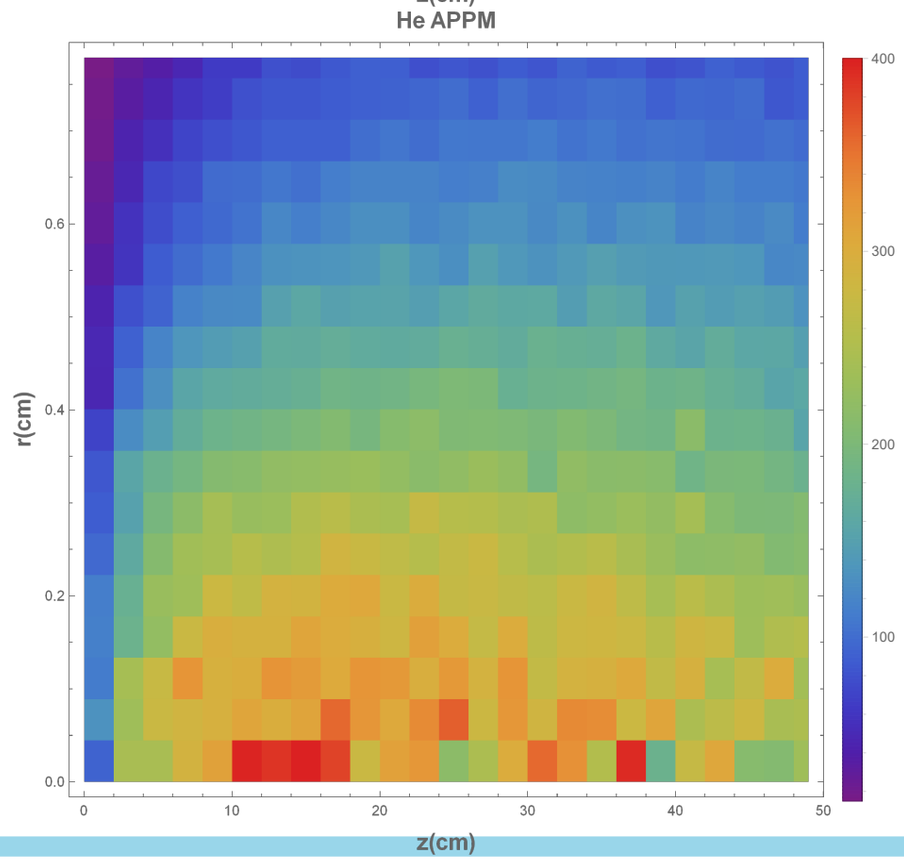
120 GeV:

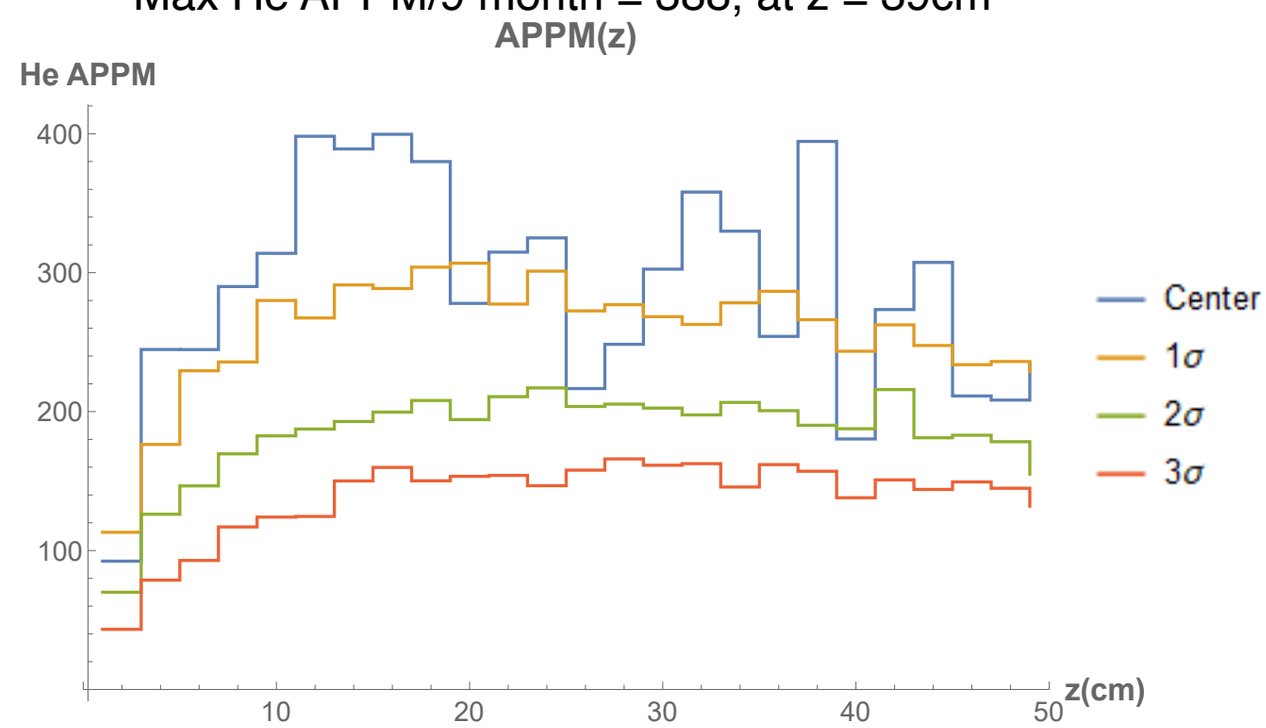




Max He APPM/9 month = 388, at z = 39cm

60 GeV:

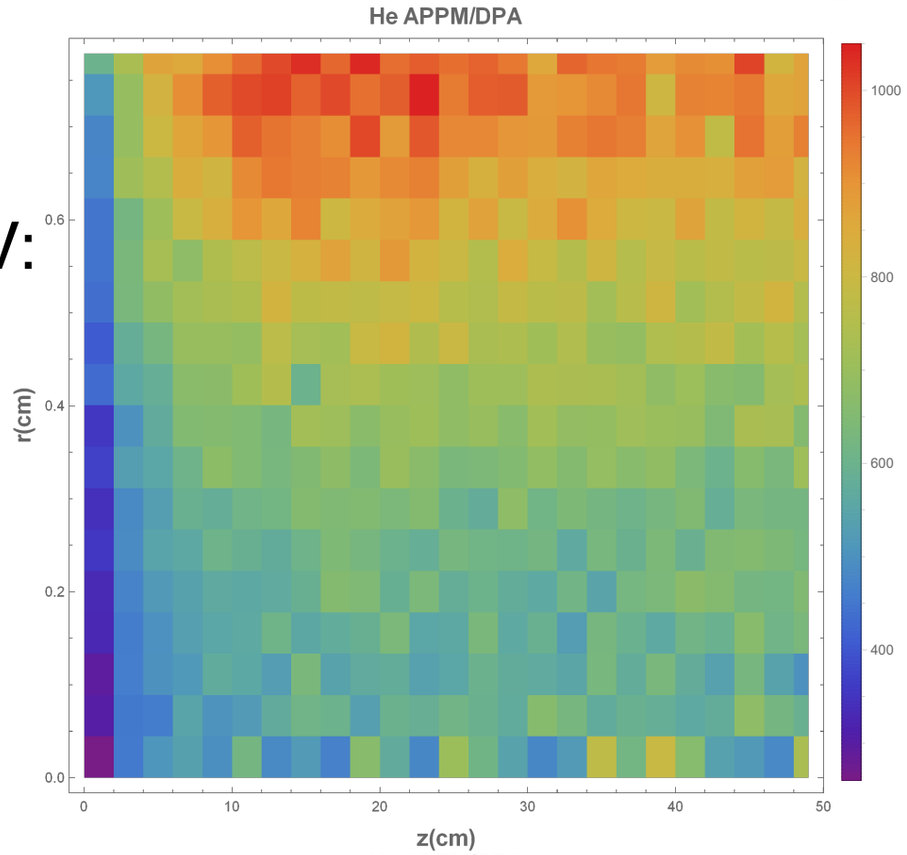


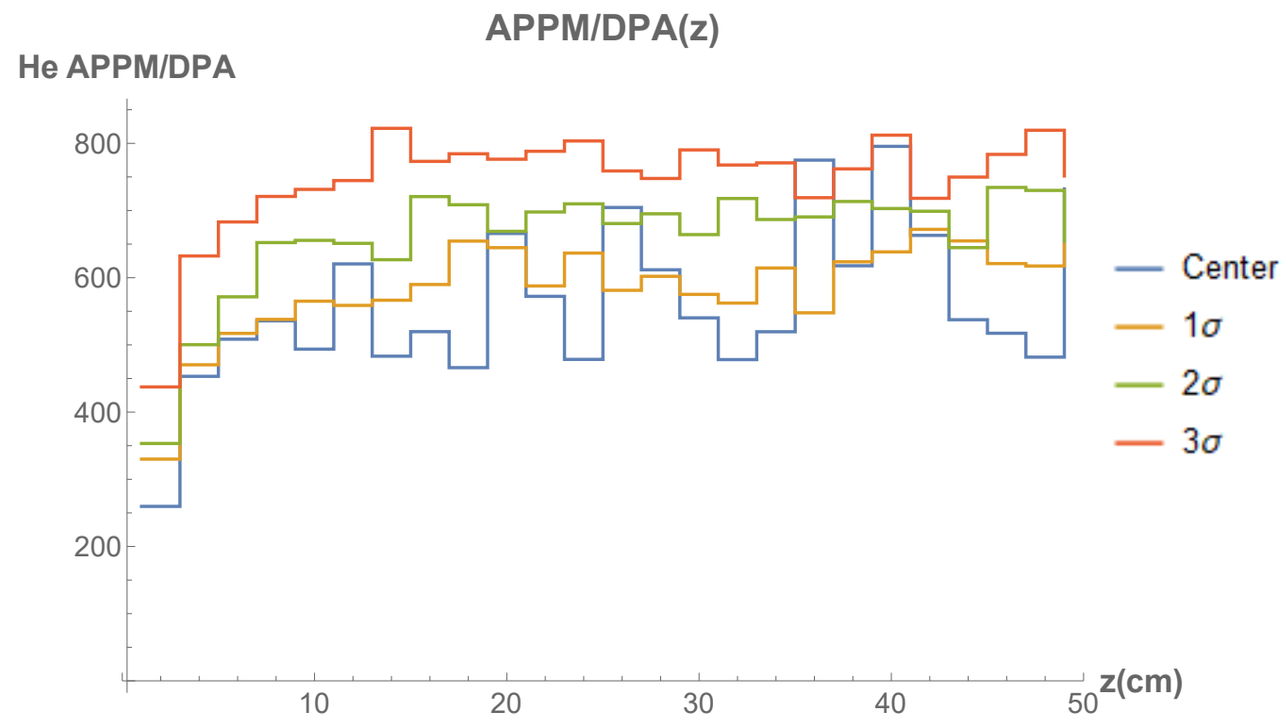


Max He APPM/9 month = 400, at z = 15cm

LBNF: Helium APPM/DPA

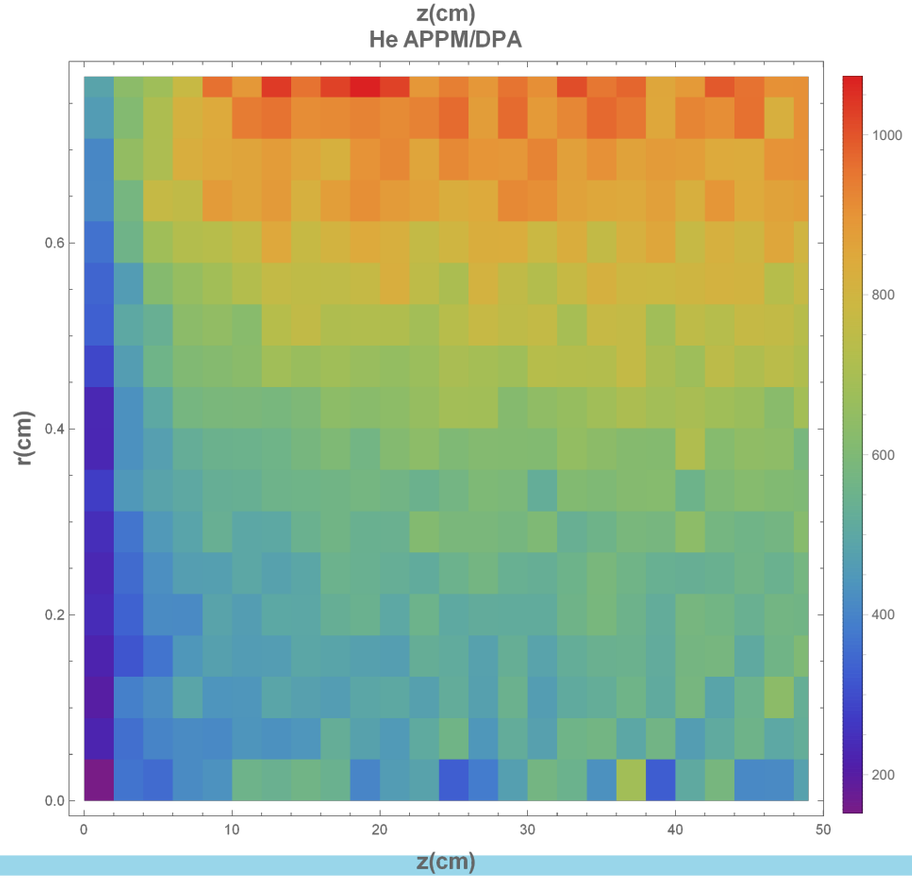
120 GeV:

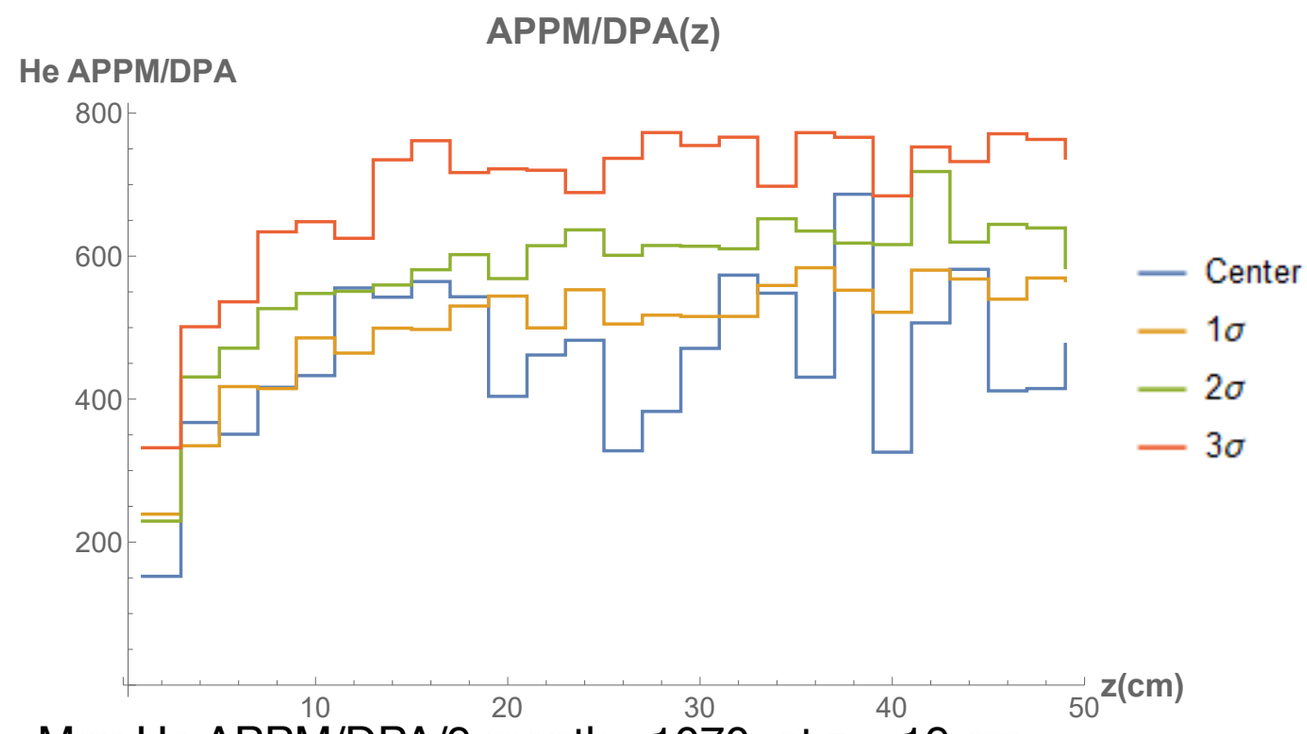




Max He APPM/DPA/9 month =1050, at z = 23cm

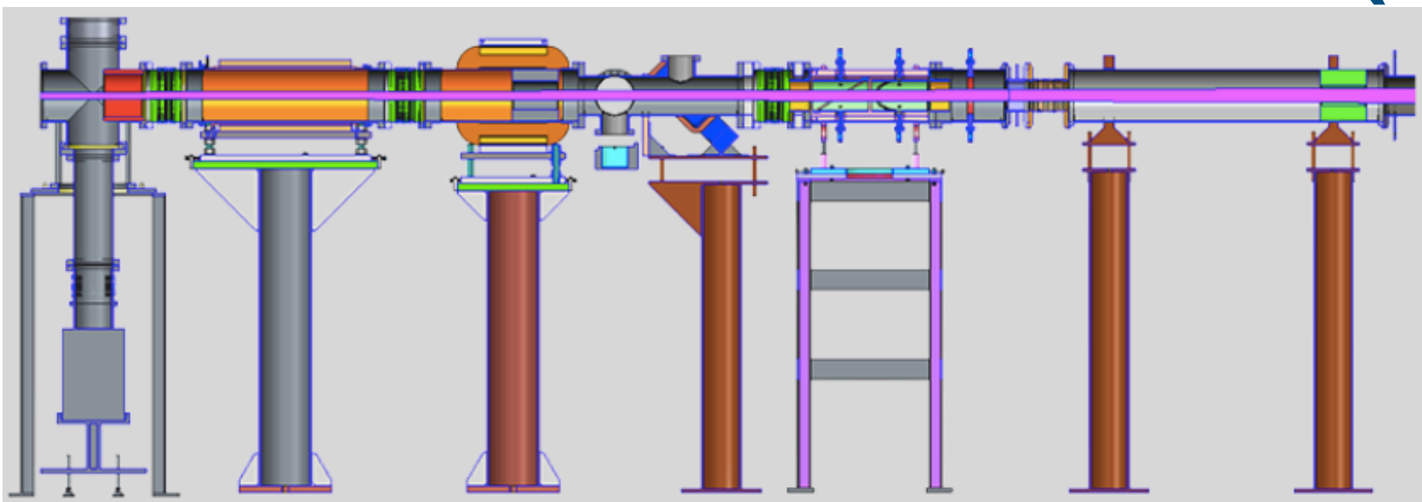
60 GeV:

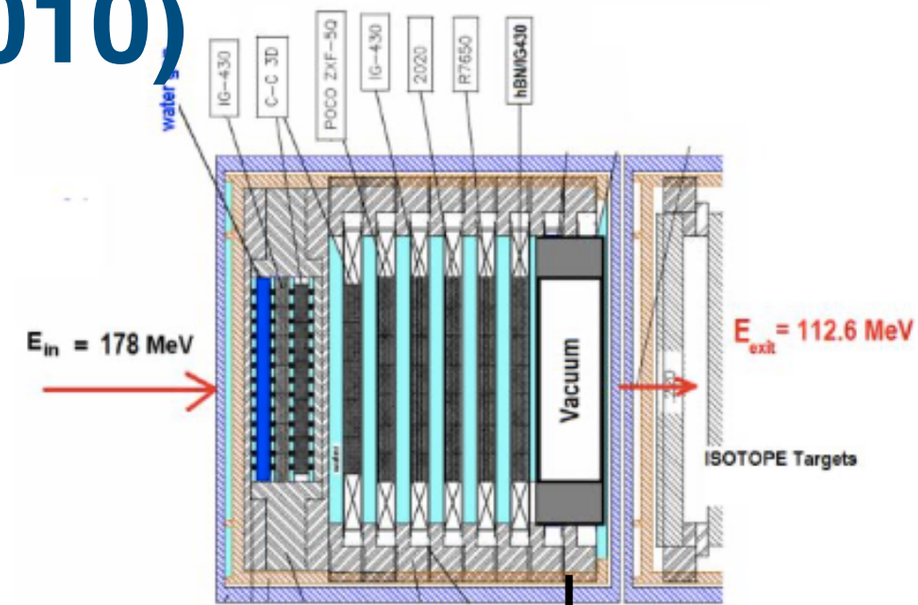


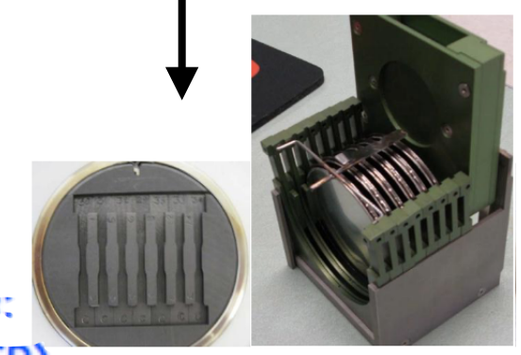


Max He APPM/DPA/9 month =1070, at z = 19 cm

BNL BLIP Test (2010)







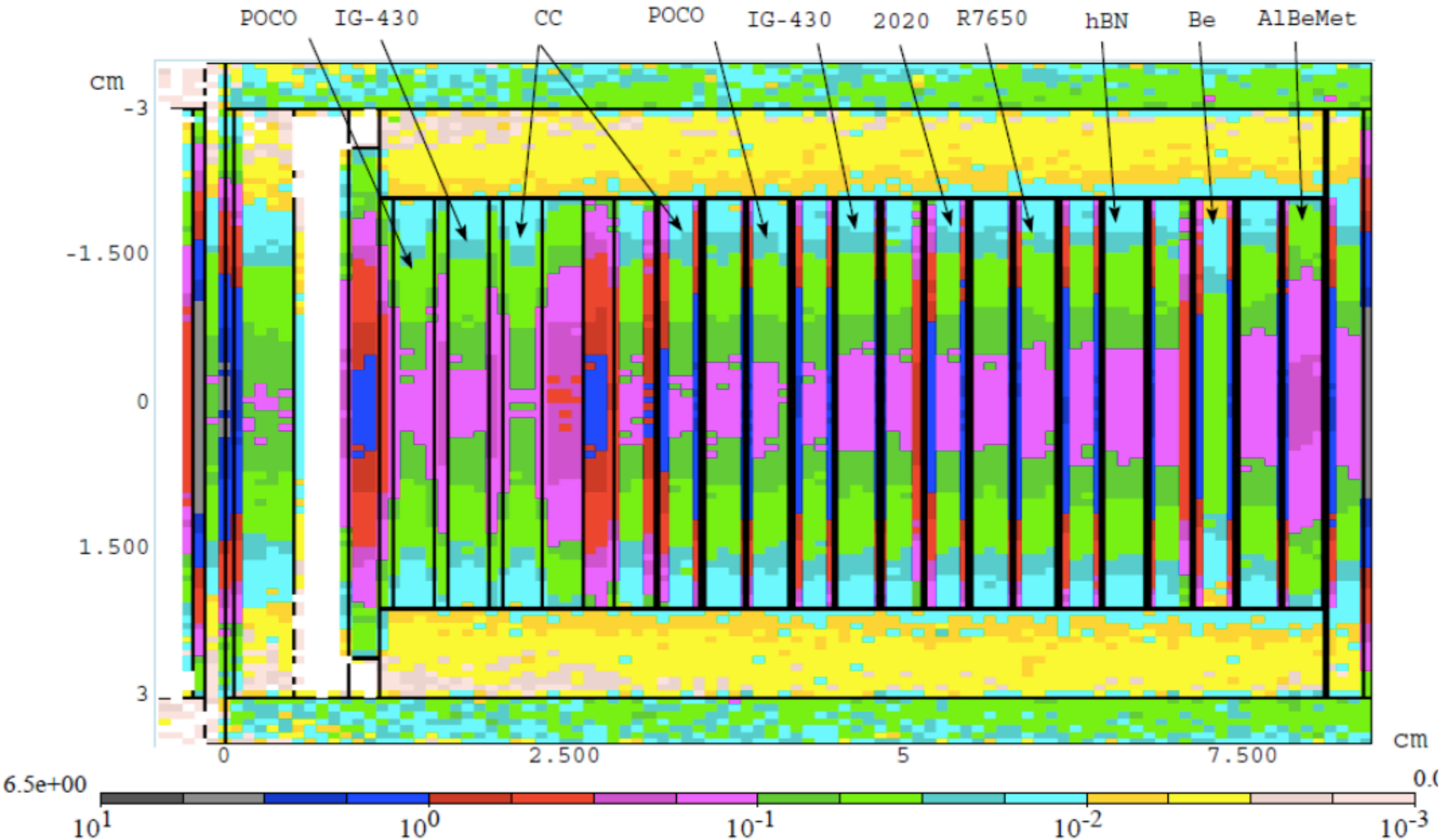
Experiment	BLIP 2010
Targets	Capsule 1-9
Energy (GeV)	0.181
Beam Pulse	Continuous
p/s	5.87E+14
σ (mm)	σx =8.92, σy=6.79
Power (kW)	17
Peak Temp. (C)	180
Min. Temp. (C)	120
POT	8.25E+20
Peak Fluence (p/cm2)	2.17E+18
Peak DPA	0.11

Physics process contribution (%) at beam axis: z=15 cm (NuMI) and Box 2 POCO graphite (BLIP)

Target	Nuclear	EM elastic	L.E. neutrons	$e^{\pm}$
NuMI	50.8	43.3	1.5	4.4
BLIP	43.5	53	3.5	0.02

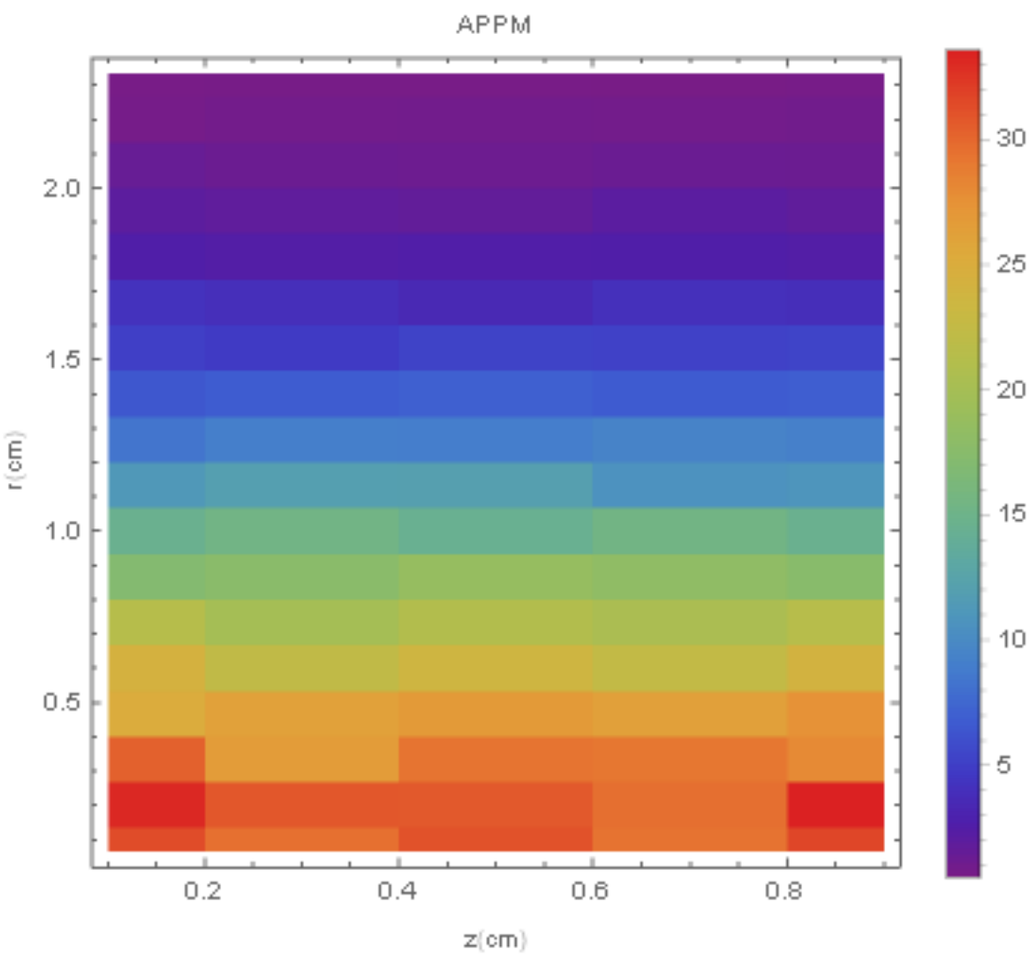
Target	E_p (GeV)	Beam σ (mm)	N_p (1/yr)	DPA (1/yr)
NuMI/LBNE	120	1.1	4.0e20	0.45
BLIP	0.165	4.23	1.124e22	1.5

BLIP: DPA calculations

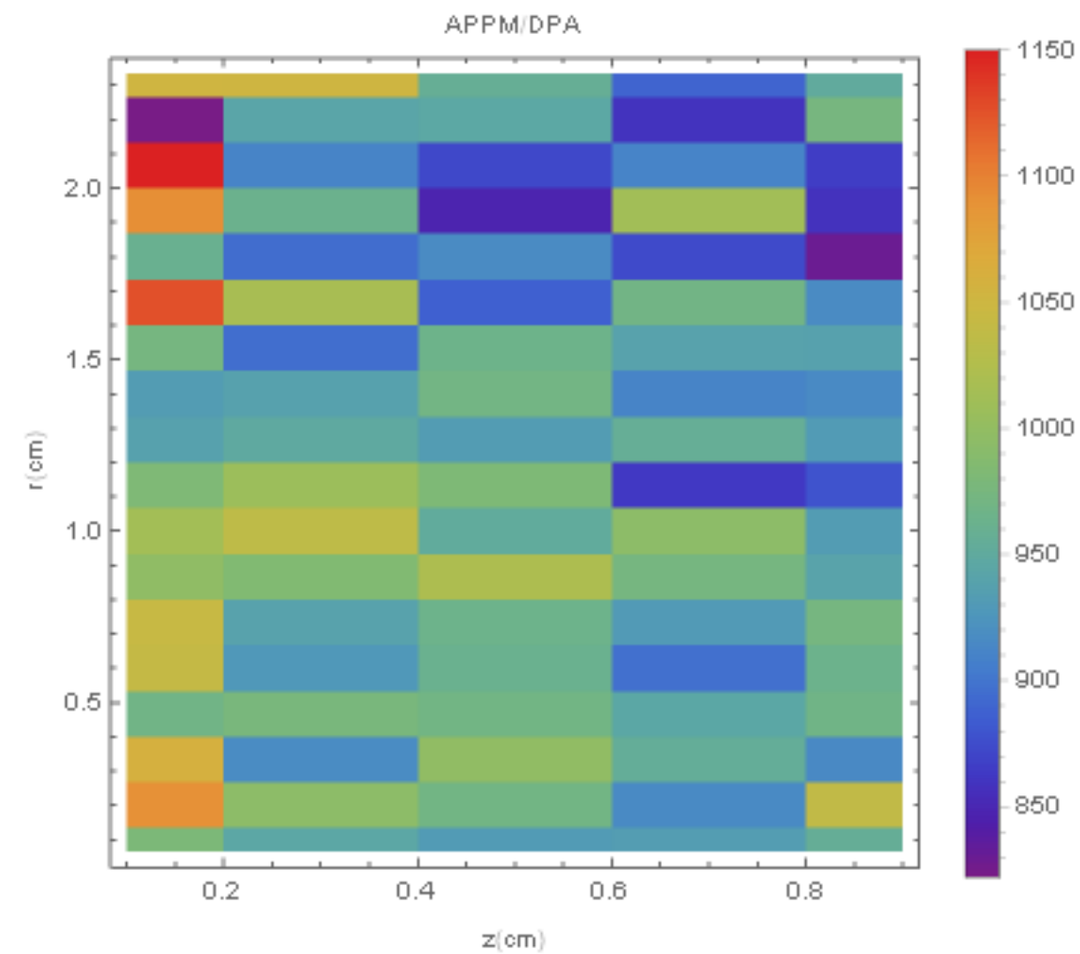


Calculation: N. Mokhov

BLIP 2010: Helium transmutation

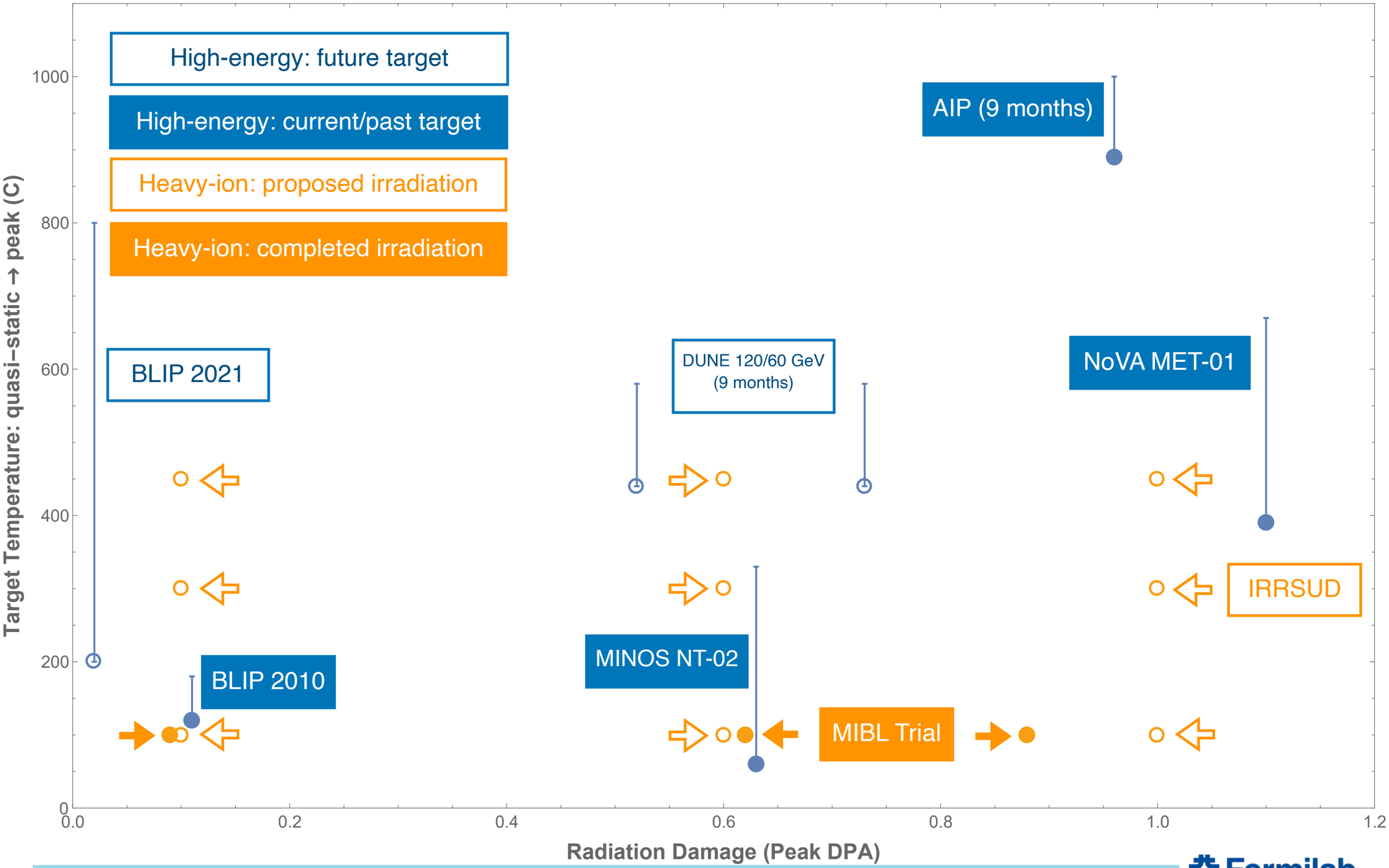


Max APPM = 34



Max APPM/DPA = 1151

Graphite Target/Ion Irradiation Roadmap



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[1] S. Bidhar, N. Simos, D. Senor & P. Hurh, Failure investigation of nuclear grade POCO graphite target in high energy neutrino physics through numerical simulation, Nuclear Materials and Energy 24 (2020) 100761

[2] K. Ammigan, NuMI-NOvA Target & Window, 10th International Workshop on Neutrino Beams and Instrumentation 20 September 2017

[3] P. Hurh, The Influence of High Energy Proton Irradiation on Fine-Grained Isotropic Graphite Grades: A Summary of Recent RaDIATE Results, High Power Targetry Workshop, 04 June 2018

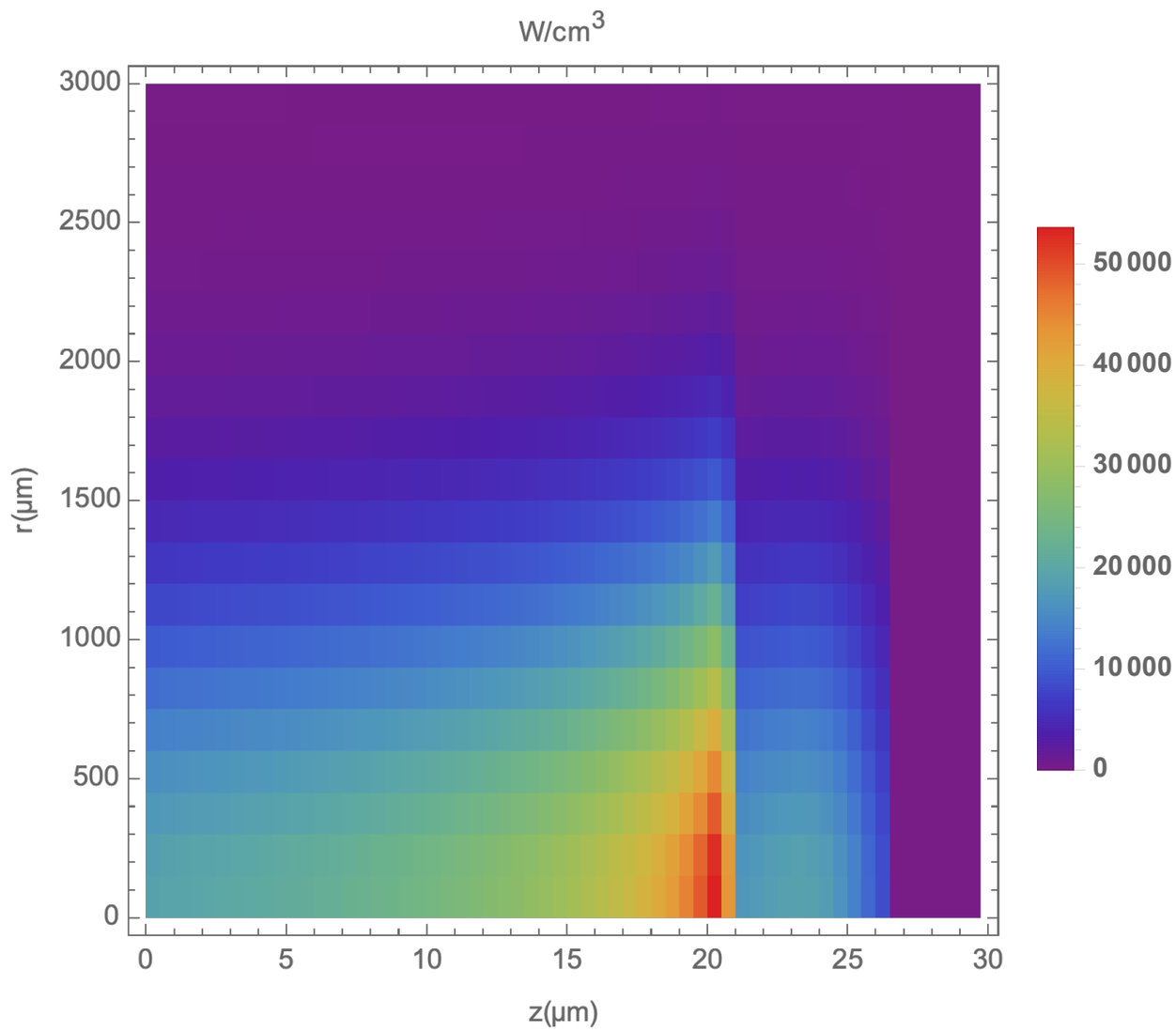
[4] B. Hartsell, Beryllium Fins in the NOvA Target, 2016-04-07

[5] D. Wilcox, Engineering Performance Comparison, LBNF Target Conceptual Design Selection Review, 24th-26th July 2019

[6] G. Was, Fundamentals of Radiation Materials Science, ISBN 978-3-540-49471-3 Springer Berlin Heidelberg New York

[7] N. Mokhov, DPA Modeling in MARS15, NBI2017+RaDIATE IVIL, Tokai, Japan, September 18-22, 2017

BONUS SLIDES



NuMI MINOS (NT-02): Target stress

Simulated stresses due to target swelling are shown below and used for transient analysis

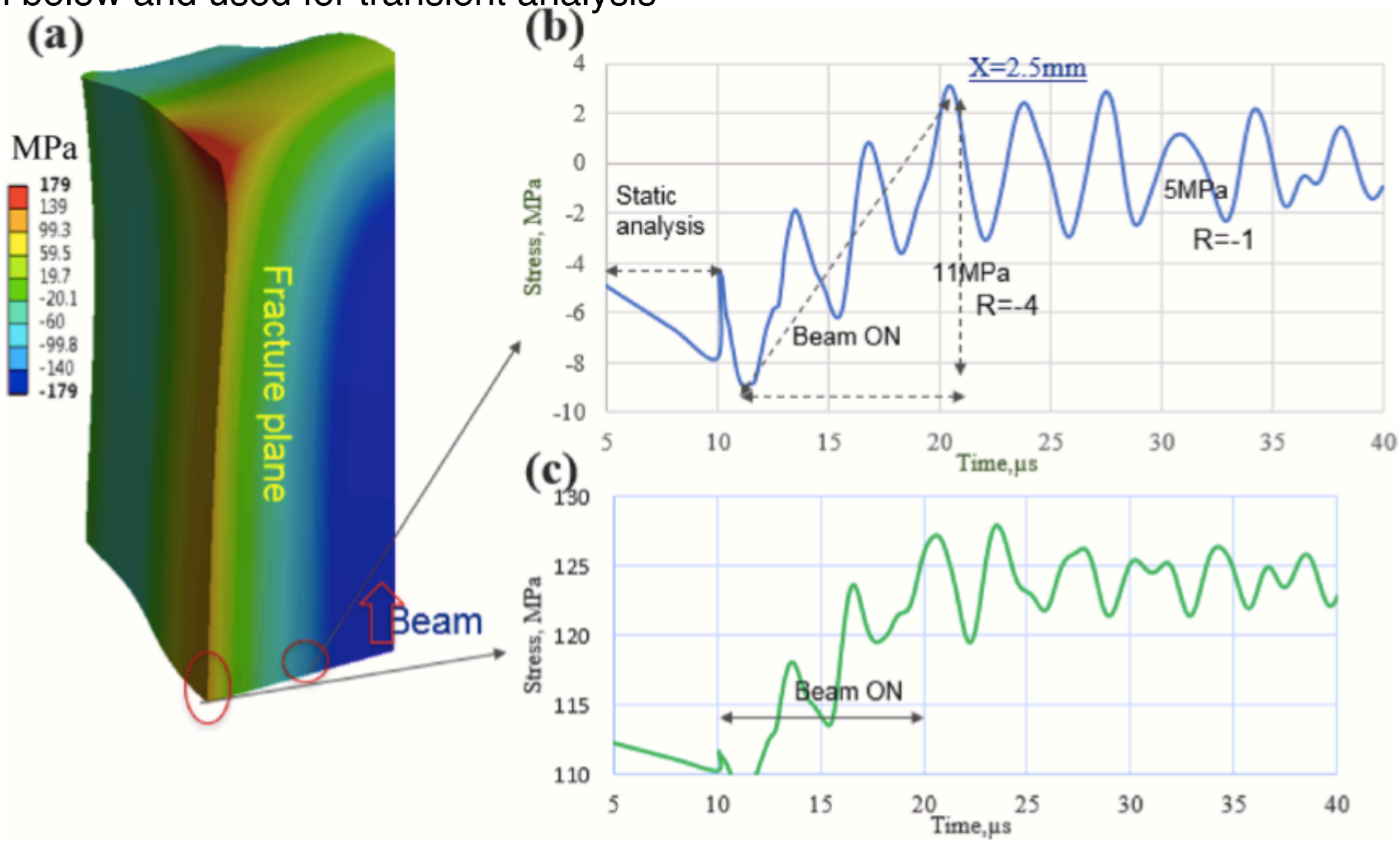
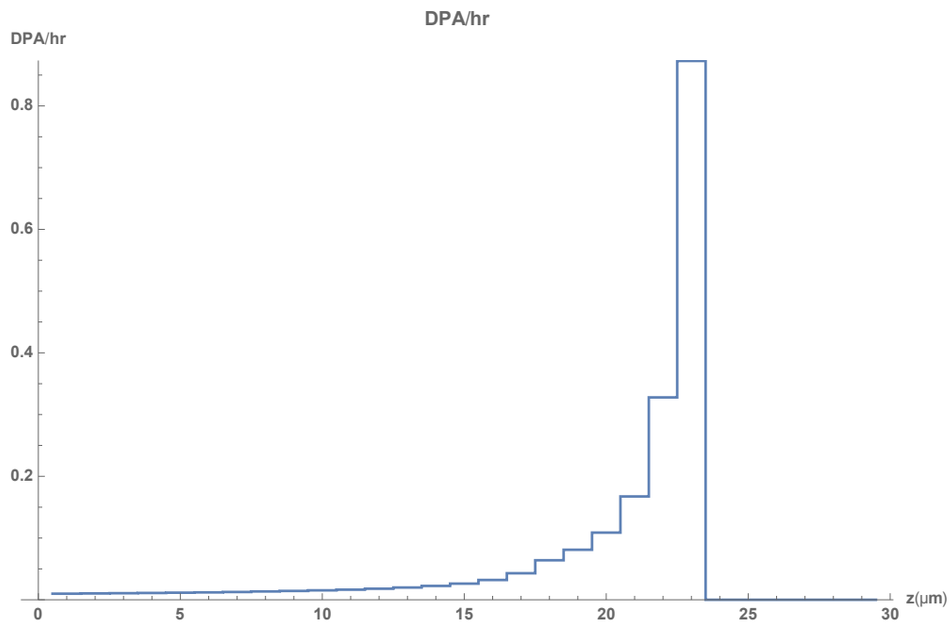


Fig. 13. a) Distribution of σ_{yy} just before beam pulse. b) dynamic normal stress at x = 2.5 mm, c) dynamic stress at the surface due to pulsed high energy proton beam.

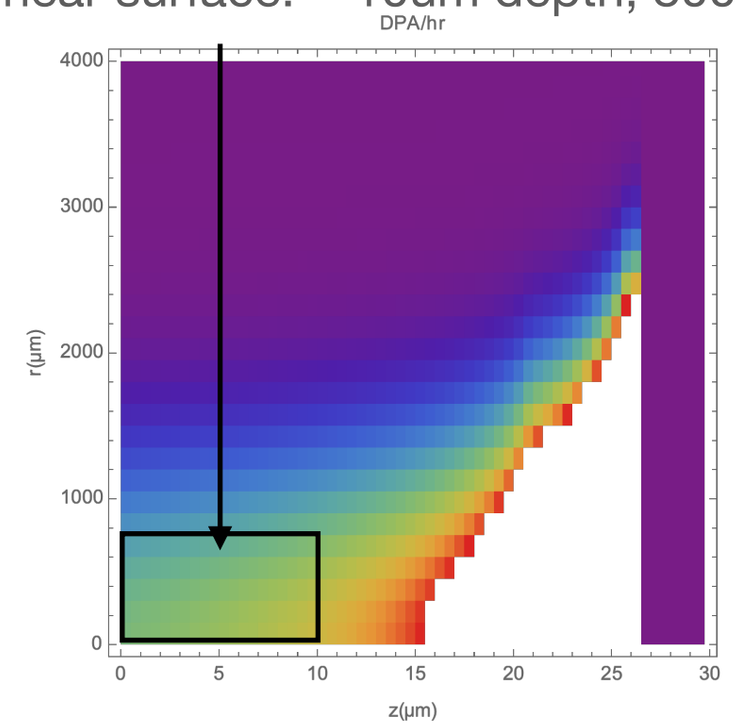
Ion irradiation advantages and limitations

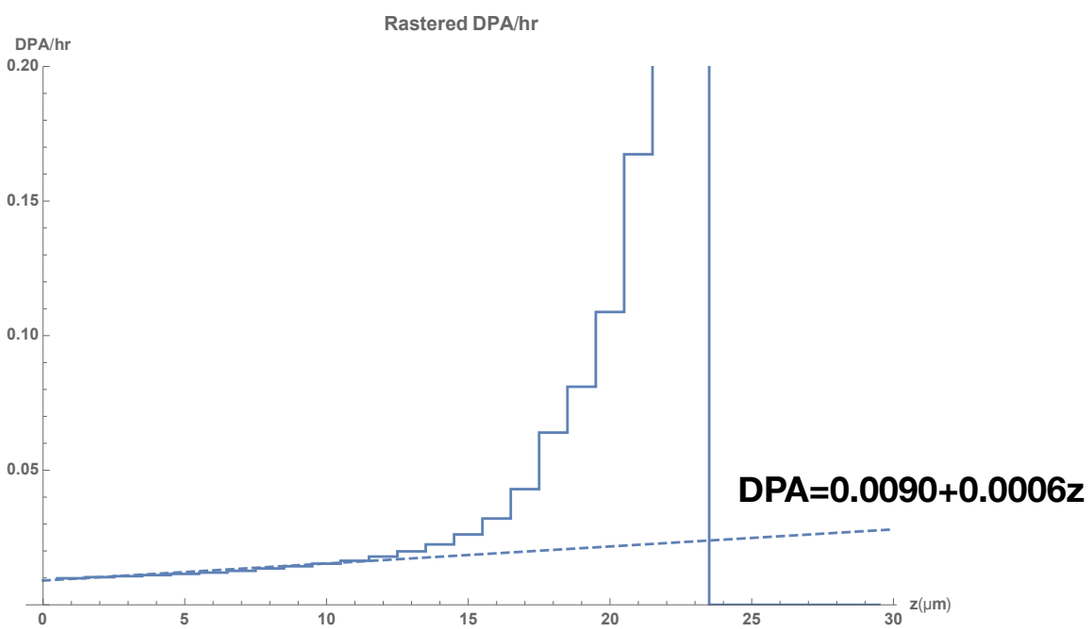
4.5MeV He++



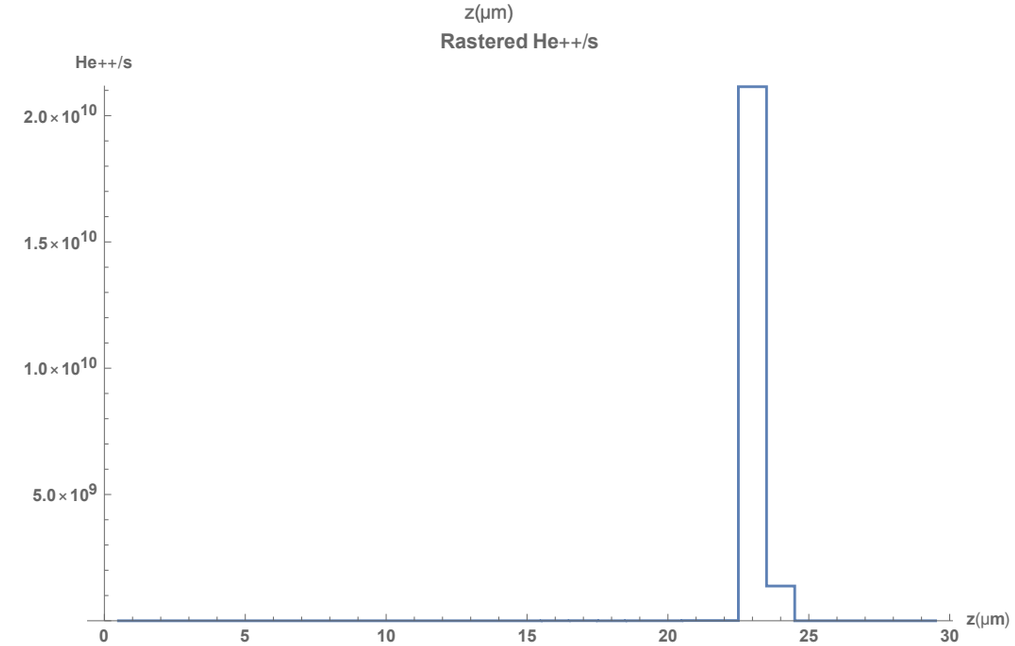
High peak DPA achievable in short times

Very small irradiated volumes compared to HE protons: linearity near surface: ~ 10um depth, 800um radius



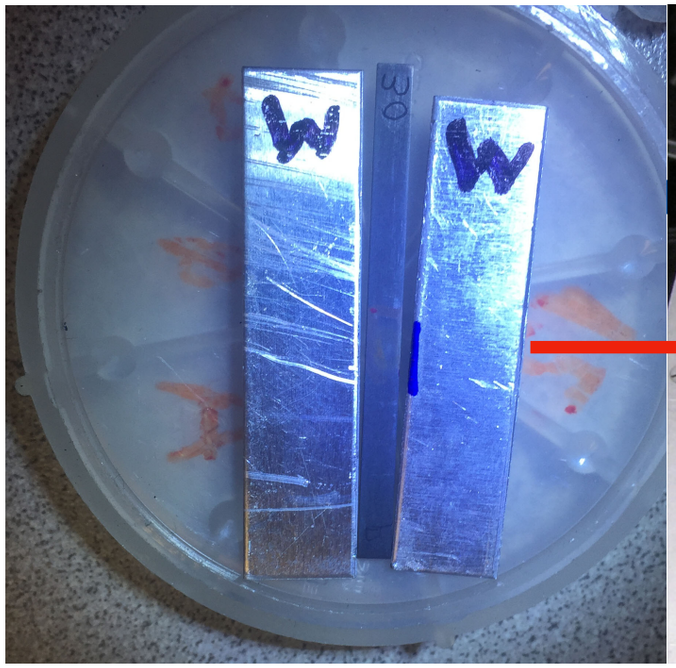


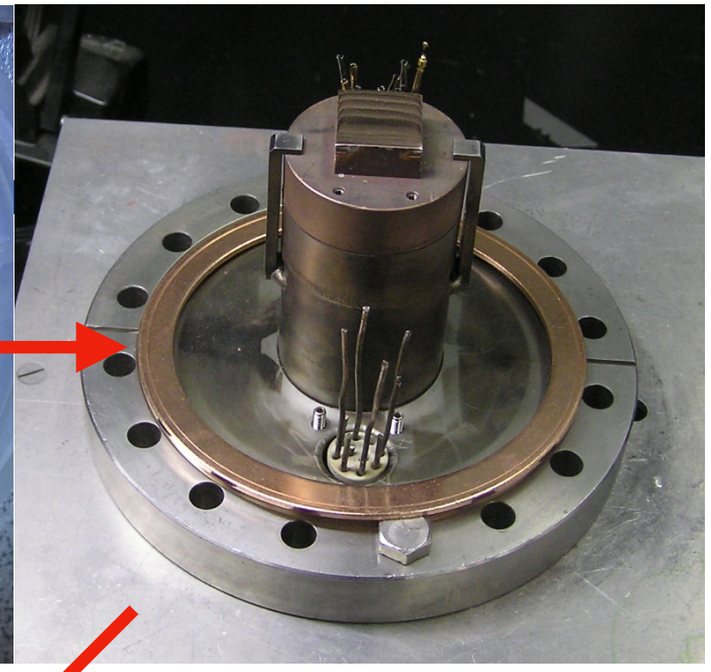
Highly linear DPA rate near the surface

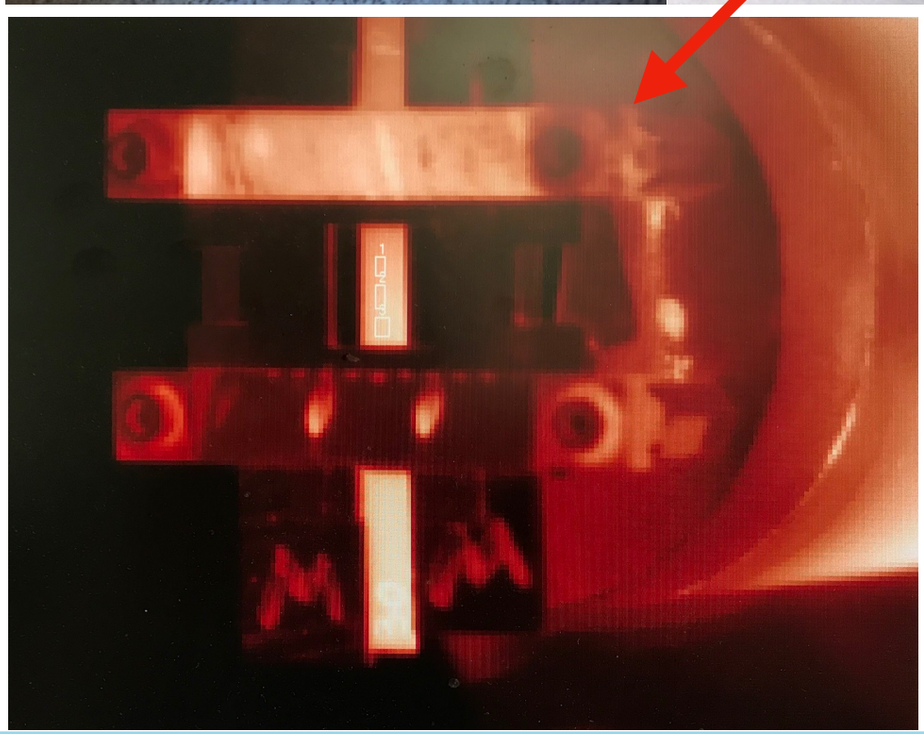


Near zero ions come to rest near the surface

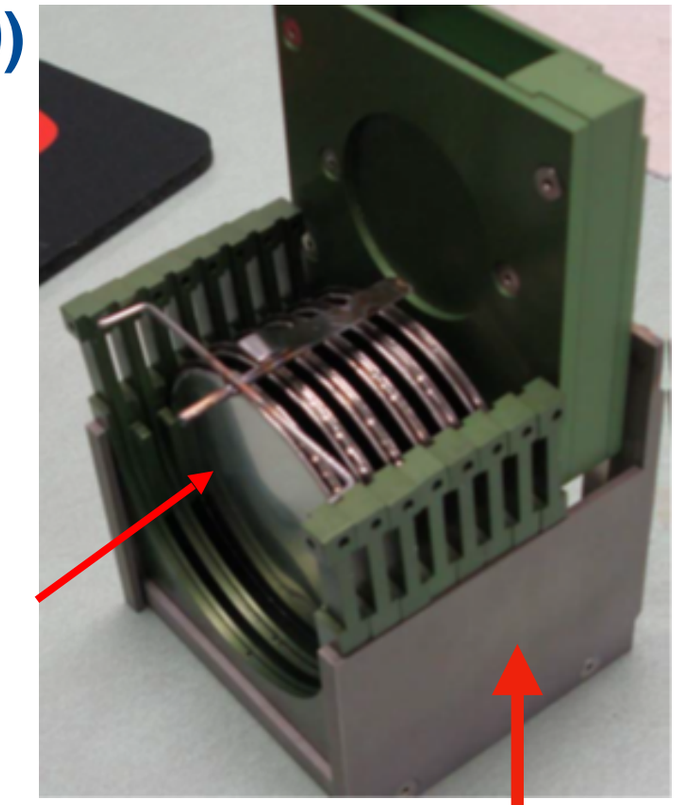
Sample preparation





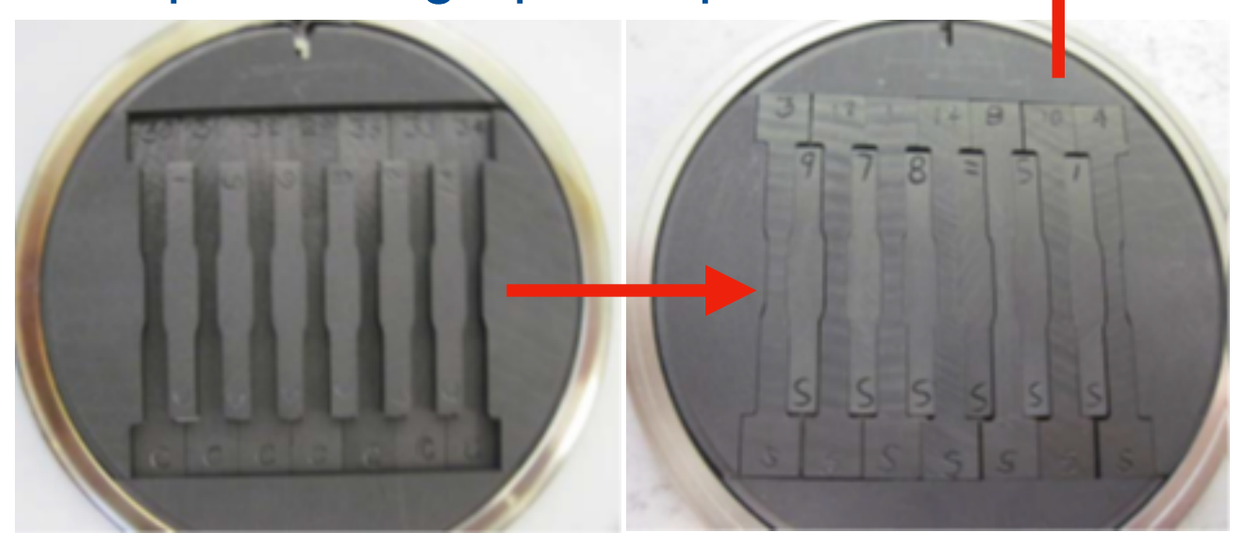


BLIP Graphite Irradiation (2010)

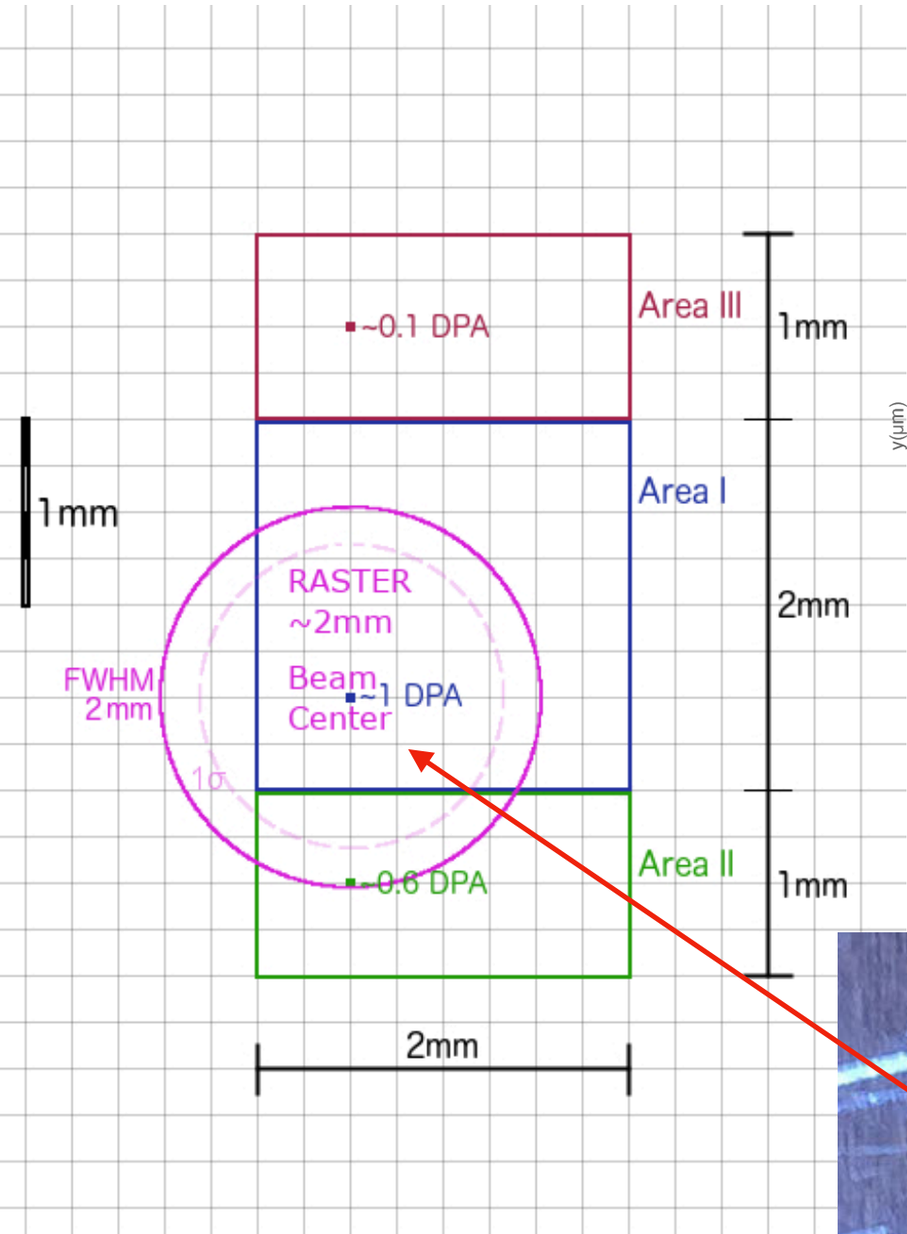


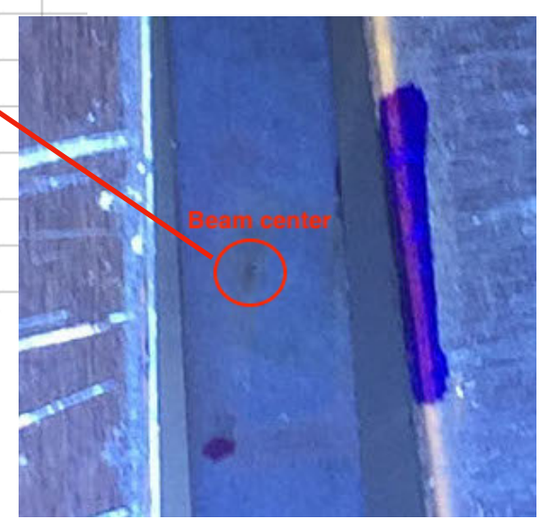
Proton beam

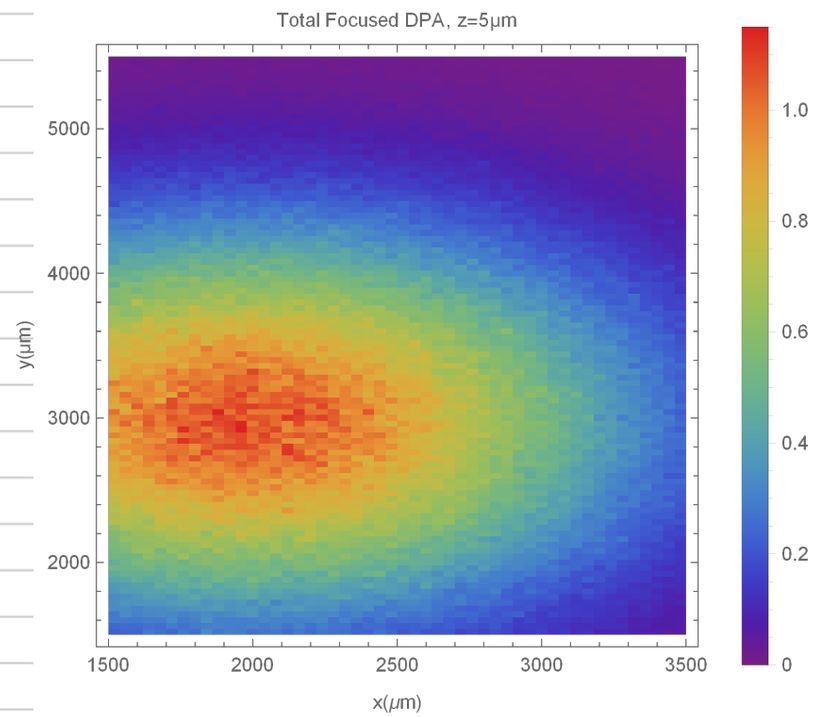
Encapsulated graphite specimens

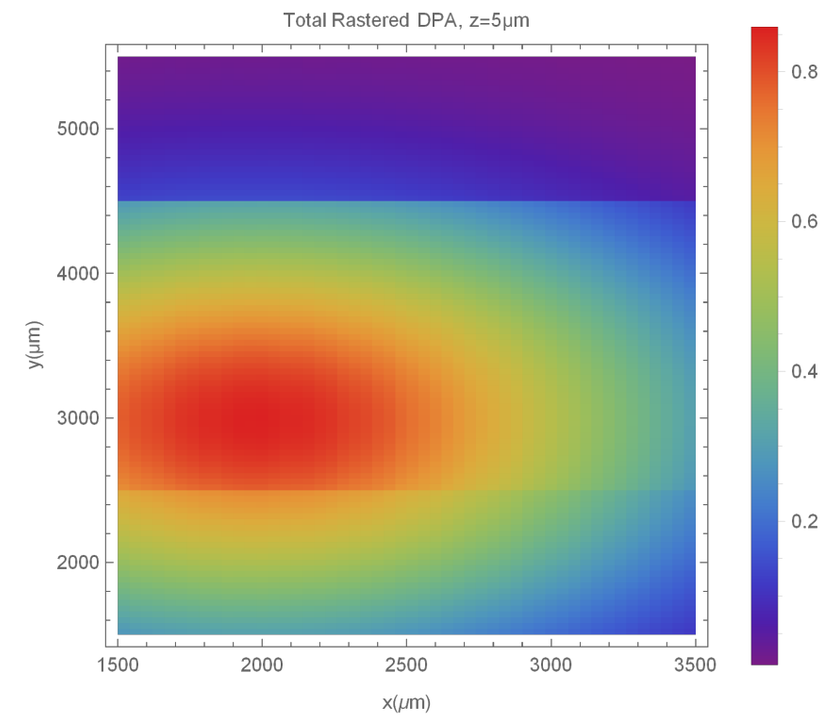


MIBL trial irradiation: PIE plans









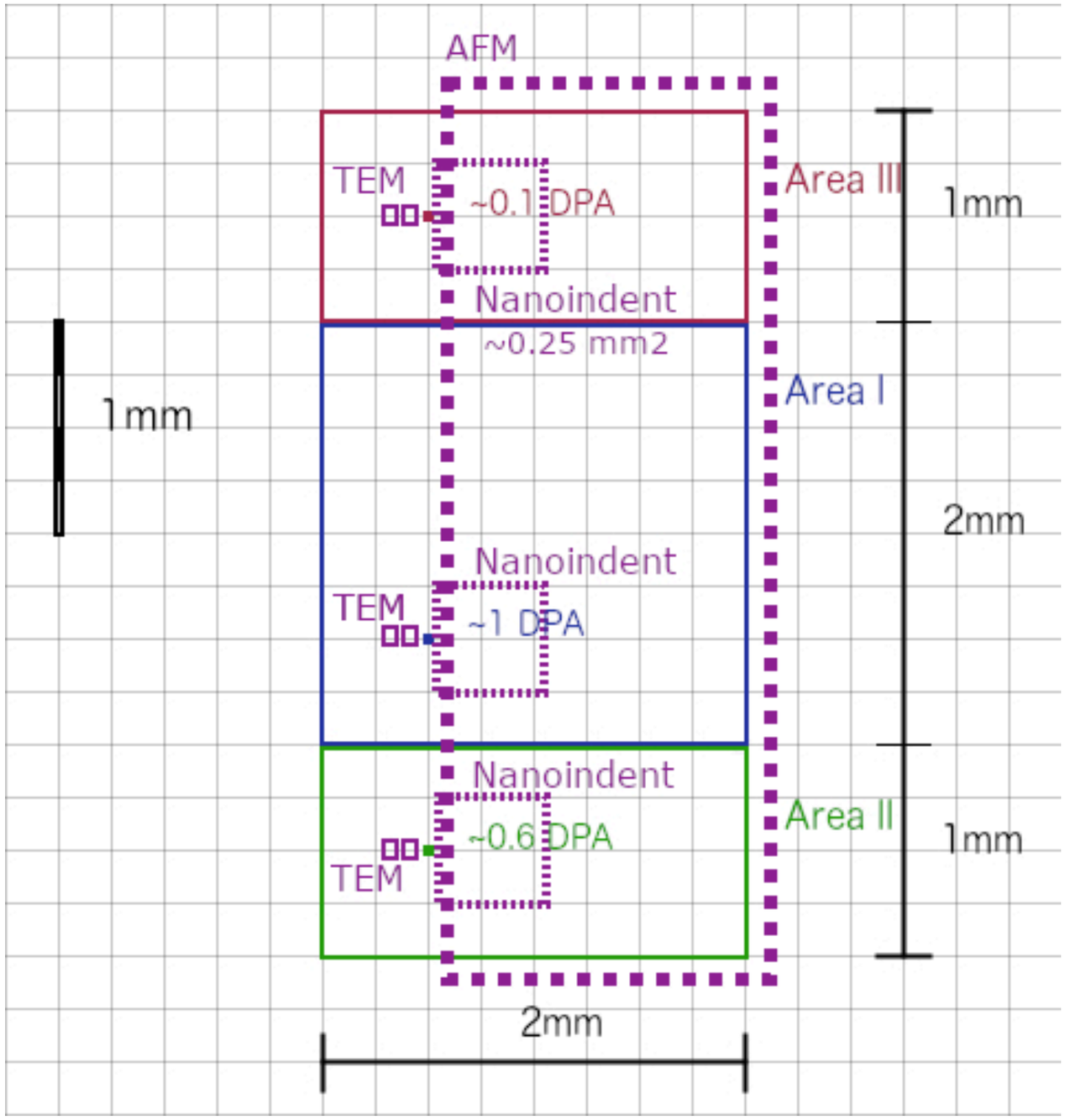
MARS simulation: total DPA accumulation (NRT w/Stoller corr.)

Irradiation plan

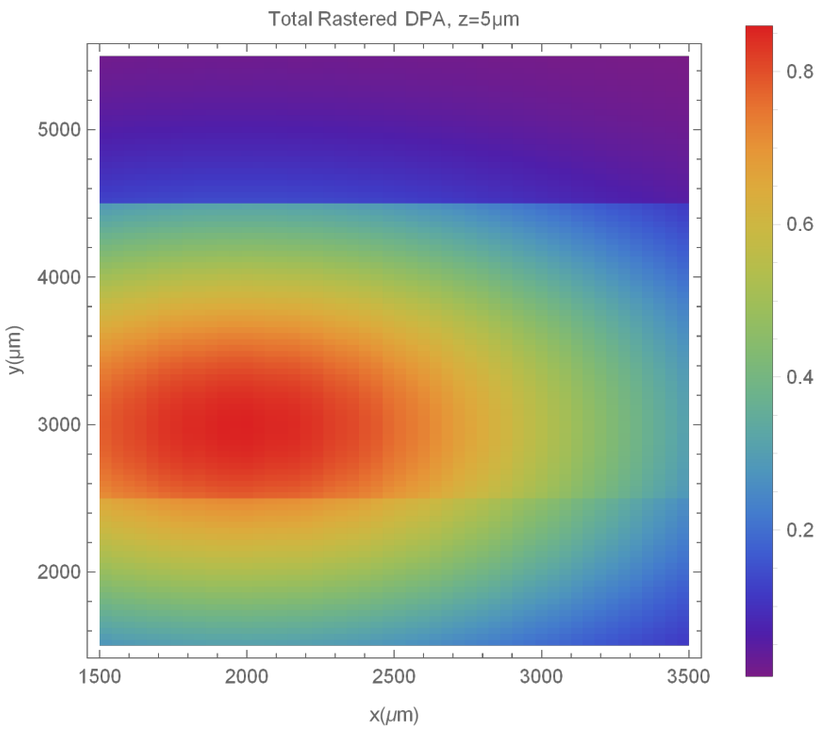
- **Irradiate Area I ~5hrs**
- **Open slits to Area II ~40hrs**
- **Open slits to Area III ~50hrs**

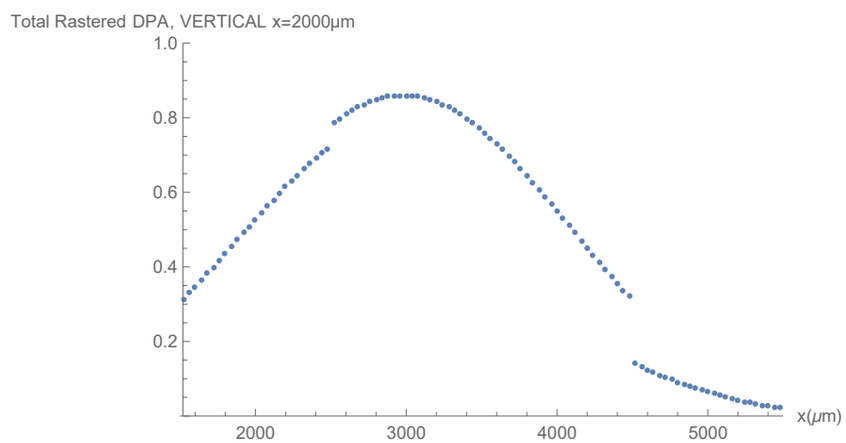
Trial irradiation: Upcoming PIE work

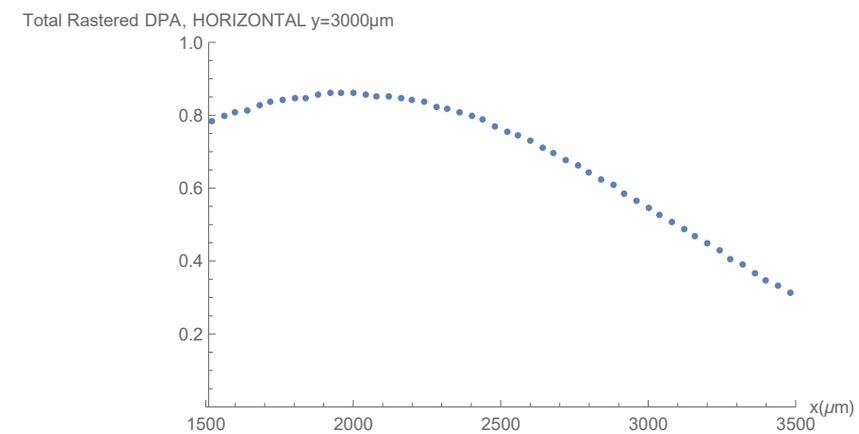
- TEM at University of Michigan Center for Materials Characterization (MC)^2 and NW NUANCE
- AFM profilometry measurements of swelling above surface at IIT
- Nanoindentation at NW NUANCE

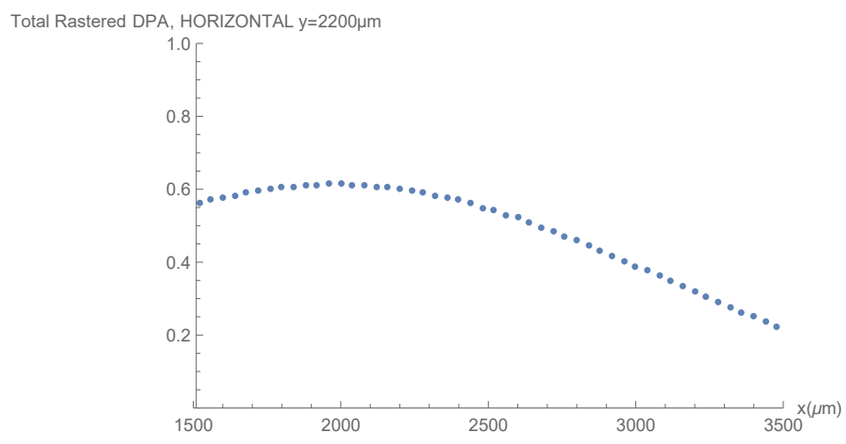


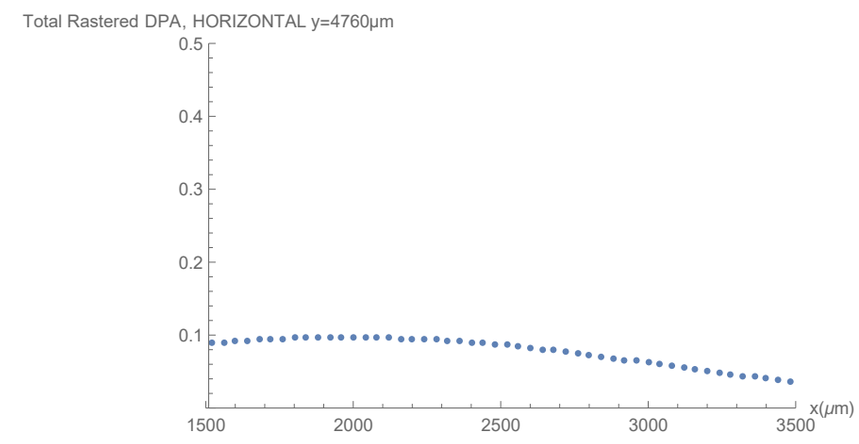
MIBL trial irradiation: PIE plans

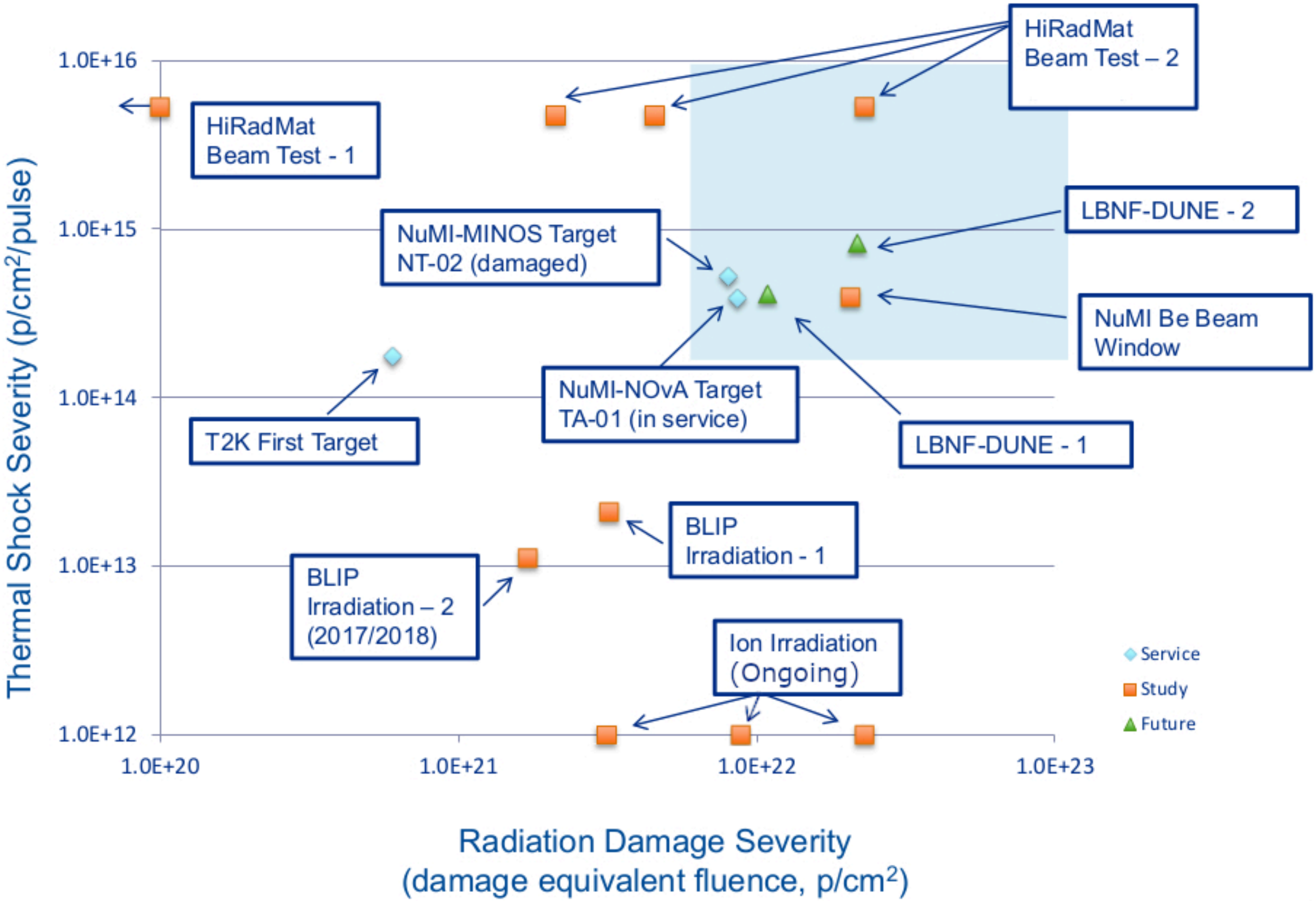











HiRadMat
Beam Test – 2
HiRadMat
Beam Test - 1
LBNF-DUNE - 2
NuMI-MINOS Target
NT-02 (damaged)
NuMI Be Beam
Window
NuMI-NOvA Target
TA-01 (in service)
T2K First Target
LBNF-DUNE - 1
BLIP
Irradiation - 1
BLIP
Irradiation – 2
(2017/2018)
Ion Irradiation
(Ongoing)
Service
Study
Future
1.0E+16
1.0E+15
1.0E+14
1.0E+13
1.0E+12
1.0E+20
1.0E+21
1.0E+22
1.0E+23
Thermal Shock Severity (p/cm²/pulse)
Radiation Damage Severity
(damage equivalent fluence, p/cm²)