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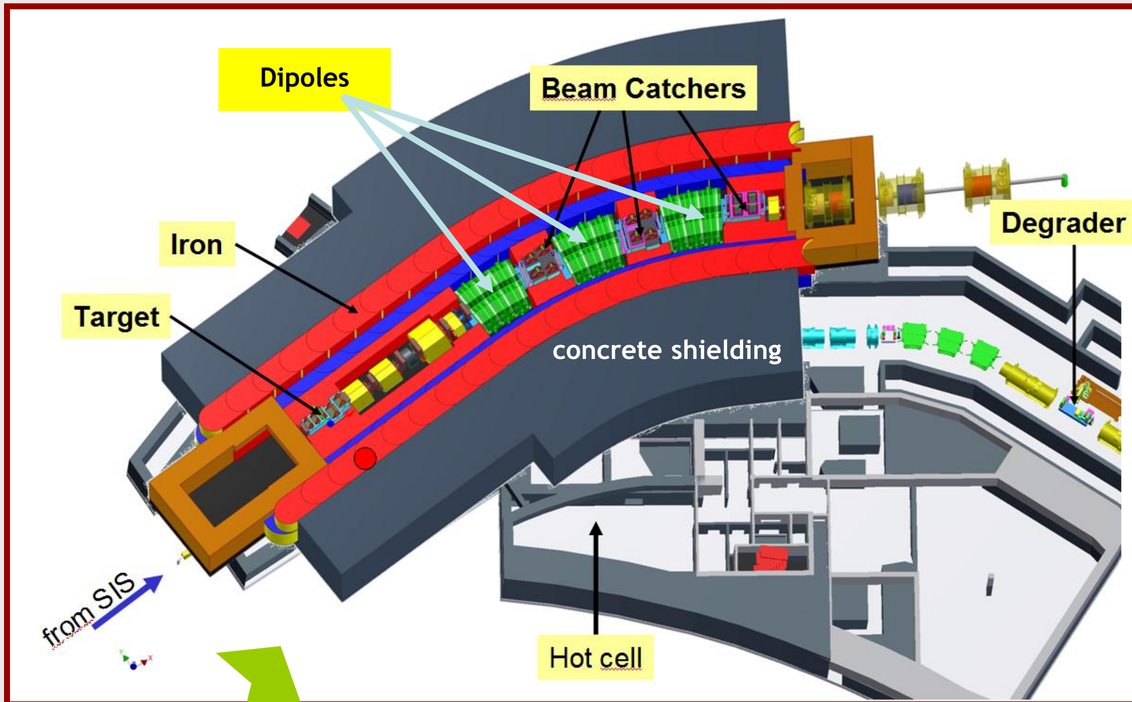
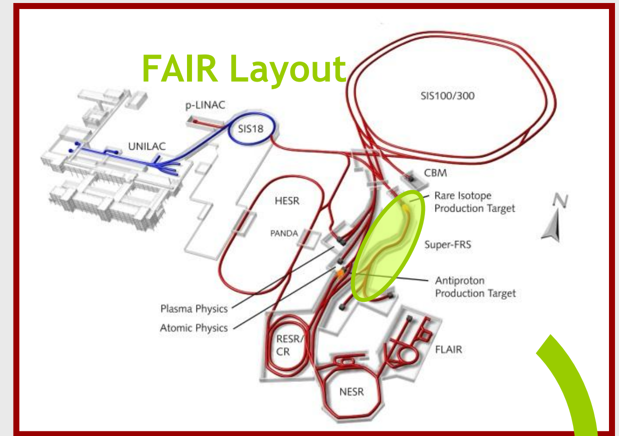
Site update: 21.11.2014

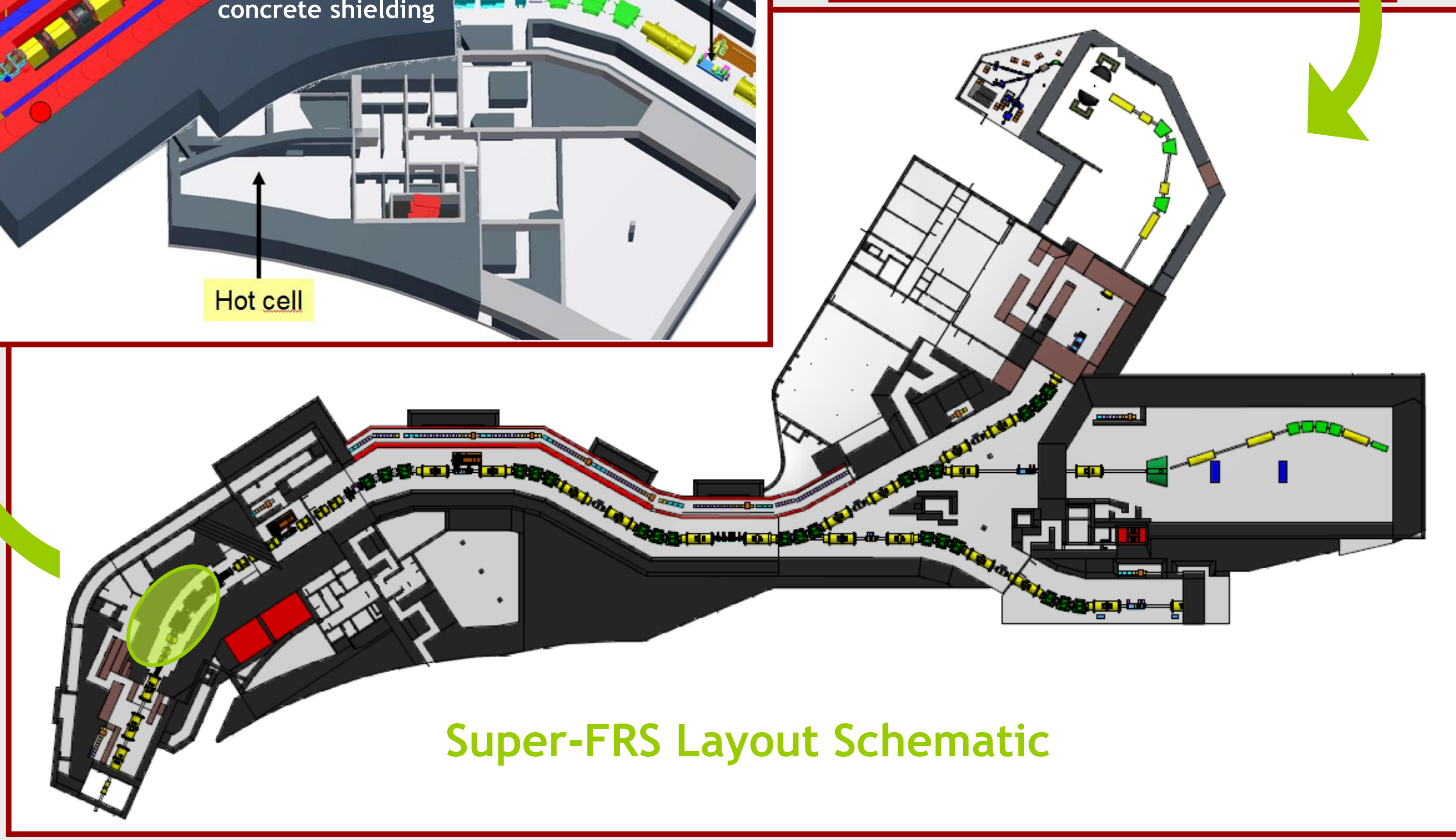
Design of Beam Stoppers for Super-FRS in FAIR Project

Dr. Avik Chatterjee CSIR-CMERI

Super FRS and Beam Stopper Layout at FAIR site



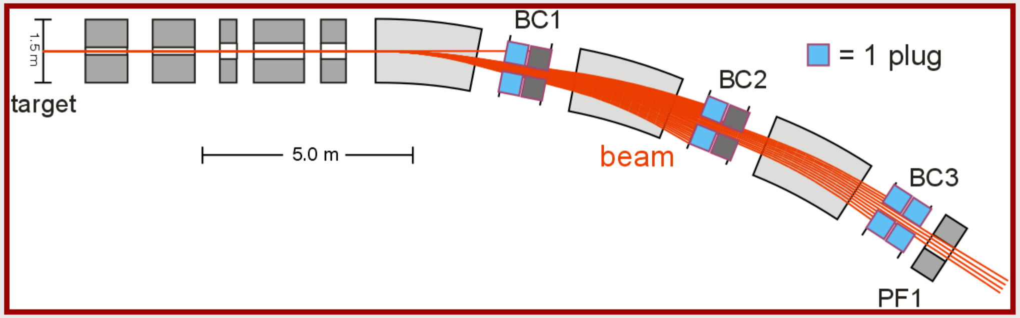




FAIR Input
2012

Function

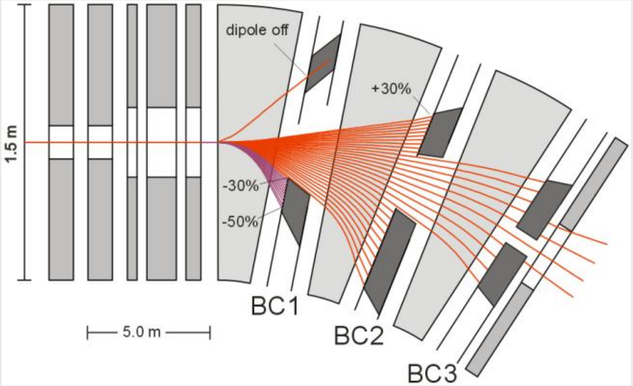
- To absorb high energy beams consisting of primary beam particles and unwanted secondary particles released by target material
- To shield the subsequent parts of the separator from high level of secondary radiation mainly fast neutrons.



The red rays : possible separation scenarios for uranium beams
The purple rays : lighter ions neutron-rich fragments.

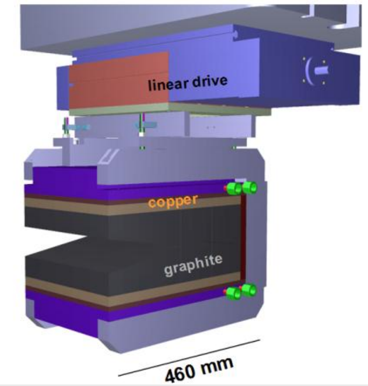
Trajectories of primary beams for different Bρ settings. Dump the beam only on dedicated beam catchers (BC)!

FAIR Input 2012



Specification FAIR-Revised 2014

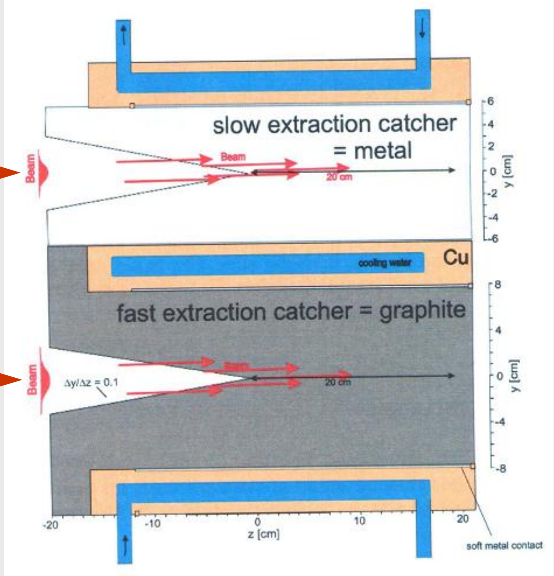
Previous concept



Initial Energy	Spot@ target	Thermal power	BC	Min Spot area @BC	Critical for
740 MeV/u	Small	**8.5 kW**	BC2	35 mm^2	Effect of low thermal conductivity, localized Bragg peak
			BC3	42 mm^2	
1500 MeV/u	Small	**17 kW**	BC2	35 mm^2	Thermal load, spread Bragg's peak, quasi DC beam
			BC3	42 mm^2	

$3x10^{11}$ ppp

Critical cases for slow extraction (quasi-DC)



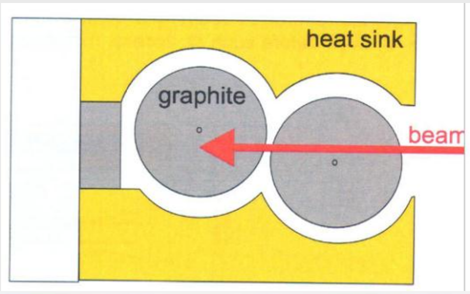
50-100 ns pulses $5x10^{11}$ ppp @ 1.67s

Critical cases for fast extraction

Initial Energy	Spot@ target	Pulse energy	Thermal power	BC	Min. spot area @BC	Critical for
740 MeV/u	Large	**14 kJ**	8.5 kW	BC2	127 mm^2	Pressure wave, due to localized Bragg peak
				BC3	340 mm^2	
1500 MeV/u	Large	**29 kJ**	17 kW	BC2	127 mm^2	Thermal load, spread Bragg peak, high energy
				BC3	340 mm^2	

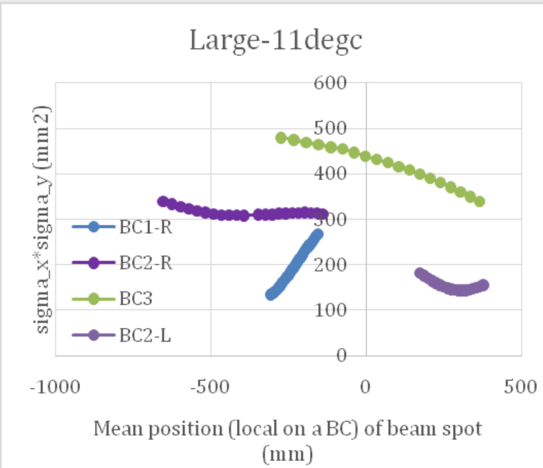
How to use the same stopper for both the modes ?

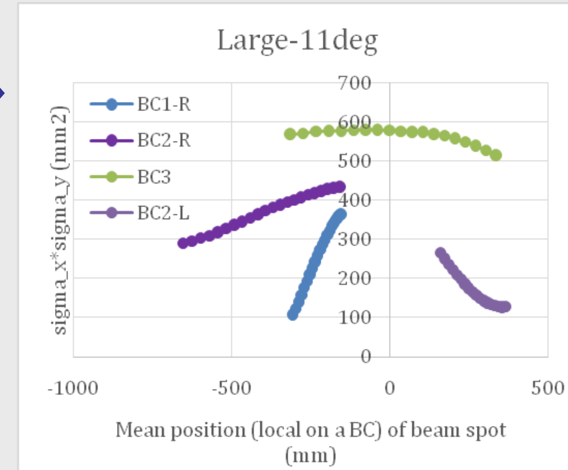
Alternate concept: Rotating absorber
Heat transfer by radiation only



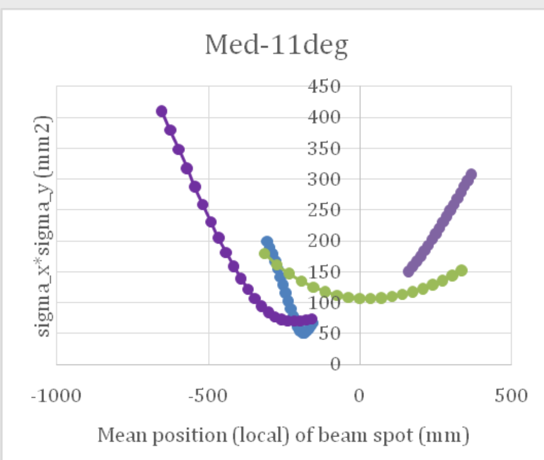
Specification FAIR-Revised 2014

Beam Spot sizes Vs Input Energy to Beam Stoppers

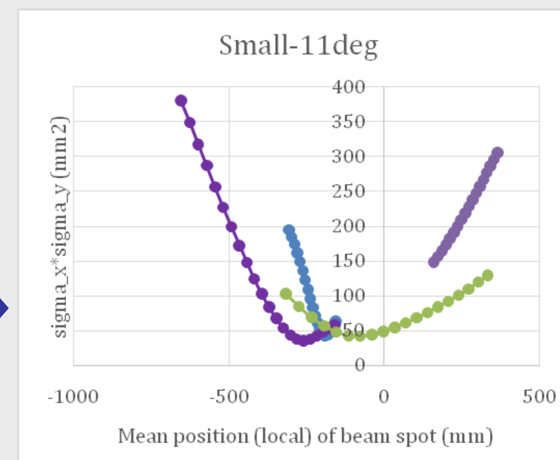




740MeV/u and 1500MeV/u
Fast Extraction mode



Fast Extraction but for
Lower energies



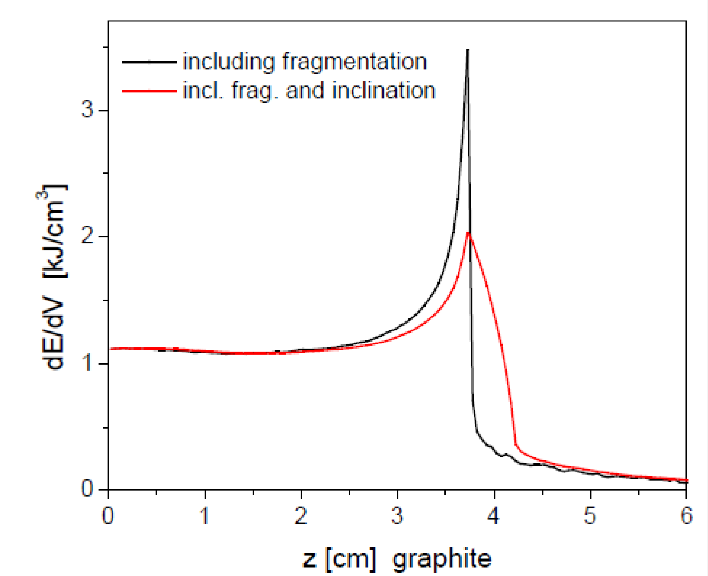
740MeV/u and 1500MeV/u
Slow Extraction mode

Specification FAIR-Revised 2014

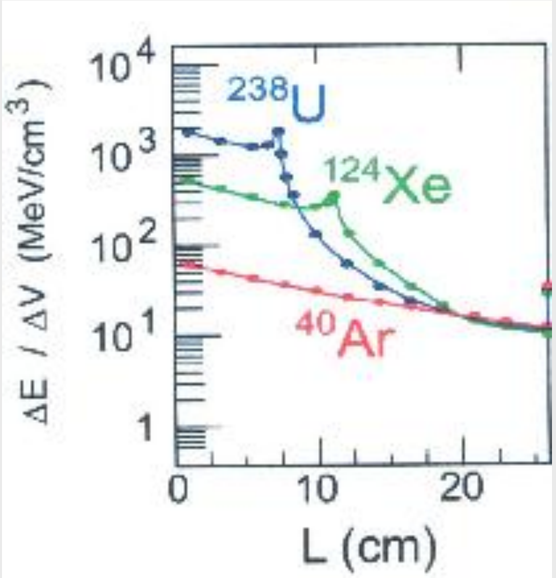
Energy distribution data with Bragg's peak in Fast Extraction

[i] 740 MeV/u, [ii] 1500 MeV/u

U^{238} ions pulses inside absorber (density Graphite : 1.84 g/cm3).



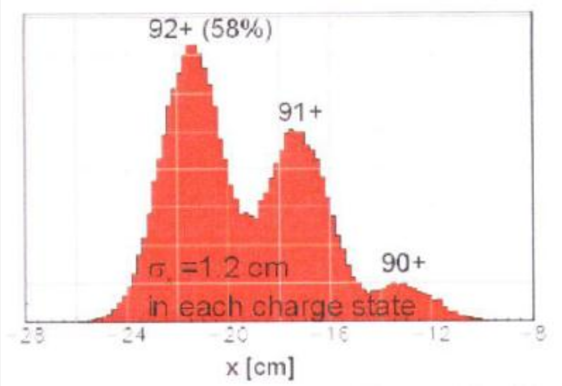
[i] 740 MeV/u

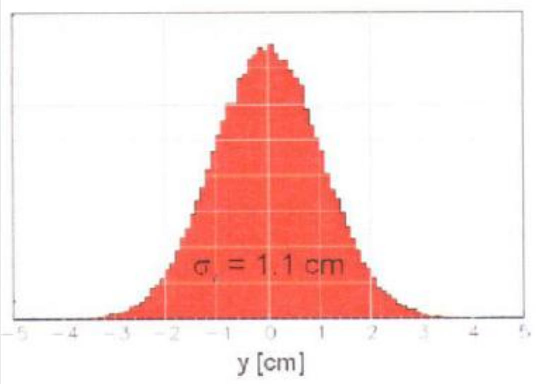


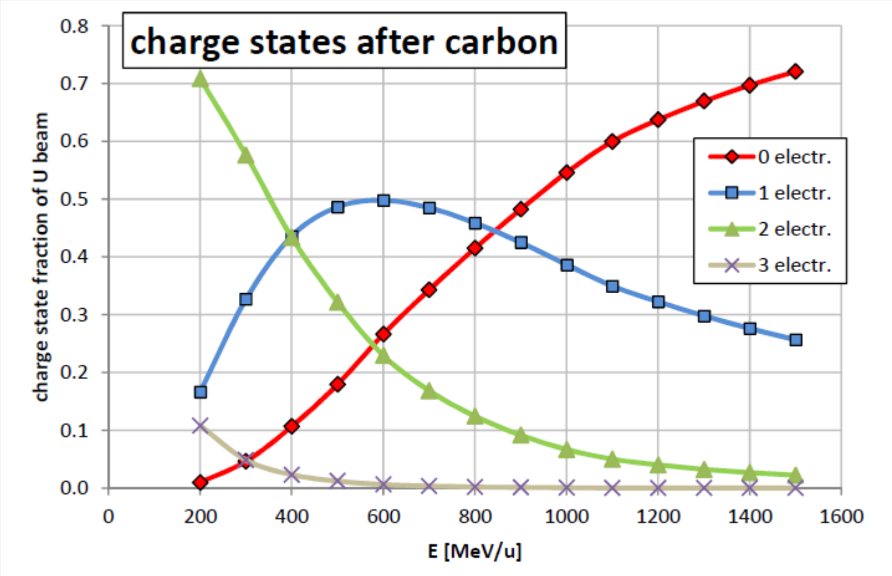
[ii] 1500 MeV/u

Specification FAIR-Revised 2014

Charge state distribution U^{238} ions with Energy levels

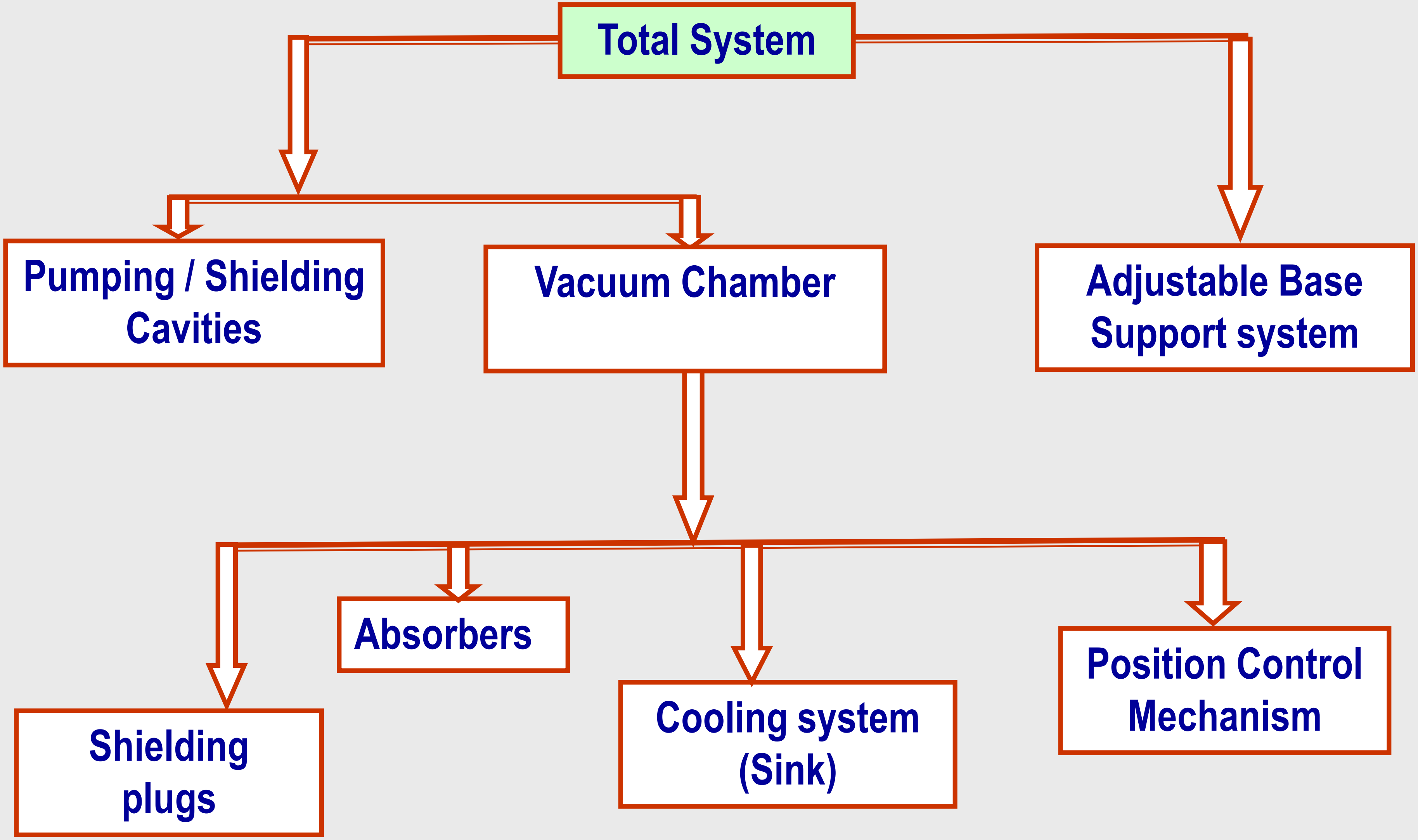




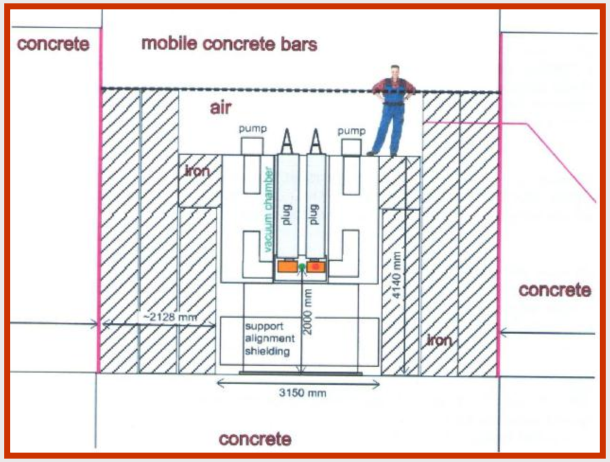


Energy [MeV/u]	92+ [%]	91+ [%]	90+ [%]	89+ [%]	88+ [%]
1500	77.7	20.8	1.5	<0.01	
1000	58.0	35.9	6.1	<0.1	
750	41.9	45.7	12.2	0.2	<0.01
500	21.8	49.5	27.7	0.9	~0.01
250	4.0	30.6	59.7	5.5	0.2

Design of Beam Stoppers

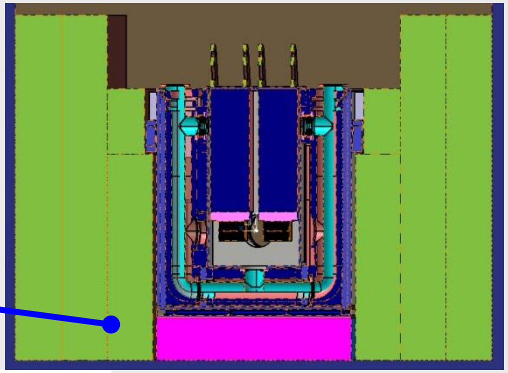


Design of BC3 Cavity

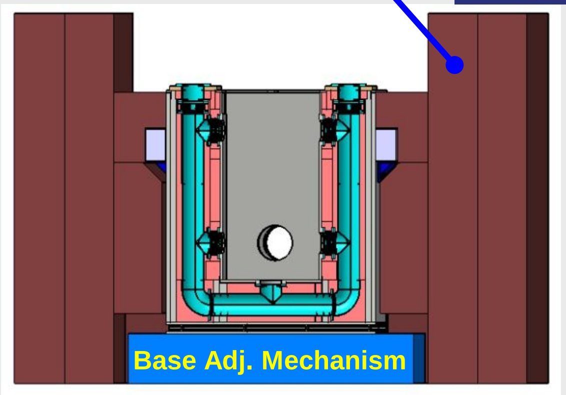


Layout of the Cross Section of the Tunnel at the location of BC3 (provided by FAIR)

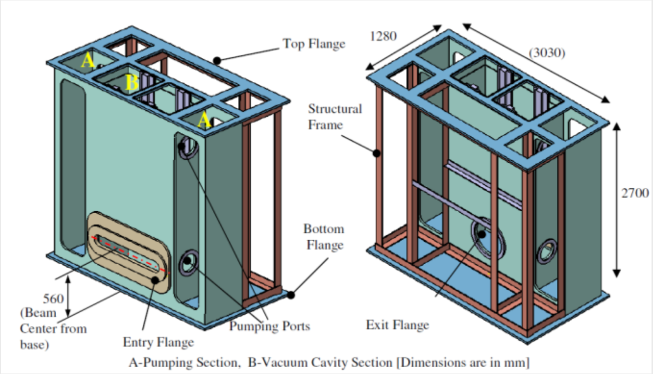
German in-kind Iron Shield



Jan-2015

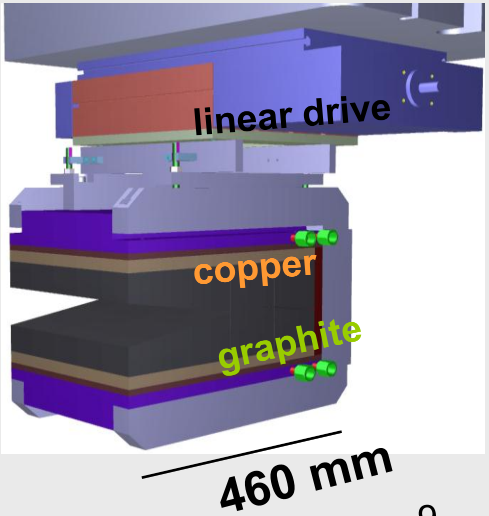


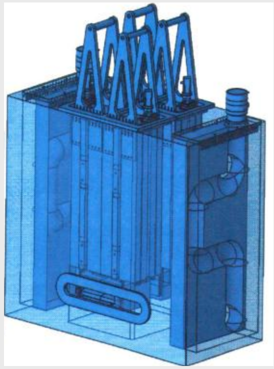
Sept-2014



June 2014

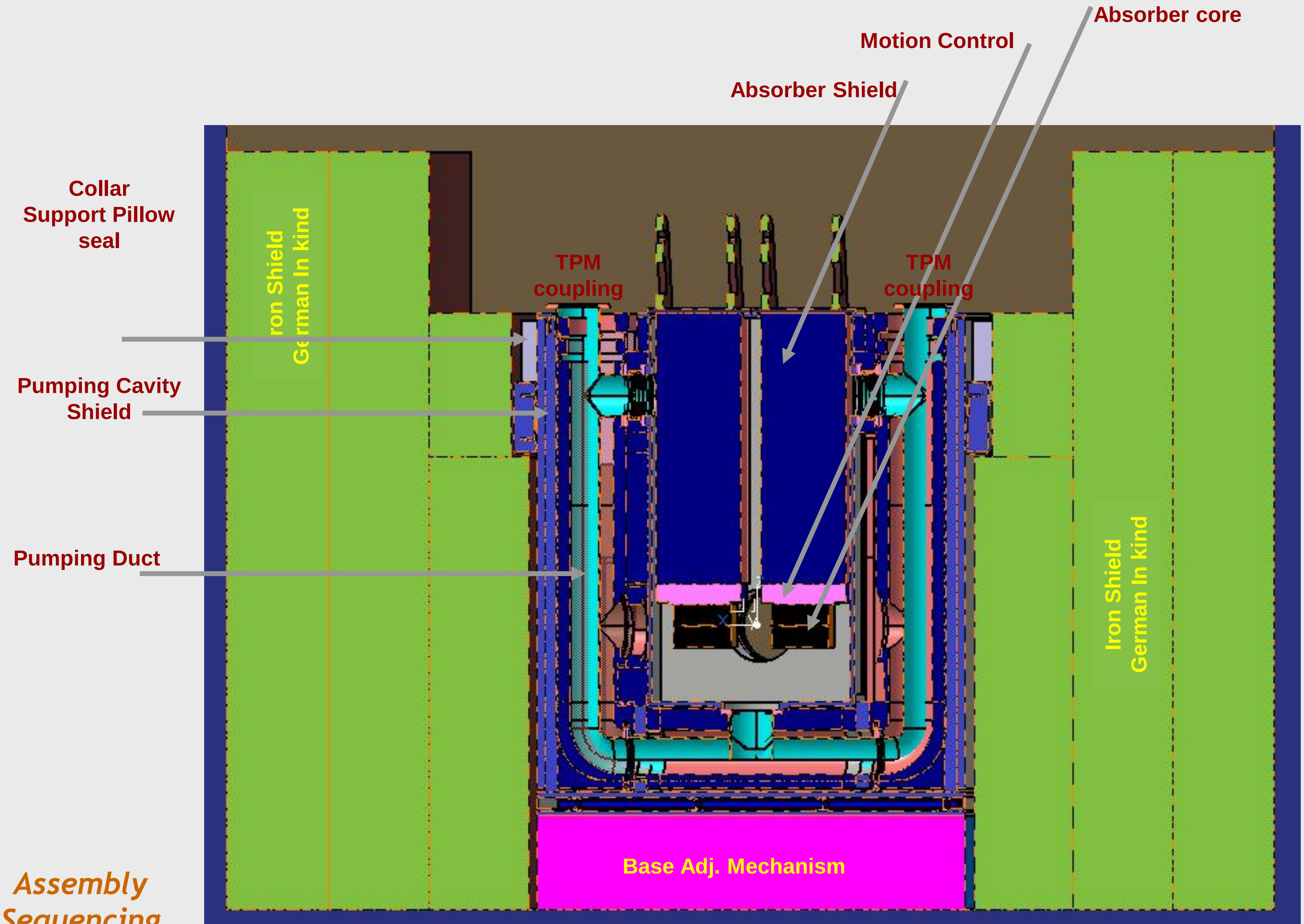
Absorber (L) Earlier Concept





Concept-2012

Beam Entry Section BC3



Assembly Sequencing

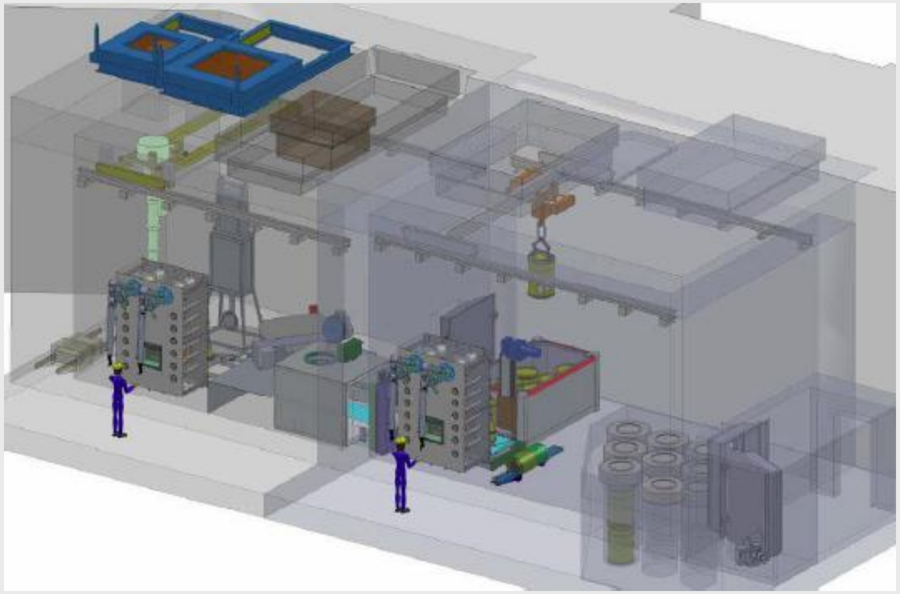
▶ Side Cavity ▶ Bottom Cavity ▶ Cavity Rear

Considerations in Cavity design (For all BC1, BC2, BC3)

After first time installation no manual intervention in the system

Neither the system is directly accessible once assembled

Modular Design for removal, transport , disassembly and re-assembly in Hot cell by remote manipulation through limited access window



- Easy extraction and insertion of absorbers
- De-coupling of the cooling system and motion control system from the absorbers
- Easy extraction and insertion of the beam stopper unit into the vacuum chamber and its subsequent docking with the shielding iron plug.

Hot cell manipulation schematic : Germany and Sweden in Kind

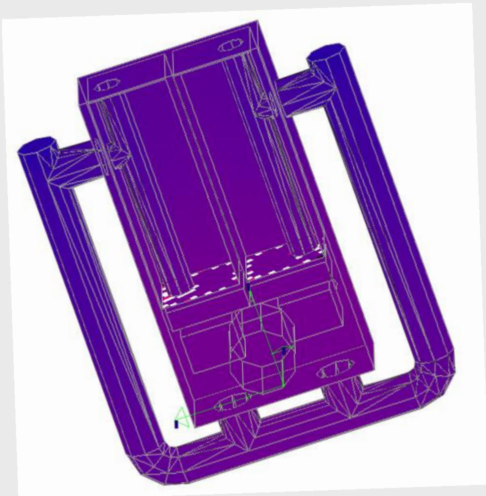
Pressure Simulation

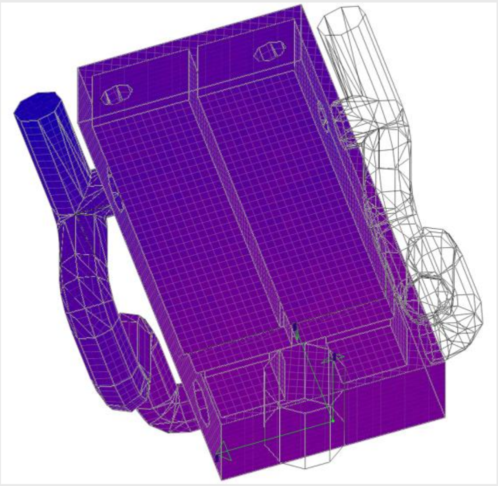
Analysis code : Molflow+ , A Monte-Carlo Simulator package [CERN].

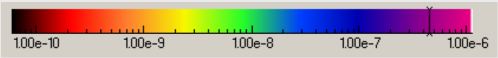
SL	Description	Area [cm2]	Desorption Input Outgassing [mbar*l/s/cm2]	Input Net Outgassing [mar*l/s]	Outgassing [mbar*l/s]	Outgassing mbar*l/s (Molflow)
1	Chamber#1	117585.0	1.00E-10	NA	1.18E-05	1.18E-05
2	Plug#1	55458.2	1.00E-10	NA	5.55E-06	5.54E-06
3	Plug#2	55458.2	1.00E-10	NA	5.55E-06	5.54E-06
4	Duct#1	35879.2	1.00E-10	NA	3.59E-06	**
5	Duct#2	35879.2	1.00E-10	NA	3.59E-06	**
6	Motion_block#1	7800.0	1.82E-10	NA	1.42E-06	1.42E-06
7	Motion_block#2	7800.0	1.82E-10	NA	1.42E-06	1.42E-06
8	Absorber#1	8000.0	2.80E-08	NA	2.24E-04	**
9	Absorber#2	8000.0	2.80E-08	NA	2.24E-04	**
10	Entry (Pillow Seal)	1636.1	NA	2.00E-06	2.00E-06	2.00E-06
11	Exit	11105.4	1.80E-10	NA	2.00E-06	**
	Total Surf. Area	**344601.3**				
			FOR BC3MOD3.GEO7Z FILE			
12	Duct#3	**19723**	1.00E-10	NA	1.97E-06	1.97E-06

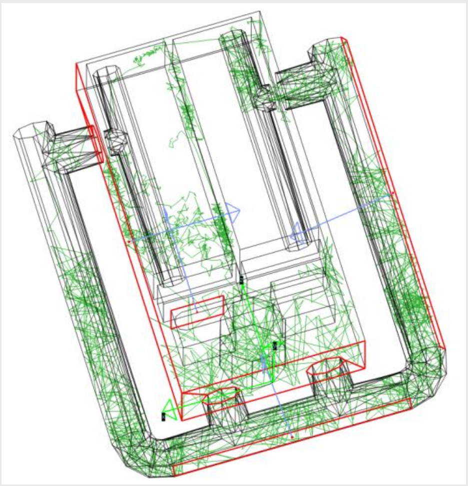
Pressure Simulation

Analysis code : Molflow+ , A Monte-Carlo Simulator package [CERN].

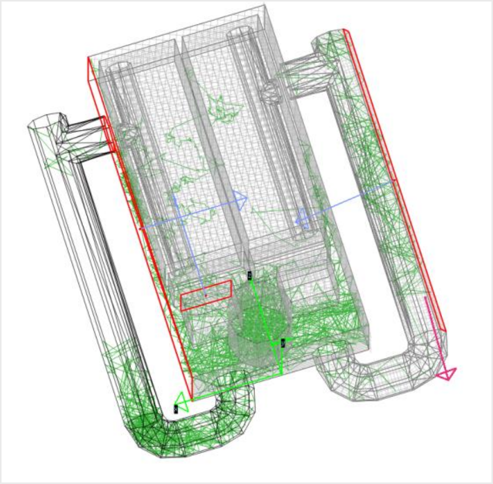




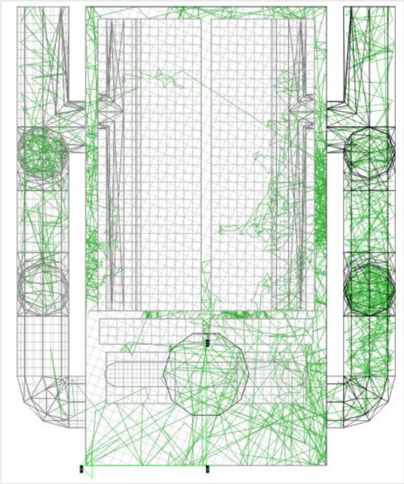




bc3_mod1.geo7z



bc3_mod2.geo7z

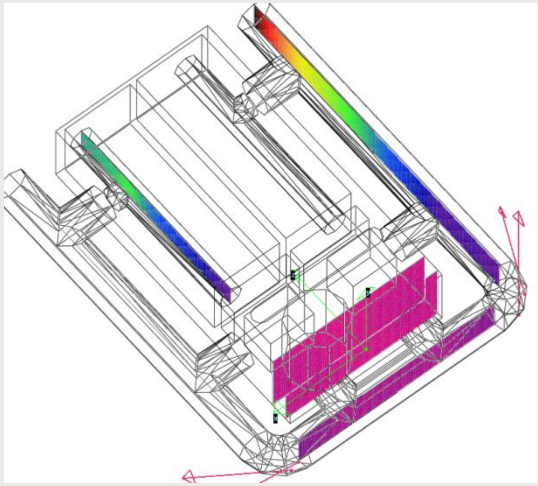


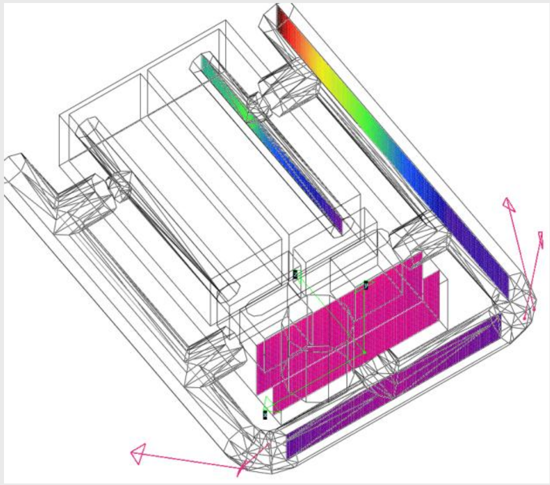
bc3_mod3.geo7z

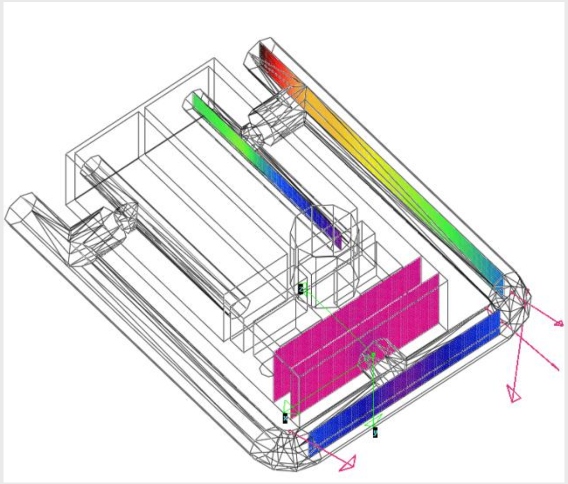
Pressure Simulation

Analysis code : Molflow+ , A Monte-Carlo Simulator package [CERN].

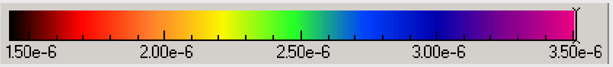
bc3_mod4.geo7z







bc3_mod4.geo7z



bc3_mod6.geo7z

Graphite out gassing with temperature : Absorber outgassing 1.2 E-7 mbar.l/s/cm2

[JM Jimenez, CERN, 2003], [Tsai et al. 2005] [Lahiri et al. 2013]

At 400 ºC , 600 ºC , and 1200 ºC, sudden outgassing bursts.

Can be controlled by prior degassing of the graphite at 970 ºC

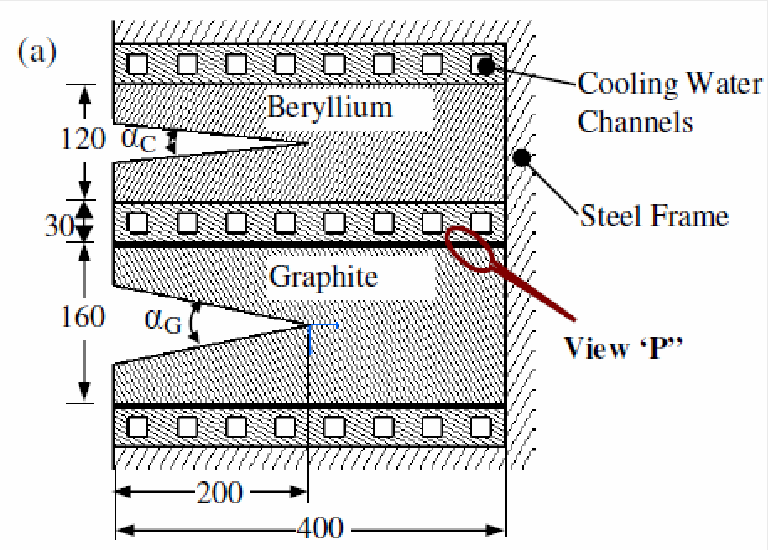
Average outgassing has been reported 1.1-1.2 E-7 mbar.l/s/cm^2 (800 ºC - 900 ºC)

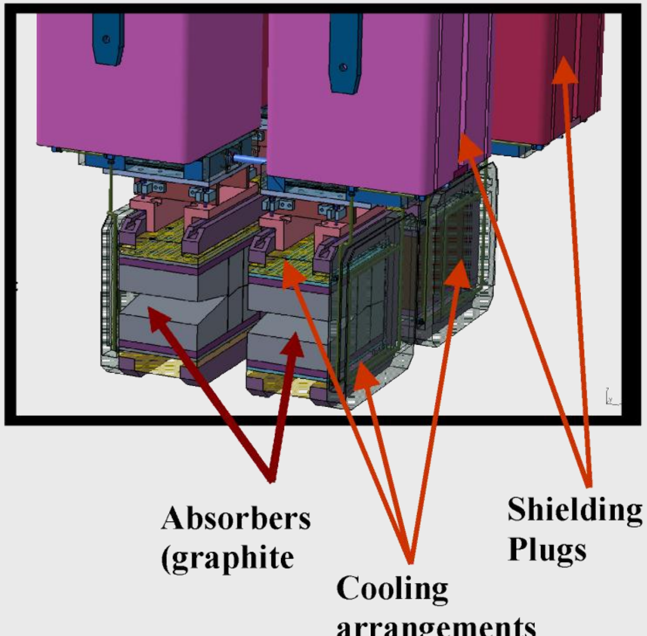
Steady state will occur after settling down

bc3_mod1.geo7z design option has been selected for BC3

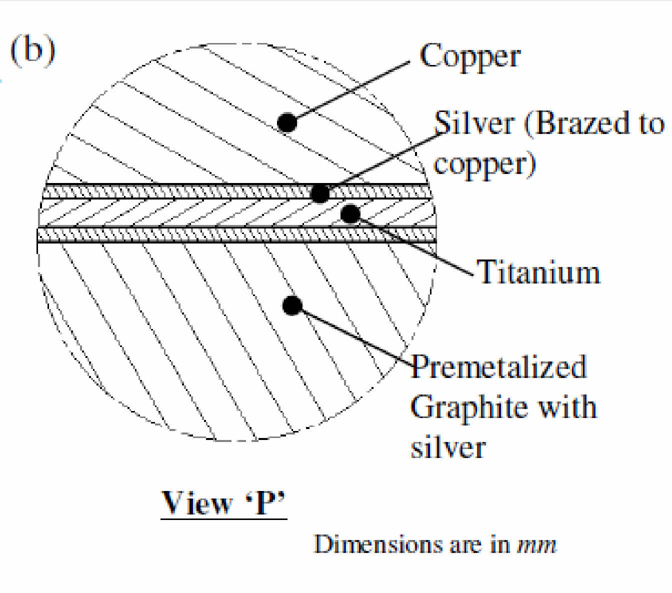
BC3 Absorber Design

High Energy Beam → Direct impact with first layer of material (absorber) → Material absorb the pressure waves / Material is cooled by a coupler heat sink



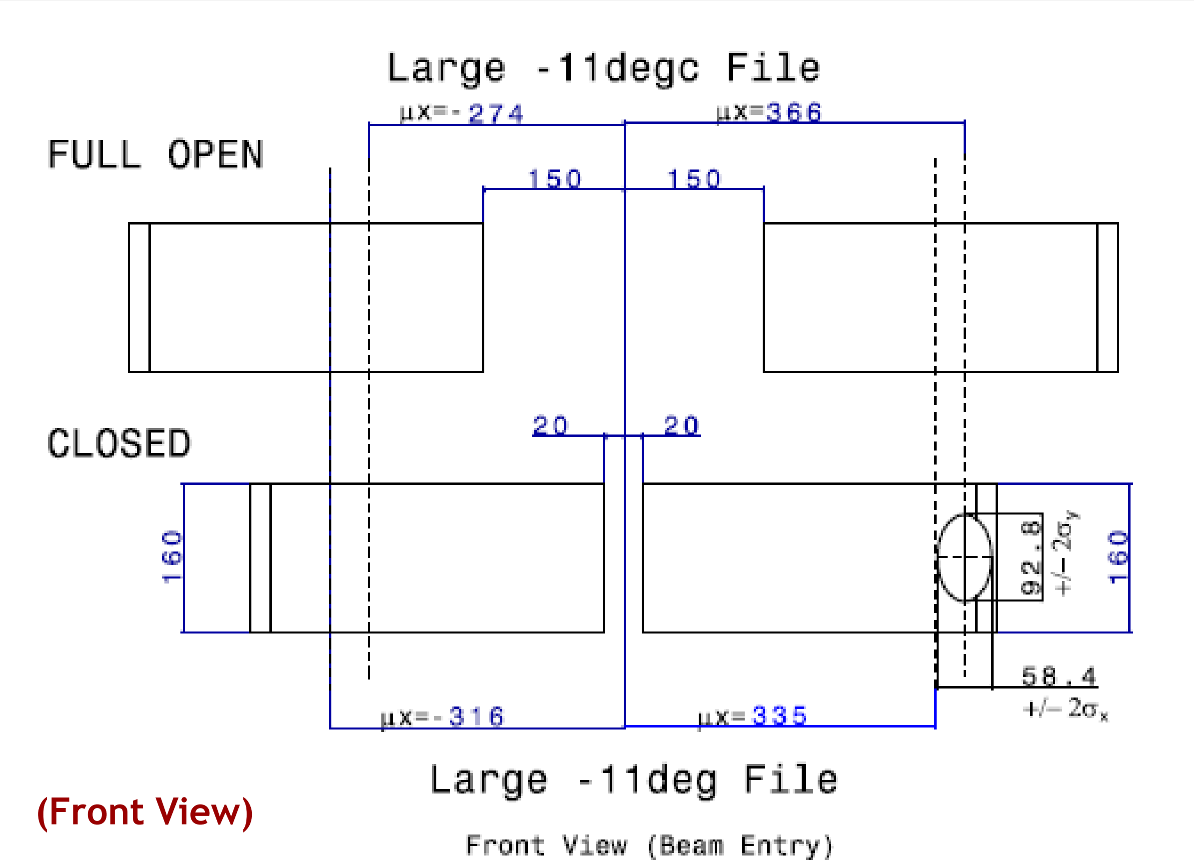


Absorbers and cooling system (Earlier concept)

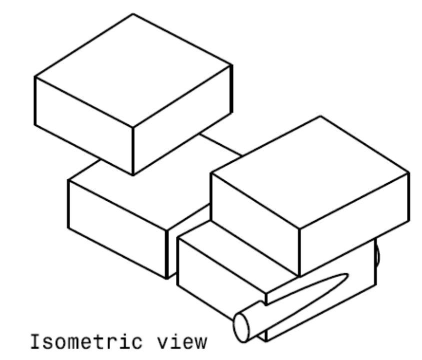


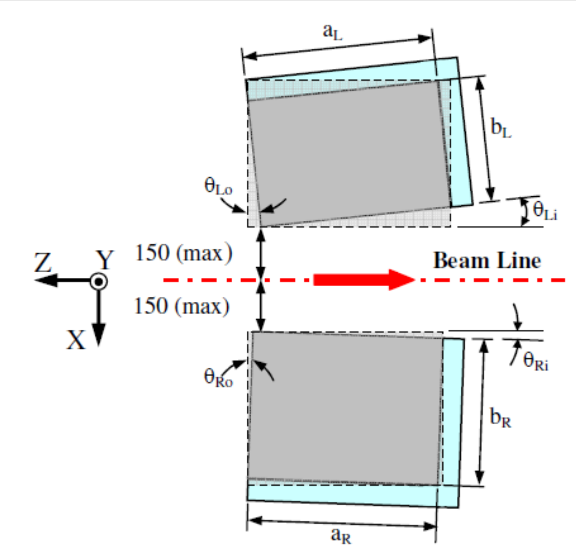
Staggered Catcher for both slow and fast extraction (Current Concept)

BC3 Absorber Design : Open and Close conditions



(Front View)



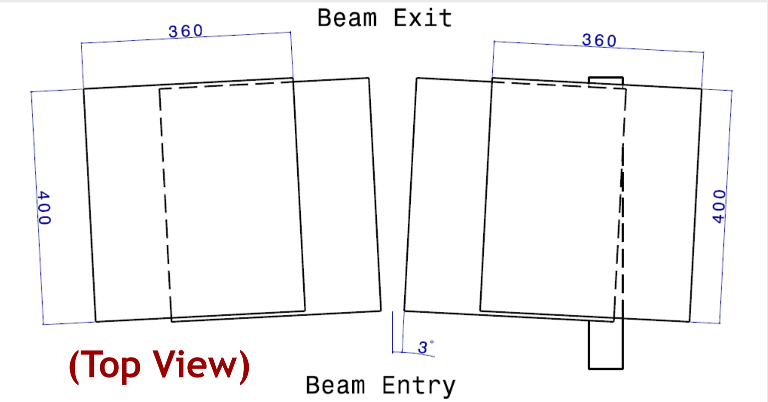


2.7 deg inclination to interrupt the beam

Motion control along X and Y for switching between

Open and Close conditions

Fast and Slow Extraction



(Top View)

Fast extraction causes:

- Instantaneous temperature rise (50-100 ns)
- Origin and propagation of compressive pressure wave
- Reflection at boundary resulting tensile wave front
- Limits given by yield strength (?) and spall strength
- Transient shock parameter and irradiation effects becomes primary factors

50-100 ns pulses 5×10^{11} ppp @ 1.67s : 14kJ (740MeV/u) and 29kJ (1500MeV/u)

- ❑ Temperature rise, melting, property change, evaporation
- ❑ Thermal stresses, deformations, failure
- ❑ Shock wave propagation spalling

Initial GSI report :

With 10^{13} ^{238}U ions/cm^2 (Low Energy in existing SIS18 facility)

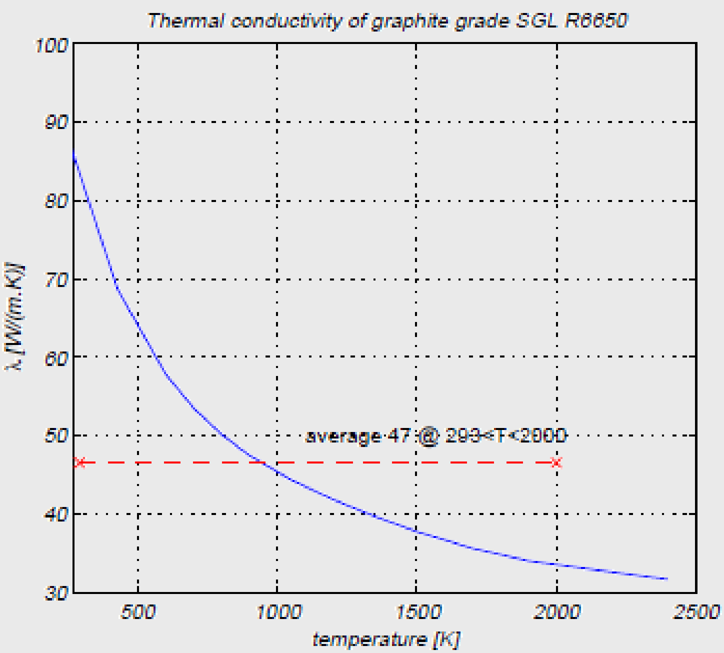
Increased Young's modulus - Good

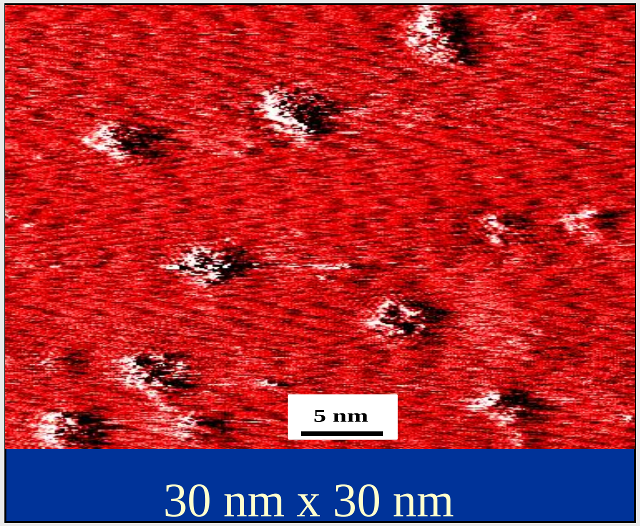
Lower thermal conductivity (~8 W/mK) - Worst !!

Lattice shift / Dislocation - Bad

Swelling (1-3%) - Bad

~M. Tomut , H. Weick : Report PHN-NUSTAR-FRS-23- 2011

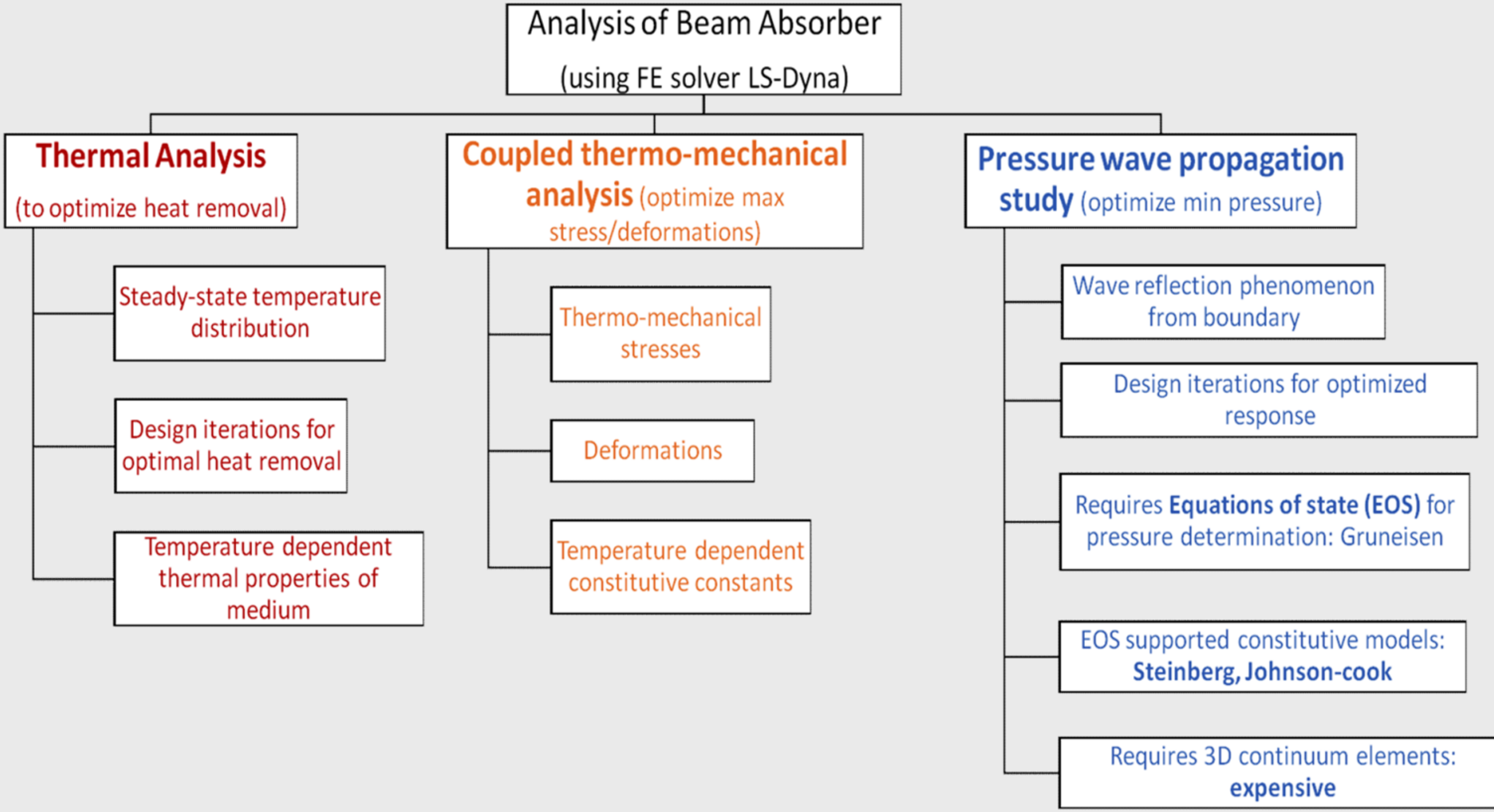




Radiation damage, STM image
U beam on graphite

M. Tomut

BC3 Absorber Design : Fast Extraction



BC3 Absorber Design : Fast Extraction : Thermal Analysis

- Solving thermal equilibrium problem considering average heat transfer coefficients h_{av} at top and bottom and neglecting radiation

- Estimation of $h_{av:}$ due to convective heat loss for a fully developed flow with no entrance and exit effects.

Cooling Channel dia = 14mm

Area (A_p) = 1.54x 10^{-4} m^2

U_m = 0.54m/s (q/60*A_p)

R_{eD} = ρ U_mD/ μ ~10000

P_r= μ Cp/ K = 5.4

[a] Dittus –Bolter Empirical Correlation

$$\overline{N}_{ufd} = 0.023 \times R_e^{0.8} \times P_r^{03} = 60.46$$

[b] Sieder –Tate Empirical Correlation gives

$$\overline{N}_{ufd} = 0.027 \times R_e^{0.8} P_r^{03} \left(\frac{\mu_b}{\mu_s} \right)^{0.14} = 69.93$$

[c] Molki & Sparrow correlation correction for short tubes.

$$\frac{\overline{N}_u}{\overline{N}_{ufd}} = 1 + a \left(\frac{L}{D} \right)^b \text{ where } a = \left(\frac{24}{R_e^{0.23}} \right) \text{ and } b = 2.08 \times 10^{-6} R_e - 0.815$$

$$\overline{N}_u = \frac{\overline{h}_c D}{K} \Rightarrow \overline{h}_c = \frac{\overline{N}_u K}{D} = \frac{86.82 \times 0.615}{0.014} = 3814 \text{ W/m}^2\text{K}$$

T_{inf} =293K (30ºC)

ρ = 995.7Kg/m^{-3}

C_p = 4176J/Kg/K

K = 0.615W/m/K

μ x 10^6 = 792.4 N-s/m^2

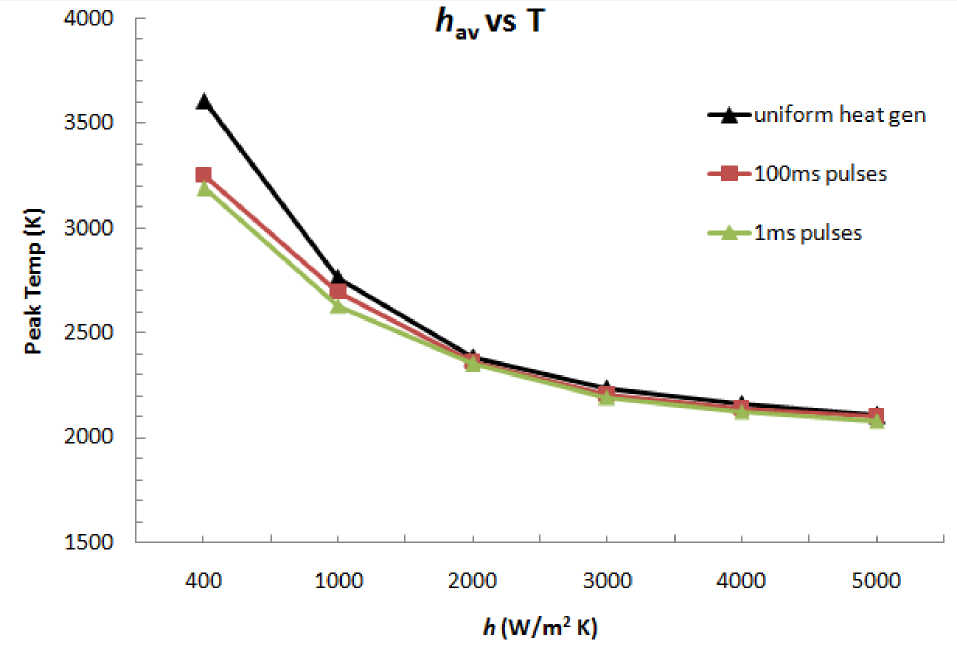
ν x 10^6 = 0.805 N-s/m2

q = 5 lit/min.

BC3 Absorber Design : Fast Extraction : Thermal Analysis

Forced Convection Tarbulent Fully Developed flow

For both uniform and pulsed energy deposition, Temperature stabilizes after h_{av} in the range of 2000 -5000 W/m²K



Element size	h_convection	Max temp (TD material)		
		Unifrom	100ms pulse*	1ms pulse*
10	400	3610	3250	3188
10	1000	2758	2695	2629
10	2000	2381	2362	2349
10	3000	2234	2205	2189
10	4000	2156	2140	2123
10	5000	2108	2104	2080
10	5800	2081		

Example:-

$$\overline{N}_u = 86.82$$

$$\overline{N}_u = \frac{\overline{h}_c D}{K} \quad => \overline{h}_c = \frac{\overline{N}_u K}{D} = \frac{86.82 \times 0.615}{0.014} = 3814 \text{ W/m}^2\text{K}$$

BC3 Absorber Design : Fast Extraction : Coupled Thermo-Mechanical Analysis

- Explicit transient FE solution
- Temp. dependent thermal properties
- Temp. dependent constitutive properties
- Failure criteria
  - **Max./ Min. Principal Stress**
  - **Von Mises**
  - **Column Mohr Equivalent stress**

BC3 Absorber Design : Fast Extraction : Pressure Wave Propagation

- Explicit transient FE solution of coupled thermo-mechanical equilibrium equations
- Total stress = hydrostatic stress (determined by EOS) + Deviatoric stress (Determined by material model)

EOS: determines hydrostatic (bulk) behavior of material.
Gruneisen EOS defines pressure of compressed material as:

$$p = \frac{\rho_0 C^2 \mu [1 + \left(1 - \frac{\gamma_0}{2}\right)\mu - \frac{b}{2}\mu^2]}{[1 - (S_1 - 1)\mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu + 1)^2}} + (\gamma_0 + b\mu)E$$

where,
- E: internal energy
- C: intercept of $u_s - u_p$ curve
- S_1, S_2, S_3: coefficients of slopes of $u_s - u_p$ curve
- γ_0: Gruneisen constant
- b: first order correction to γ_0

$$\mu = \frac{1}{V} - 1$$

Gruneisen parameters are available for many materials including Graphite

Material Models: those support EOS calculations and temperature dependent constitutive calculations:
015- JOHNSON-COOK PLASTICITY or 011- STEINBERG

BC3 Absorber Design : Fast Extraction : Pressure Wave Propagation

Material Property Inputs

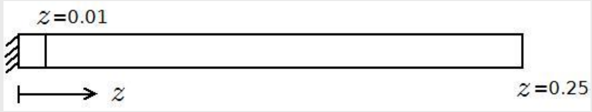
Material: **SGL Graphite grade: R6650**, grain size: 2-7micron/ Cu

	Parameters	Source
Physical properties	Mass density ρ	SGL*
Thermal Properties	Heat Capacity, Thermal conductivity	SGL*
Elastic, Plastic and Thermo-mechanical Constitutive constants	E, G, α	SGL*
	Steinberg/Johnson-cook parameters	-
Equation of State model (Gruneisen) parameters	C, S_1, S_2, S_3, γ_0, α	Lawrence Livermore National Laboratory, 1996*
Strength /failure criteria parameters	Maximum Compression, Maximum Pressure	Lawrence Livermore National Laboratory, 1996*
	Max Pr. stress, Min Pr. stress	SGL*

*"A thermomechanical analysis of the central column tiles", Report by R. Chavan, CRPP / EPFL - Lausanne, 1998 - 1999

BC3 Absorber Design : Fast Extraction : Pressure Wave Propagation

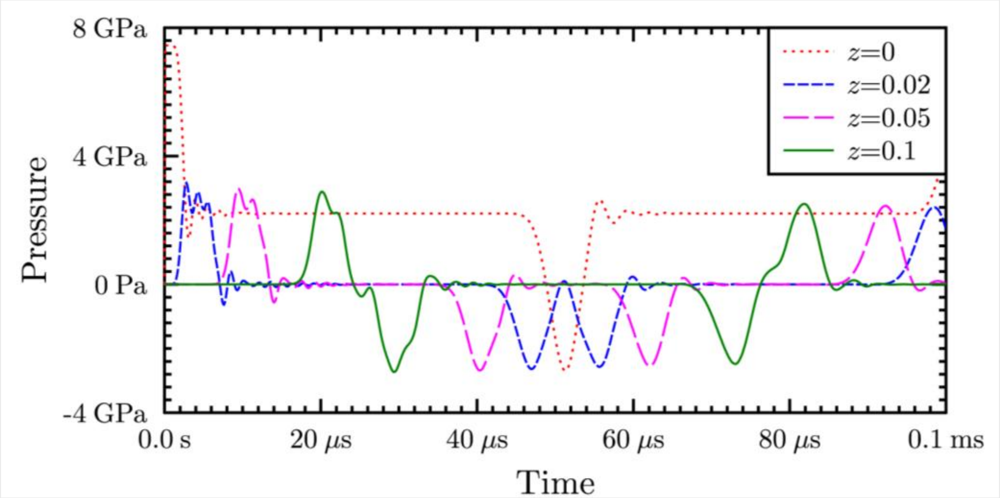
Numerical Validation of 1D Model in LS Dyna

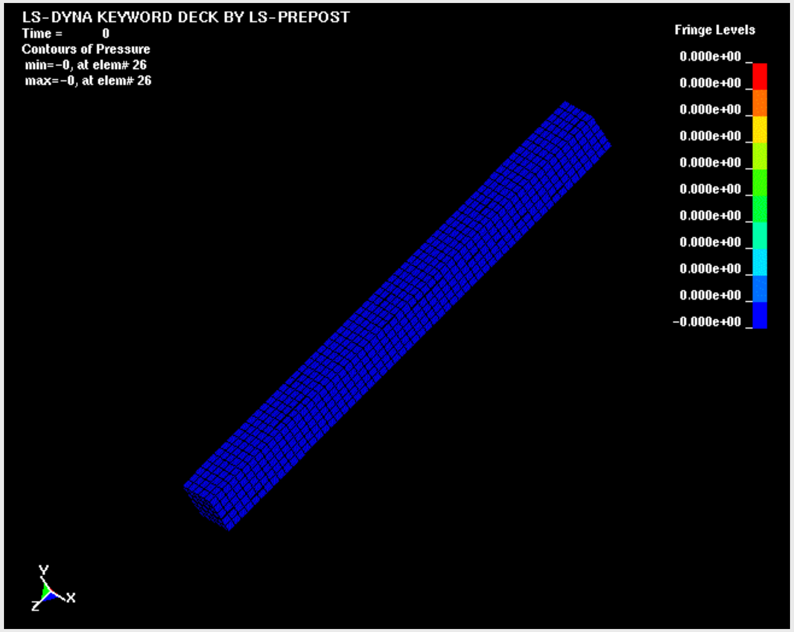


Heat generation triangular pulse width 100 ns
Peak 7.6 x 10^{16} W/m^3
Left end of the bar is fixed
Convective dissipation at the right end with h=1.
T_{inf}=300K
Mie-Gruneisen Polynomial form in EOS
Material : Cu hence very high |P|

Results agree with 1D Analytical model

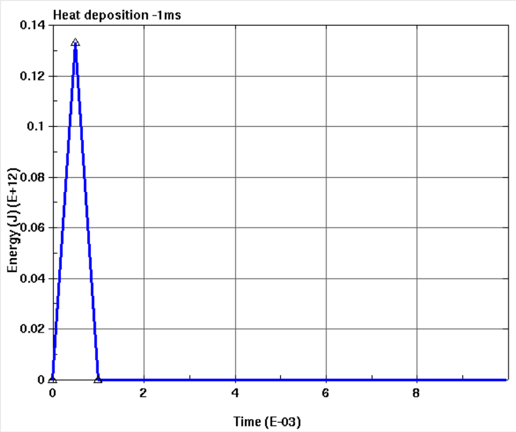
But the energy deposition region of the bar (i.e. z=0) is retaining the pressure even after the pulse propagates out of it ?



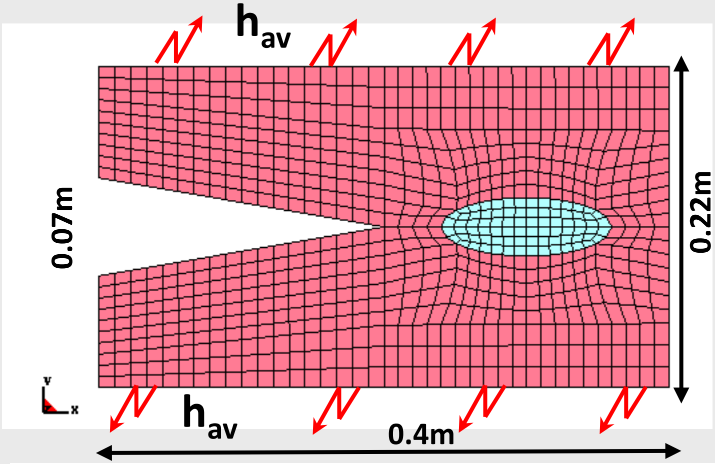


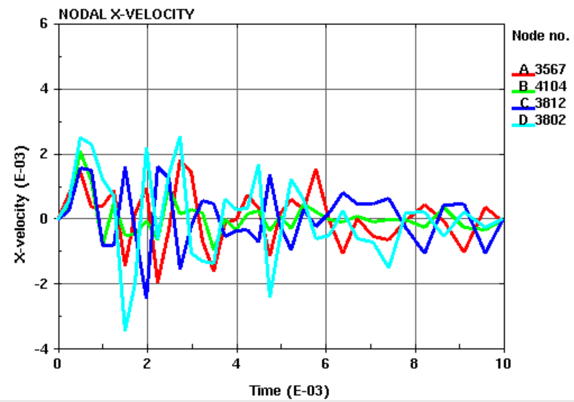
BC3 Absorber Design : Fast Extraction : Pressure Wave Propagation

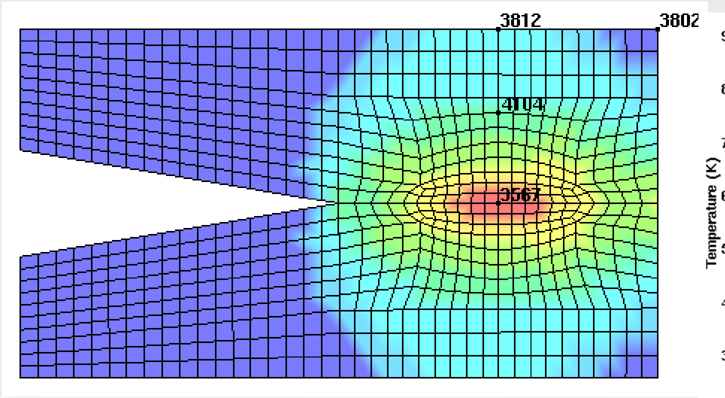
2D Model Numerical Analysis

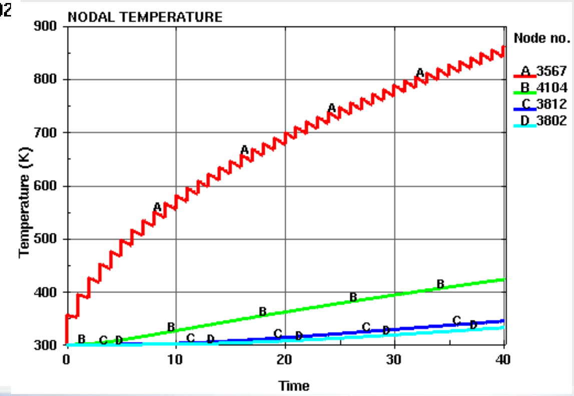


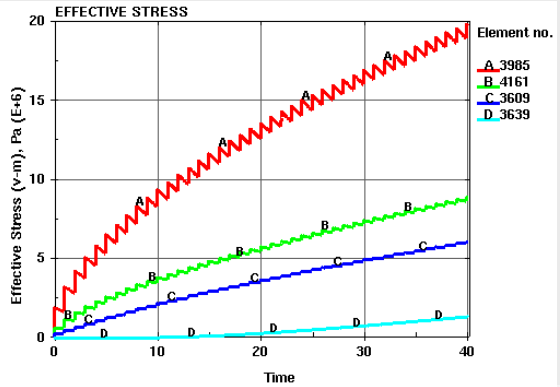
Analytical model under formulation.
Numerical analysis with 1ms triangular pulse depositing 57kW
Explicit time integration : dt = E-6
Coupled thermo-mechanical time step
Material Graphite : R6650
Stopped after 17 Hrs (40s duration)











BC3 Absorber Design : Fast Extraction Discretization of Heating Volume BC3

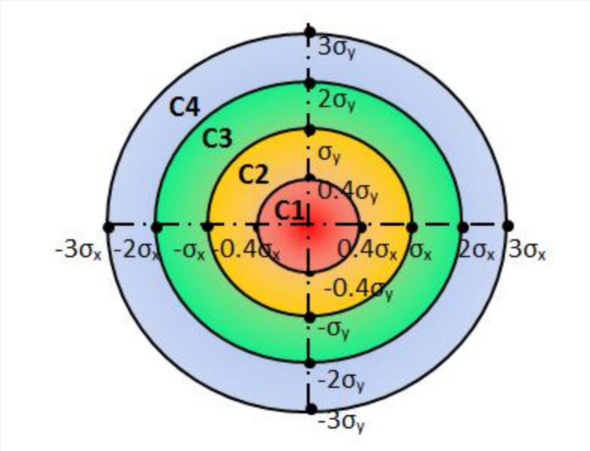
Beam profile 2D Gaussian with sharp Brags peak (740MeV) but flatter (1500MeV)

Radial Discretization

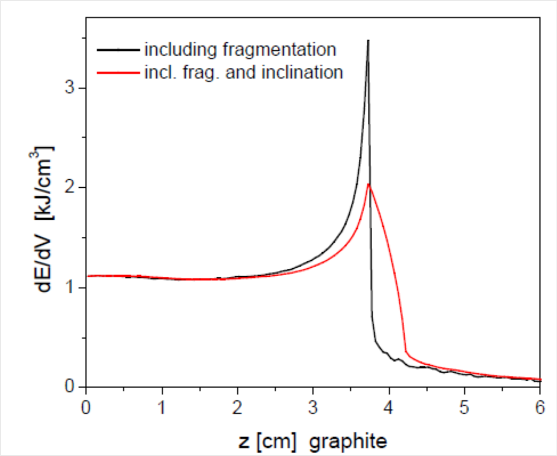
Radial zone (C_i)	Sigma level	Annular Area (dA_i)	Energy Fraction (α_i)
C1	0 – 0.4	$0.16\pi\sigma_x\sigma_y$	0.097
C2	0.4 – 1	$0.84\pi\sigma_x\sigma_y$	0.369
C3	1 – 2	$3\pi\sigma_x\sigma_y$	0.445
C4	2 – 3	$5\pi\sigma_x\sigma_y$	0.084

Spot size as function of the location along x (μ_x)

Critical spot size is minimum of σ_x x σ_y

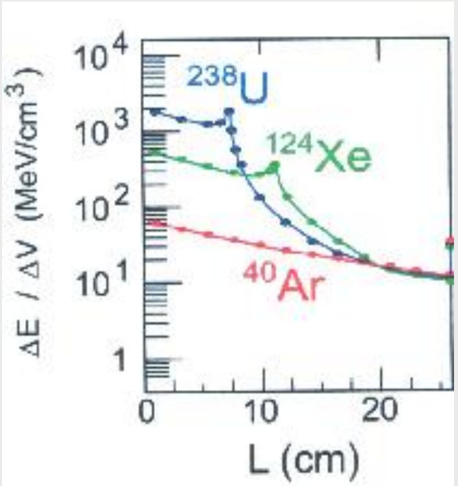


Axial Discretization

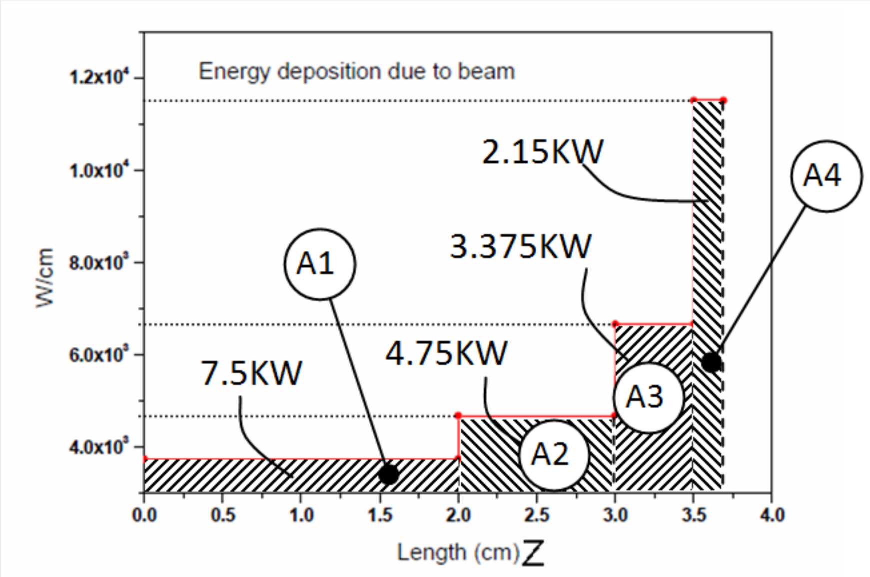


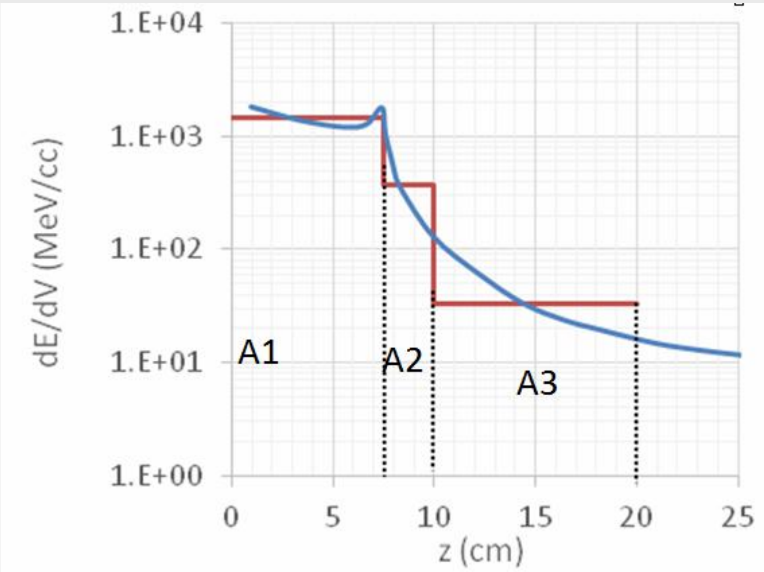
740MeV/u

U^{238} ions pulses in graphite (ρ = 1.84 g/cm³).



1500MeV/u



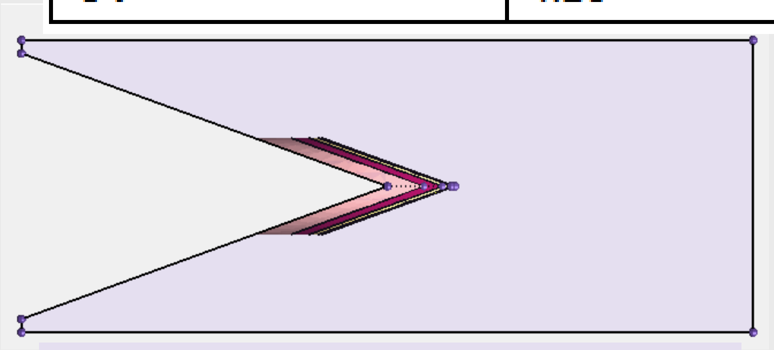


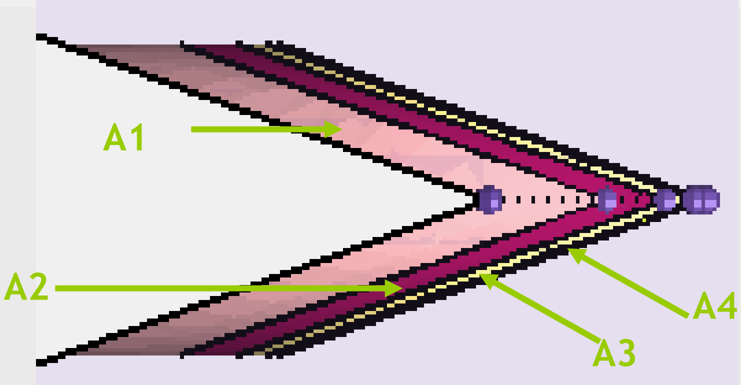
BC3 Absorber Design : Fast Extraction *Discretization of Heating Volume BC3*

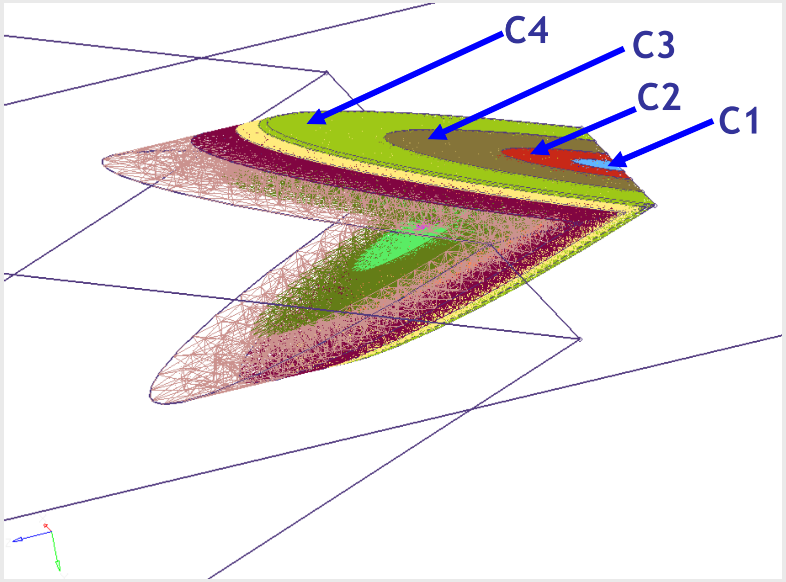
μ_x 365.5mm σ_x=1.46 cm σ_y=2.32 cm *Critical spot size*

740MeV/u

Energy density (J/cc)				
	Energy density (J/cc) dE/dV = $(E/dA_i.dz_j).\alpha i.\beta j$			
Ci \ Aj	A1	A2	A3	A4
C1	152.03	192.38	273.80	466.23
C2	110.72	140.11	199.41	339.55
C3	37.34	47.25	67.25	114.52
C4	4.21	5.32	7.58	12.90





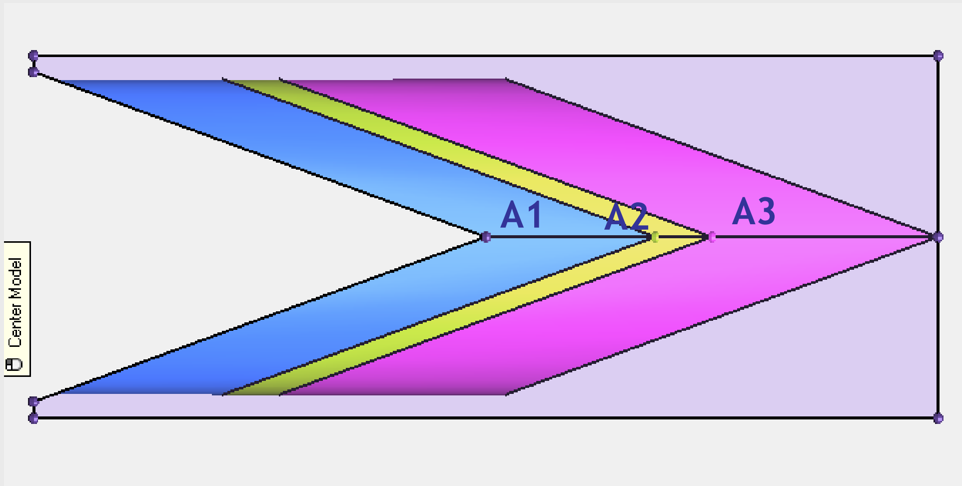


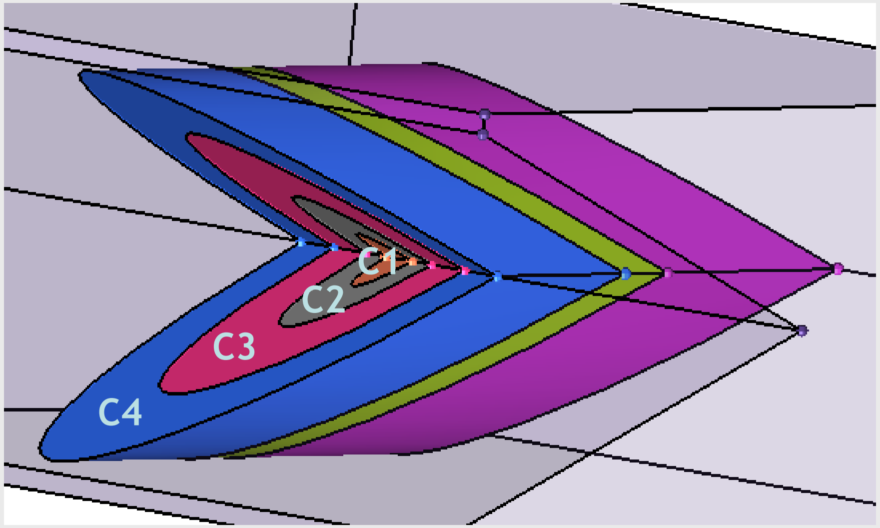
BC3 Absorber Design : Fast Extraction *Discretization of Heating Volume BC3*

μ_x 365.5mm σ_x=1.46 cm σ_y=2.32 cm *Critical spot size*

1500MeV/u

Energy density (J/cc)			
	Energy density (J/cc) $dE/dV = (E/dA_i.dz_j).\alpha i.\beta j$		
Ci \ Aj	A1	A2	A3
C1	169.42	46.74	7.30
C2	123.39	34.04	5.32
C3	41.62	11.48	1.79
C4	4.69	1.29	0.20





Computationally very expensive :
Analysis on process

CSIR-CMERI
- Dr. Avik Chatterjee
- Abhijit Mahapatra
- Amit Kumar

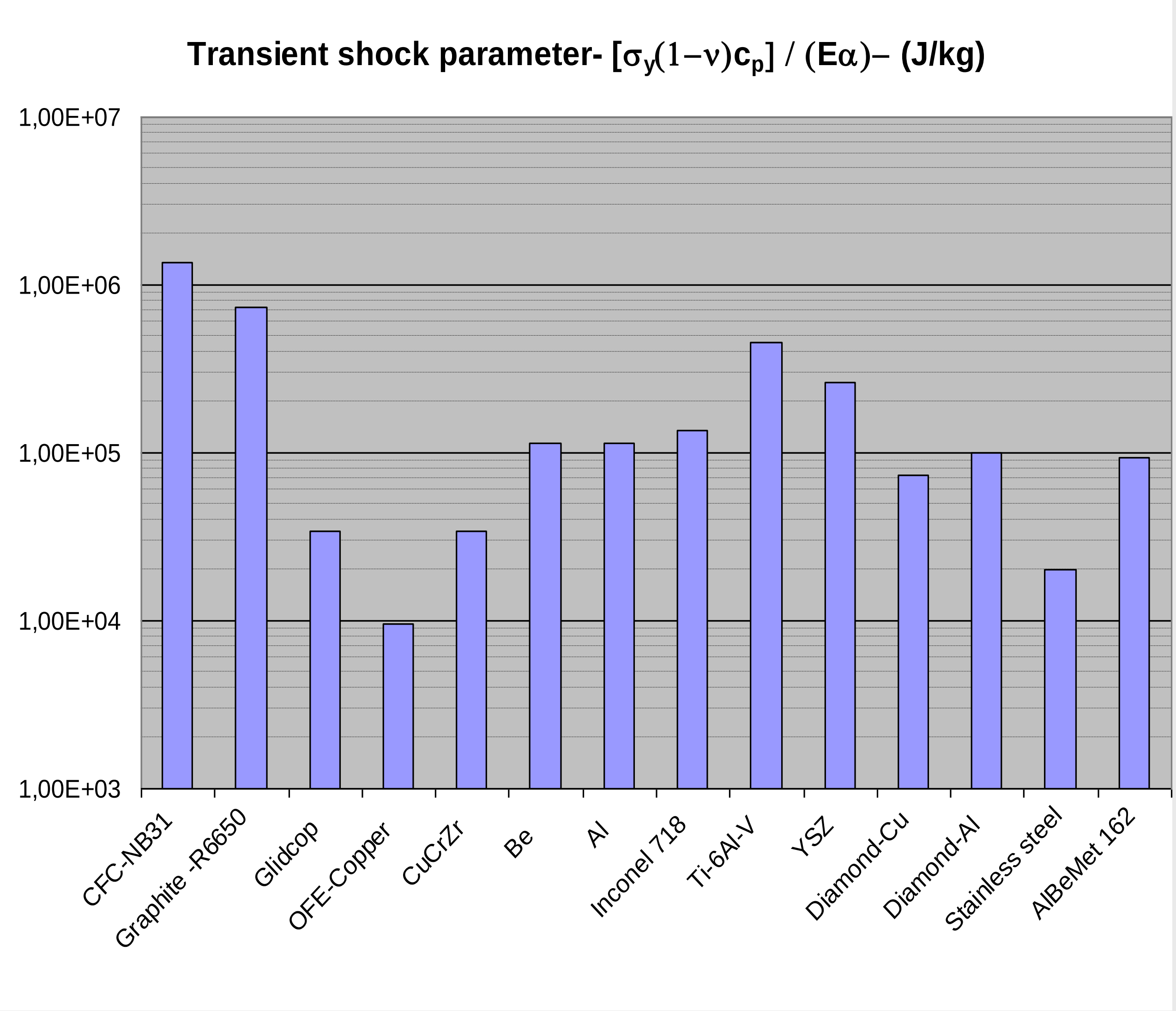
FAIR@GSI
- Dr. Helmut Weick
- C.Karagiannis

IFCC-BI
- Dr. Subhasis Chattopadhyay

Interactions ?

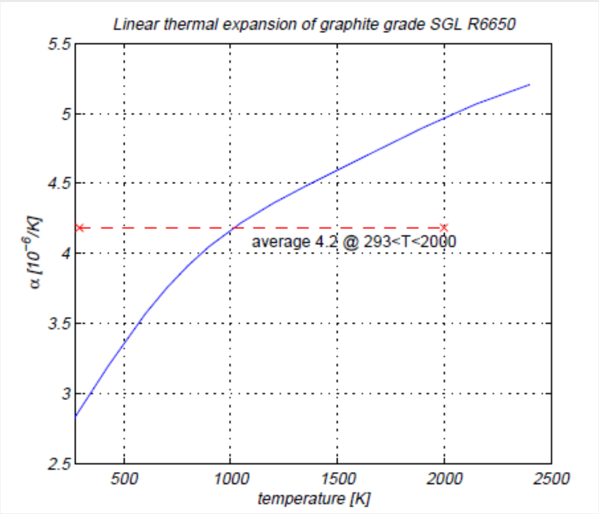
Thank you !!

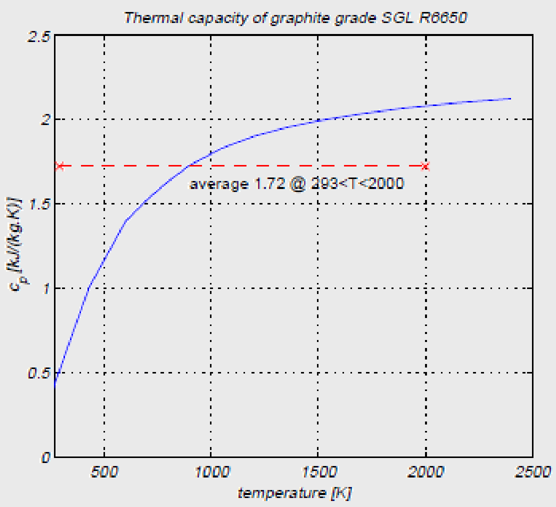
Appendix : Material Consideration

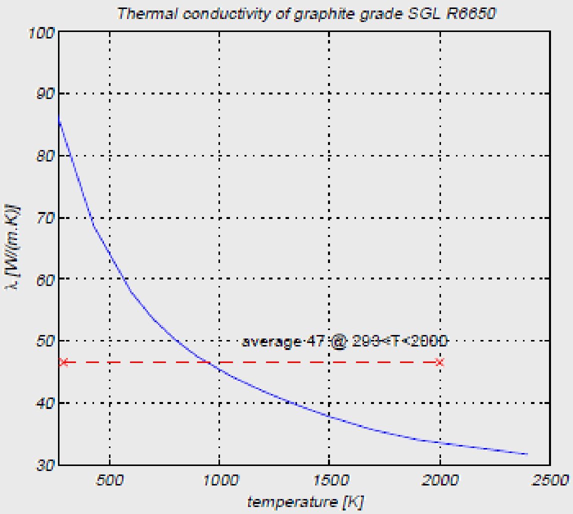


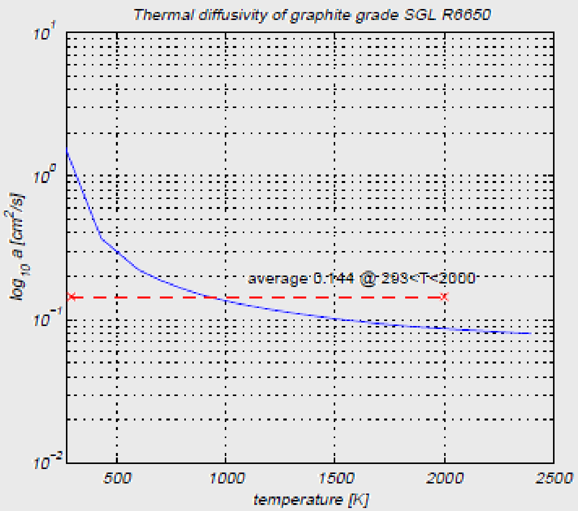
Appendix : Material Property

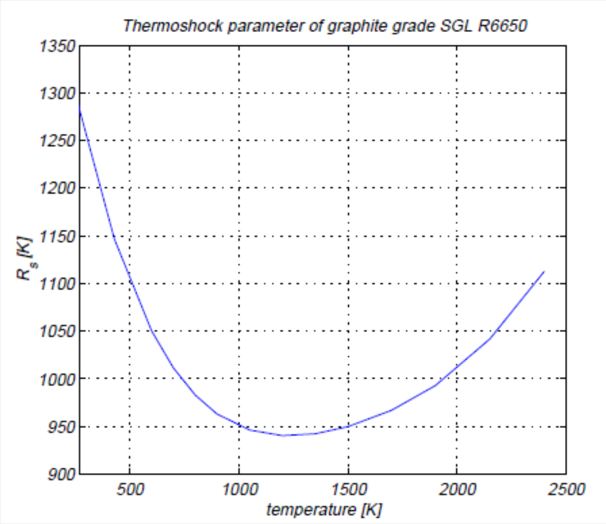
Source: **Manufacturer (SGL)**

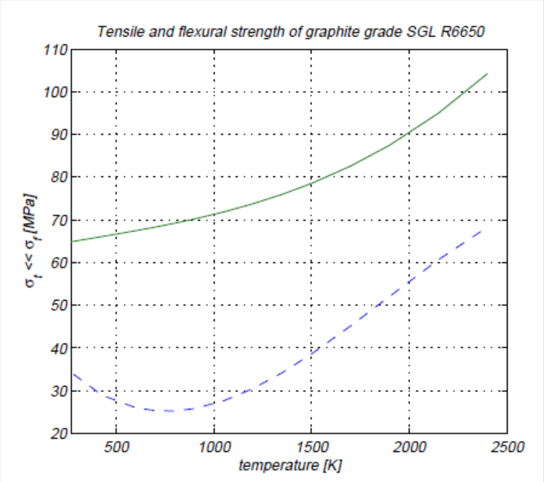












ρ= 1870 Kg/m³. ***E =13.5E+9 Pa*** ***G =5.4E+9 Pa*** ***PR =0.25***

Appendix : Material Property (EOS)

Source: **Lawrence Livermore National Laboratory, 1996**

- Gruneisen EOS parameters:

C_0	S_1	S_2	S_3	γ_0	b
0.39	2.16	1.54	-9.43	0.24	0.

$$p = \frac{\rho_0 C^2 \mu\left[1 + \left(1 - \frac{\gamma_0}{2}\right)\mu - \frac{b}{2}\mu^2\right]}{\left[1 - (S_1 - 1)\mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu + 1)^2}\right.} + (\gamma_0 + b\mu)E$$

where, $\boldsymbol{E}$: internal energy

$\boldsymbol{C}$: intercept of $u_s - u_p$ curve

$\boldsymbol{S_1}, \boldsymbol{S_2}, \boldsymbol{S_3}$: coefficients of slopes of $u_s - u_p$ curve

$\boldsymbol{\gamma_0}$: Gruneisen constant

$\boldsymbol{b}$: first order correction to γ_0

$$\mu = \frac{1}{V} - 1$$

- Maximum Compression = 1.45

- Maximum Hugoniot Pressure = 0.46 Mbar

Appendix : Thermo-mechanical Equilibrium equations

$$\sigma_{x,x} + \tau_{xy,y} + \tau_{xz,z} + b_x = \rho \ddot{u}$$

$$\tau_{xy,x} + \sigma_{y,y} + \tau_{yz,z} + b_y = \rho \ddot{v}$$

$$\tau_{zx,x} + \tau_{yz,y} + \sigma_{z,z} + b_z = \rho \ddot{w}$$

$$k_x T_{,xx} + k_y T_{,yy} + k_z T_{,zz} + Q = c\rho \dot{T}$$

$$\{\varepsilon\} = [S]\{\sigma\} + \{\alpha\} T$$

Appendix : Stress wave propagation solution

Dilatational wave

$$(\lambda+2\mu)\nabla^2\Delta=\rho\frac{\partial^2\Delta}{\partial t^2}$$

$$\nabla^2\Delta=\frac{1}{c_1^2}\frac{\partial^2\Delta}{\partial t^2}$$

$$c_1=\sqrt{\frac{(\lambda+2\mu)}{\rho}}$$

$$\Delta=\nabla.u=\varepsilon_x+\varepsilon_y+\varepsilon_z$$

Distortional wave

$$\mu\nabla^2\varpi=\rho\frac{\partial^2\varpi}{\partial t^2}$$

$$\nabla^2\varpi=\frac{1}{c_2^2}\frac{\partial^2\Delta}{\partial t^2}$$

$$c_2=\sqrt{\frac{\mu}{\rho}}$$

$$\varpi=\nabla\times u$$

Plane wave solutions

- Simple Harmonic wave solution

$$u=C_1e^{i(kx+\omega t)}+C_2e^{-i(kx-\omega t)}$$

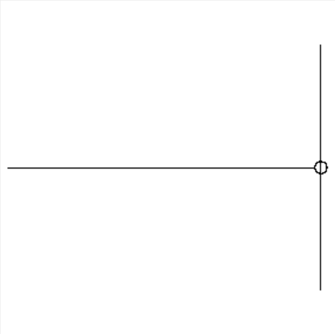
- D'Alembert (general) Solution

$$u=f(x+ct)+g(x-ct)$$

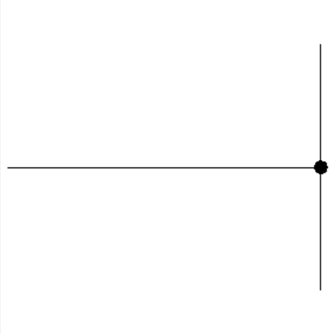
where, C_1, C_2 and the forms of f and g are obtained from boundary and initial conditions

Wave reflection from boundary

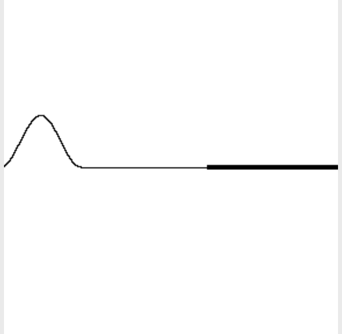
Soft boundary



Hard boundary



Low density to High density



GIF Source: Pennsylvania State University