13th International Workshop on Spallation Materials Technology

31st Oct., 2016@ Chattanooga

Investigation of target material for muon production under high power proton beam irradiation

J-PARC Center, High Energy Accelerator Research Organization, KEK

Shunsuke Makimura

Challenger: silicon carbide

against king of Low-Z target material, polycrystalline graphite

Many thanks to everyone, (^_^)/

Collaborators

☐Muon Section, J-PARC Center, High Energy Accelerator Research Organization:

Shunsuke Makimura, Shiro Matoba, Naritoshi Kawamura , Koichiro Shimomura

☐J-PARC Center, KEK and JAEA:

Taku Ishida, T. Nakadaira, S. Mihara, E. Wakai, M. Teshi and T2K, COMET, JAEA collaboration

☐Accelerator Division, Fermi National Accelerator Laboratory:

Patrick G Hurh, K. Ammigan, and RaDIATE collaboration (BNL, PNNL,,,)

☐Target group, CERN: M. Calviani, A. P. Marcone, C.L.T. Martin, and CERN collaboration

☐Osaka University, RCNP: Akira Sato, K. Ninomiya, T. Shima, T. Suzuki, M. Aoki

☐Muroran Institute of Technology: Joon-Soo PARK, A. Kohyama, and OASIS collaboration

This program for SiC coated graphite is supported by US-JP funding at KEK.

This program for SiC/SiC is supported by JSPS Kakenhi “16H03994”.

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- Silicon carbide: SiC coated graphite, NITE SiC/SiC composite
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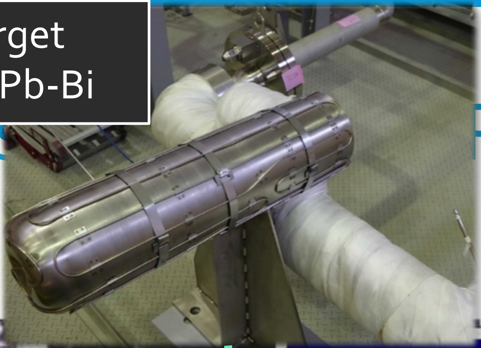
- PROS 2: Oxidation resistance of Silicon carbide
- CONS 3: Residual radionuclides
- Plans for irradiation tests of the SiC coated graphite: RaDIATE, BLIP
- Plans for irradiation tests of the SiC/SiC composite: RCNP, OASIS
- Summary

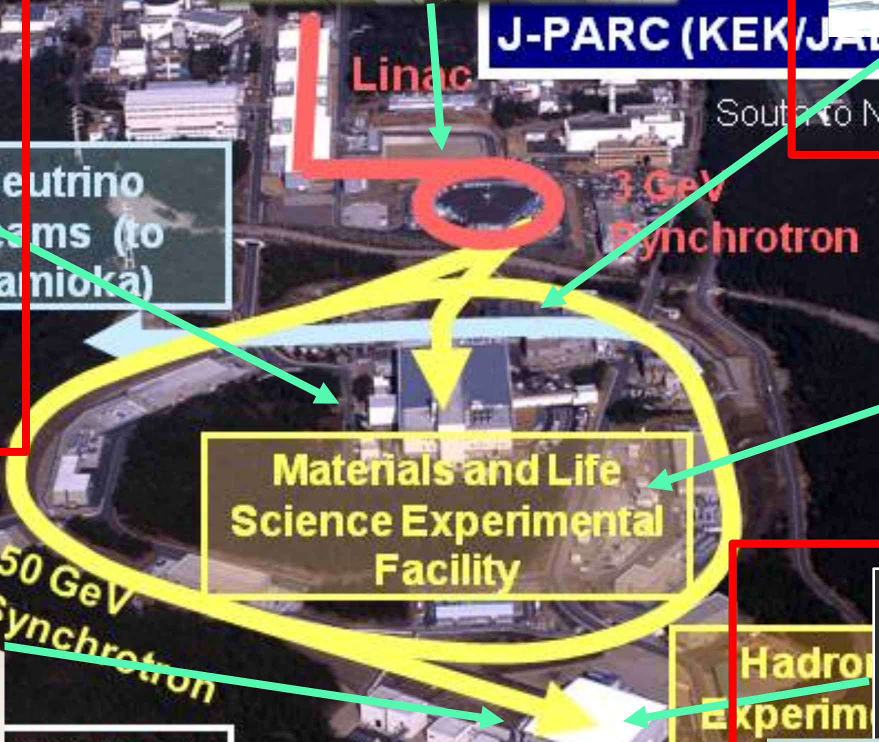
Various PARC

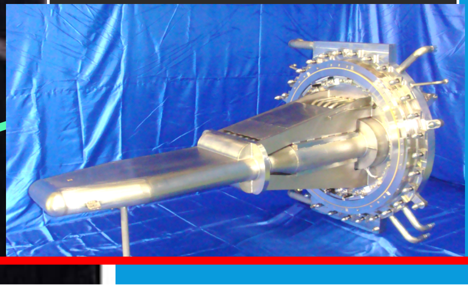


ADS target
Liquid, Pb-Bi

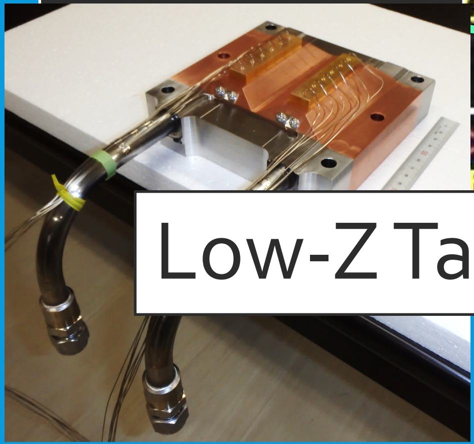
Neutrino target
He-gas-cooled, fixed,
Graphite

Muon target
Rotating, Th. Radiation
Graphite

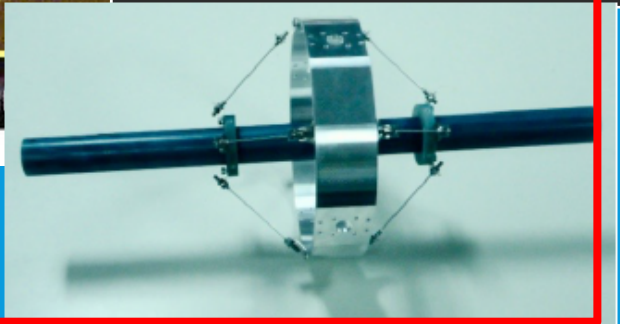




Neutron target
Liquid metal, Mercury



Hadron target
Indirect-water cooled,
Fixed, Gold



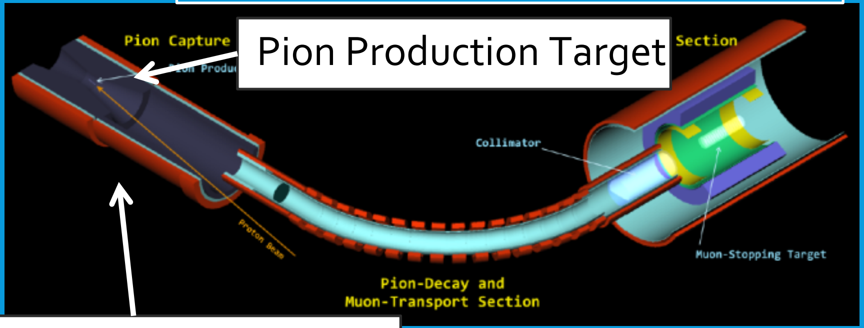
COMET target, Fixed
#1: Th. Radiation, Graphite
#2: ??, high-Z, tungsten?

Low-Z Target (Graphite)

Graphite Target at J-PARC and RCNP/Osaka

Muon Rotating target at MLF
3 GeV, 1 MW, thickness 20 mm
Thermal radiation in vac.
950 Kelvins @ 1MW

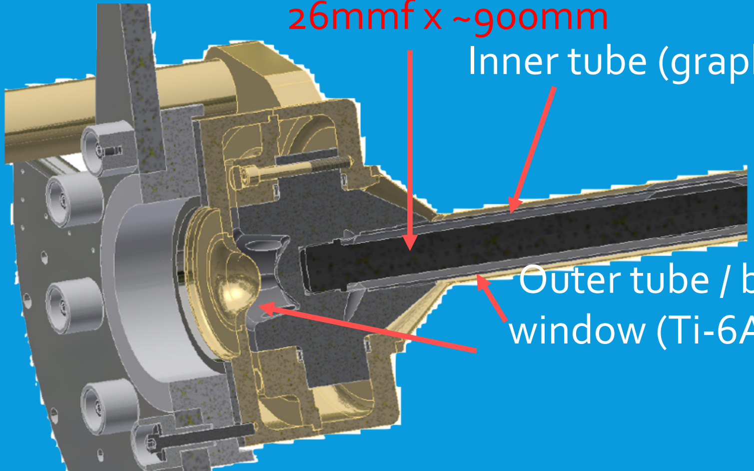
COMET target
8 GeV, 4 kW, thickness 400 mm
Thermal rad. In vac. 500 K



Pion Production Target

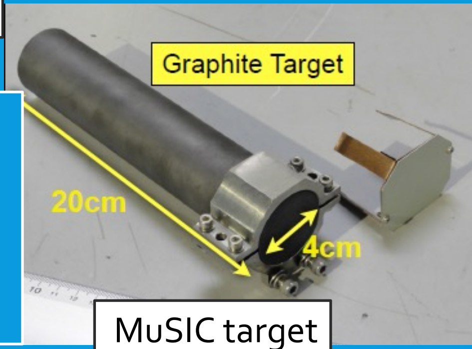
Pion Capture Solenoid

Neutrino target
30 GeV, 750 kW, thickness 900 mm
He-cooling: 1010 Kelvins @ 750 kW



Graphite target IG-430U
26mmf x ~900mm
Inner tube (graphite)
Outer tube / beam window (Ti-6Al-4V)

MuSIC target at RCNP
400 MeV, 400 W,
thickness 200 mm
Thermal rad. In vac. 600 K



MuSIC target

Polycrystalline graphite

King of Low-Z target material, especially for muon/pion production

PROS

- High thermal resistance (1600 degC @Vac.)
- Mech. properties (Low Young's modulus, Low thermal expansion, High resistance to thermal shock)
- Experience as irradiation material (Nuclear fission reactor)

CONS

- Low density (Volume of muon/pion source should be small for efficient transport.)
- Easy oxidation at high temperature (Unexpected air introduction)

Silicon carbide (SiC) as a new candidate of target material

Overview of my talk

WHY SILICON CARBIDE ?

Comparison with graphite

What kinds of SiC will be investigated?

PROS

① Density: 1.76 times higher than graphite (3.2 g/cc vs 1.82 g/cc), Higher efficiency of transportation due to small spatial volume of pion/muon source

② High oxidation resistance ~ dependence on partial pressure of oxygen, Protection against unexpected air introduction

CONS

③ Higher residual radiation dose, Gamma emitter

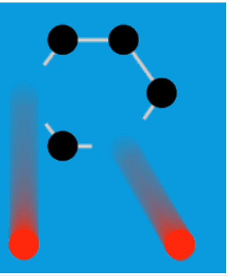
SiC has 8 times larger risk for thermal stress. (Large Young’s modulus and beam loss), Furthermore, SiC is brittle.

Monolithic silicon carbide cannot be used as target material.

SiC coated graphite

1: Not satisfied, 2: Satisfied

3: Not so bad



SiC composite material (NITE-SiC/SiC)

1: Satisfied, 2: Satisfied

3: Very bad

JSPS Kakenhi

SiC coated graphite & NITE SiC/SiC

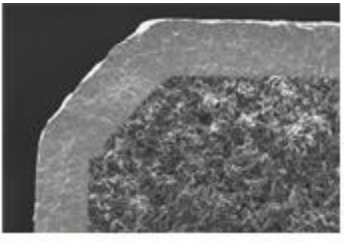
SiC coated graphite

- ☐ Commercially available at Graphite manufacturers
- ☐ CVD-SiC coating (Dense coating)
- ☐ Study for fission nuclear reactor with higher oxidation resistance

NITE SiC/SiC
Nano-powder Infiltration and Transient Eutectic

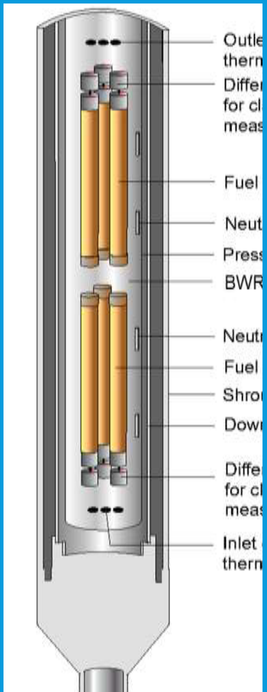
- ☐ Developed at Muroran T. I./OASIS
- ☐ Composed of SiC-fiber and matrix
- ☐ Controllable thermal & mechanical properties
- ☐ Pseudo ductility
- ☐ Resistance to irradiation

Toyo-tanso Co., LTD



Ibiden Co., LTD

1/3 model for muon target



Irradiation tests at Harden/ Norway

PROS 1

More efficient transport of Pions/Muons due to higher density

Meaning of existence for Accelerator Target

3.2 g/cc vs 1.82 g/cc

- From physics requirements, especially fundamental physics, the most important.
- If 1.3 times more efficient, 5-years experiment will be 4-years experiment.

Not from target engineering

Efficiency doesn’t depend only on the density of target material but also on the purpose of physics, the dimensions, the beam energy, the optics of the transport and so on.

Efficiency of SiC at MLF for DeeMe Project

by Aoki at Osaka Univ.

Muon-electron Conversion Search on the target material

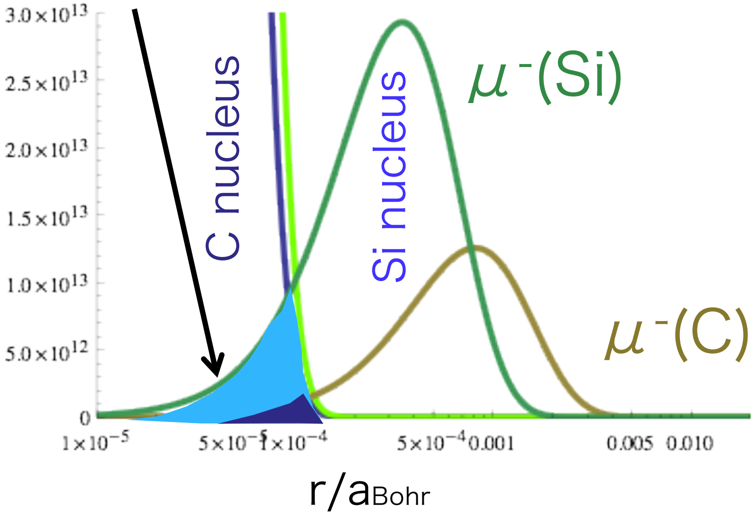
Representative; M. Aoki, Osaka University

$$\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)$$

- Forbidden in the Standard Model(SM) of particle physics.
- No signals found yet.
- Discovery of the signal
  → a proof of the physics beyond SM.
  - Complementary to high-energy frontier experiments: LHC, ILC.
  - Can explain the neutrino oscillation phenomena (Seesaw Mechanism).

Efficiency strongly depends on the atomic number of target material in this experiment.

Graphite (C) → Si: 11-times larger overlap
μ^- reaction ε: 8%(C)→67%(Si)



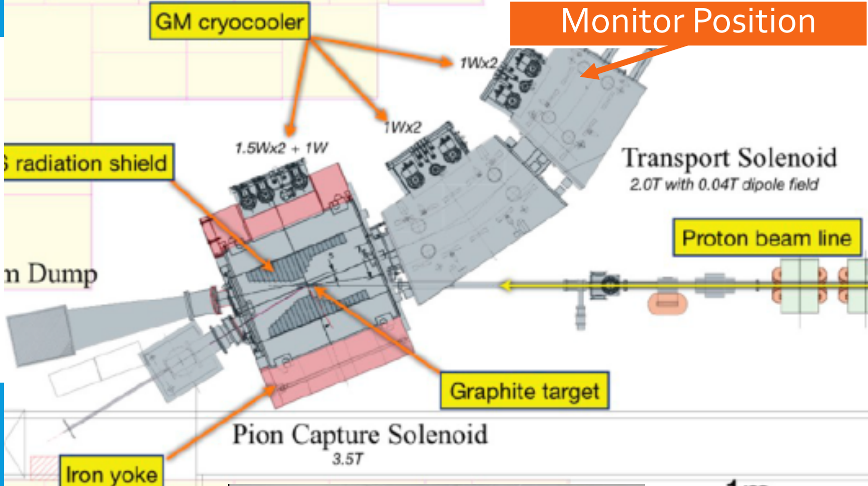
Silicon Carbide

Eff. of Muon Reaction: 6 times larger than C.

Efficiency of SiC will be 6 times larger than graphite!!

Efficiency of MuSIC

By Sato at Osaka Univ./RCNP



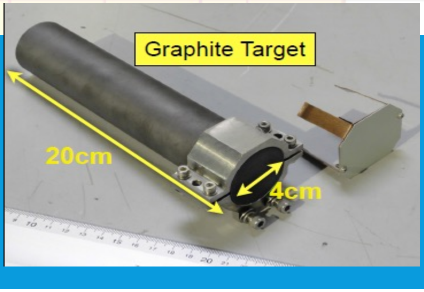
400 MeV proton beam

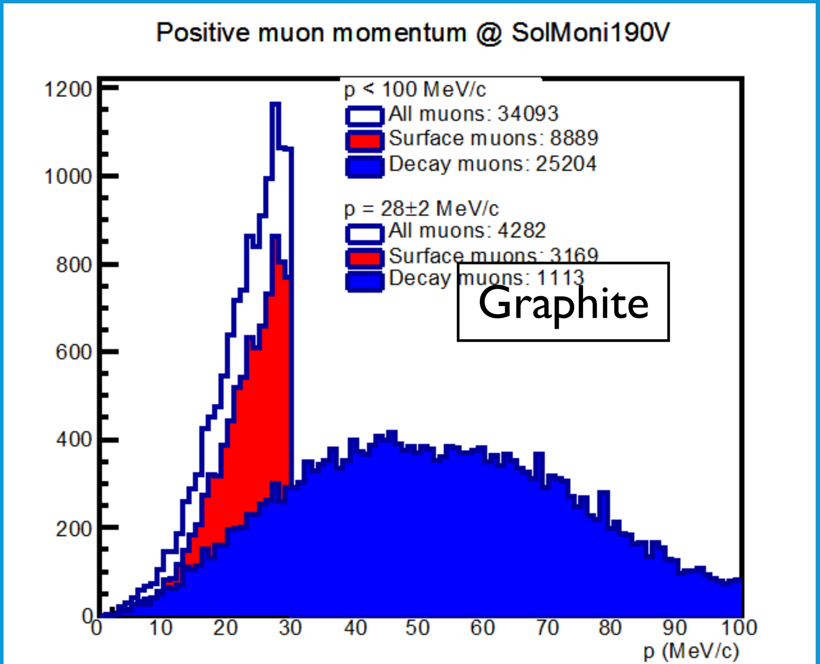
Number of muons is decreased at 10 %.

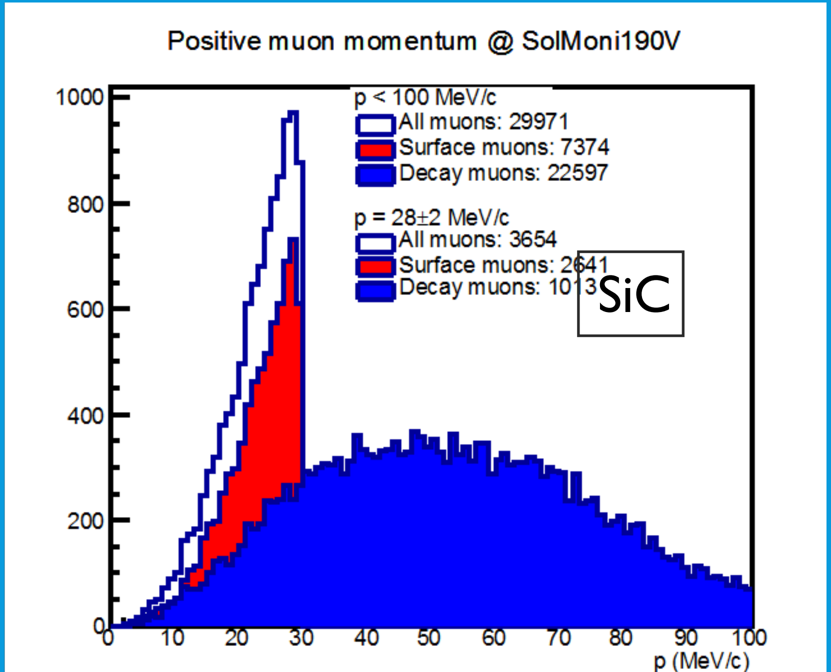
☐ In case of graphite, high energy of protons are consumed in target.

☐ How much low energy pions can come out.

☐ Beam profile must be considered for diameter.



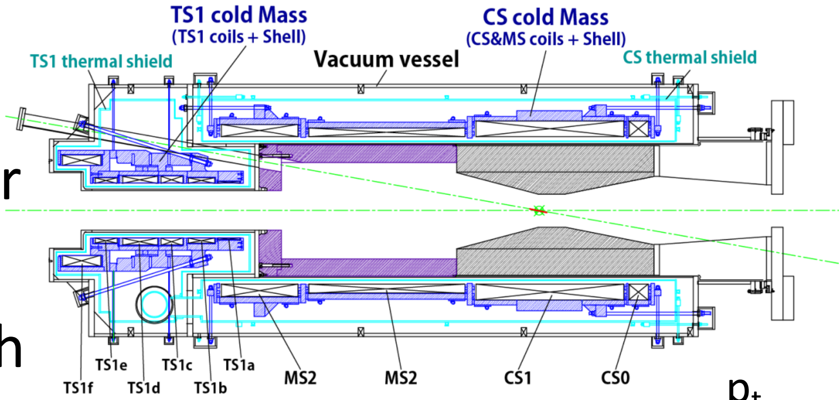


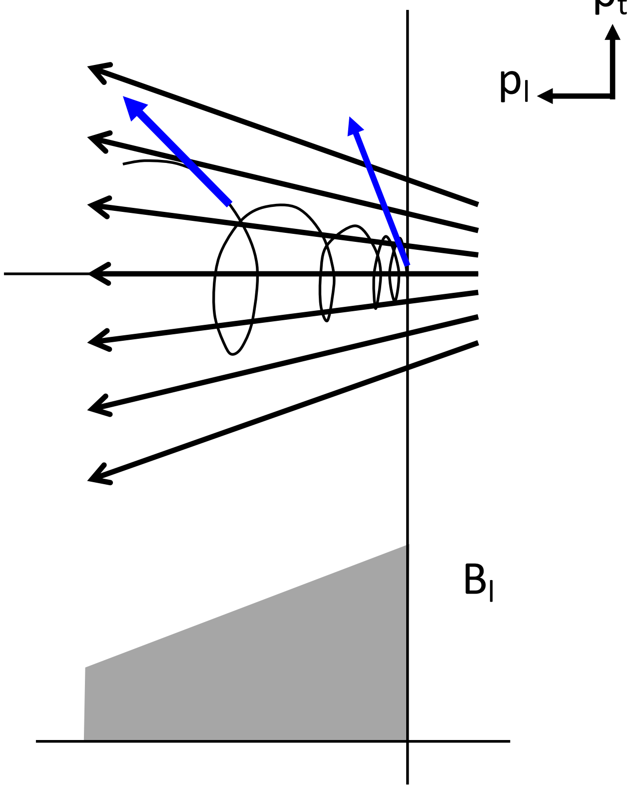


by Mihara at COMET/KEK.

COMET Pion Production Target

- Base design of the target
  - 26mm (r) x 700 mm (L), Graphite for 8GeV 3.2kW proton beam
- SiC target (with same interaction length as Graphite) is expected to provide higher muon stopping rate due to the smaller target image at production
  - 30% increase of muon yield





Efficiency is not always increased. But in general, efficiency will be higher due to higher density of SiC.

PROS 2

Oxidation resistance of Silicon carbide

- Accidental Loss of Vacuum during beam operation
- Loss of target material through O_2, impurity during normal beam operation

Resistance to unexpected air introduction

- Oxidation tests of NITE SiC/SiC are on-going by OASIS.
- Oxidation tests of SiC coated graphite are planned by Hitachi co., ltd.

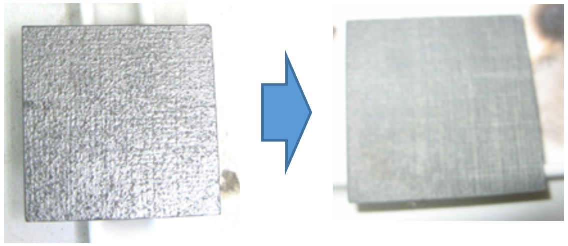
<Background>

By Dr. Park

Oxidation of Graphite and SiC

Softening of oxide film

SiC/SiC composites



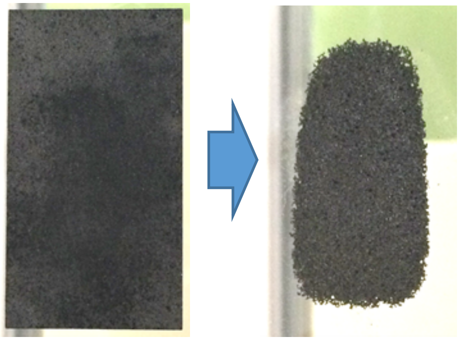
Protective(Passive) oxidation

Oxide film formed on SiC surface

$(SiC + 3/2O_2 \Rightarrow SiO_2 + CO)$

$(SiC + 2O_2 \Rightarrow SiO_2 + CO_2)$

Carbon (T-6)



1000℃

Burn off

Artificial graphite

500℃

Burn off

Amorphous graphite

0℃

<Current study: Under preparation>

By Dr. Park

Verification of oxidation resistivity of NITE-SiC/SiC composites

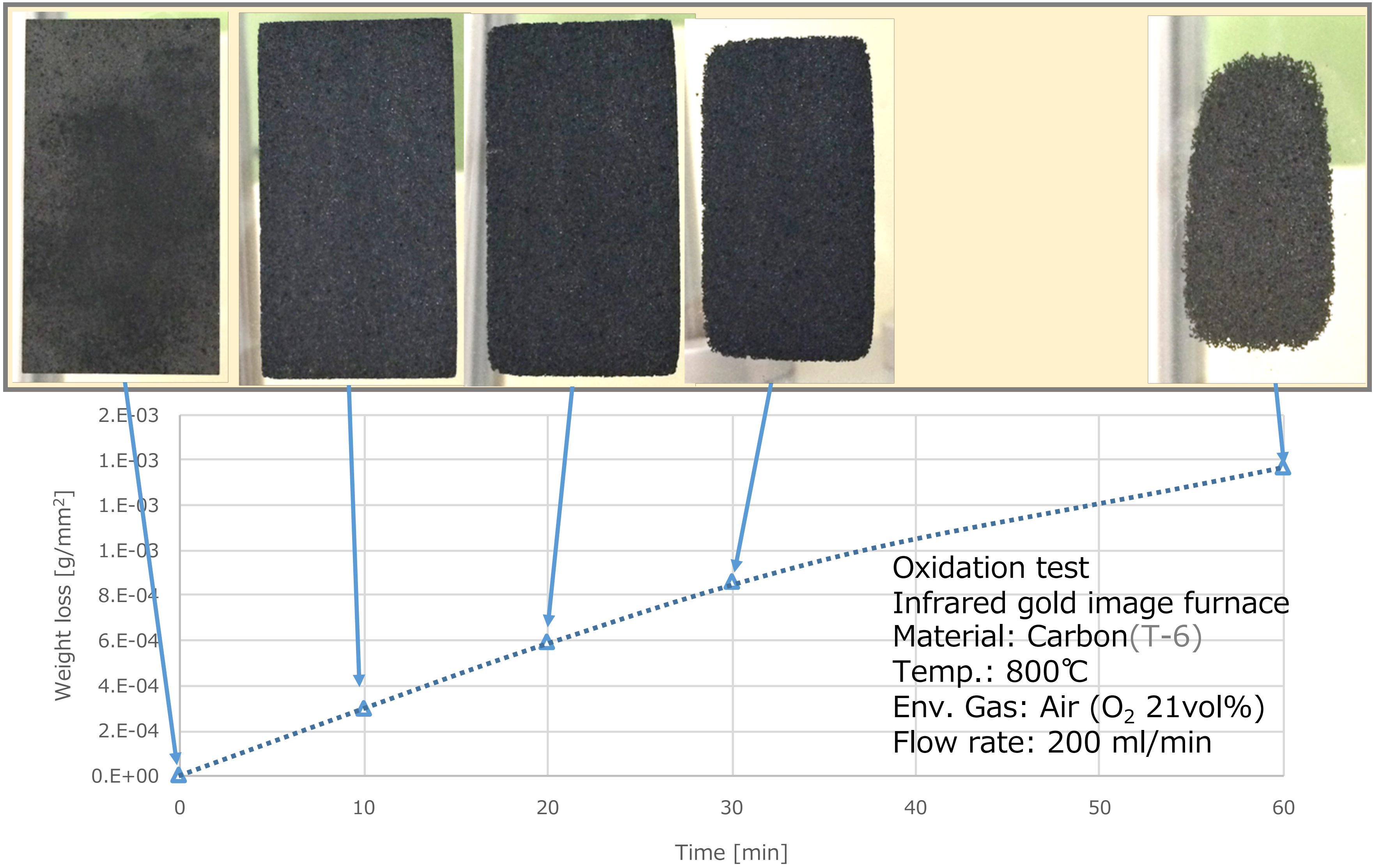
- Objectives
  - Verification of oxidation resistivity of NITE-SiC/SiC composites under LOVA (Loss of vacuum accident).
    - Effects of oxygen concentration
    - Effects of test temperature
- Materials:
  - Carbon (T-6, IG-430U) as reference material
  - NITE-SiC/SiC composites
  - CVD-SiC coated NITE-SiC/SiC composites
- Experimental condition
  - Equipment: Infrared gold image furnace
  - Temp: ~ max. 1100℃
  - Env. gas : Air(O_2 21vol%), N_2+O_2 (O_2 1vol%)
  - Gas flow rate: ~ max. 500 ml/min

<Current study: preliminary results>

By Dr. Park

OASIS
環境・エネルギーシステム材料研究機構
Organization of Advanced Sustainability
Initiative for Energy System/Materials
室蘭工業大学
Muroran Institute of Technology

Oxidation test results (Graphite)



Oxidation test
Infrared gold image furnace
Material: Carbon(T-6)
Temp.: 800℃
Env. Gas: Air (O_2 21vol%)
Flow rate: 200 ml/min

<Current study: Under preparation>

By Dr. Park

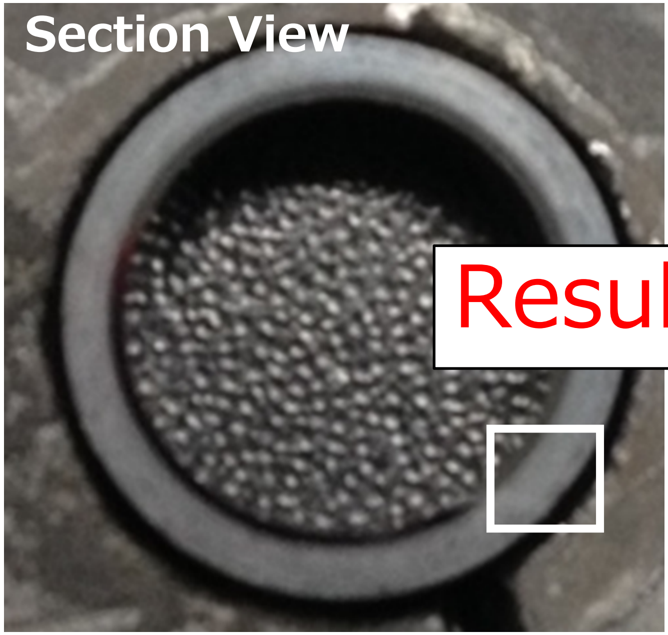
OASIS
環境・エネルギーシステム材料研究機構
Organization of Advanced Sustainability Initiative for Energy System/Materials
室蘭工業大学
Muroran Institute of Technology

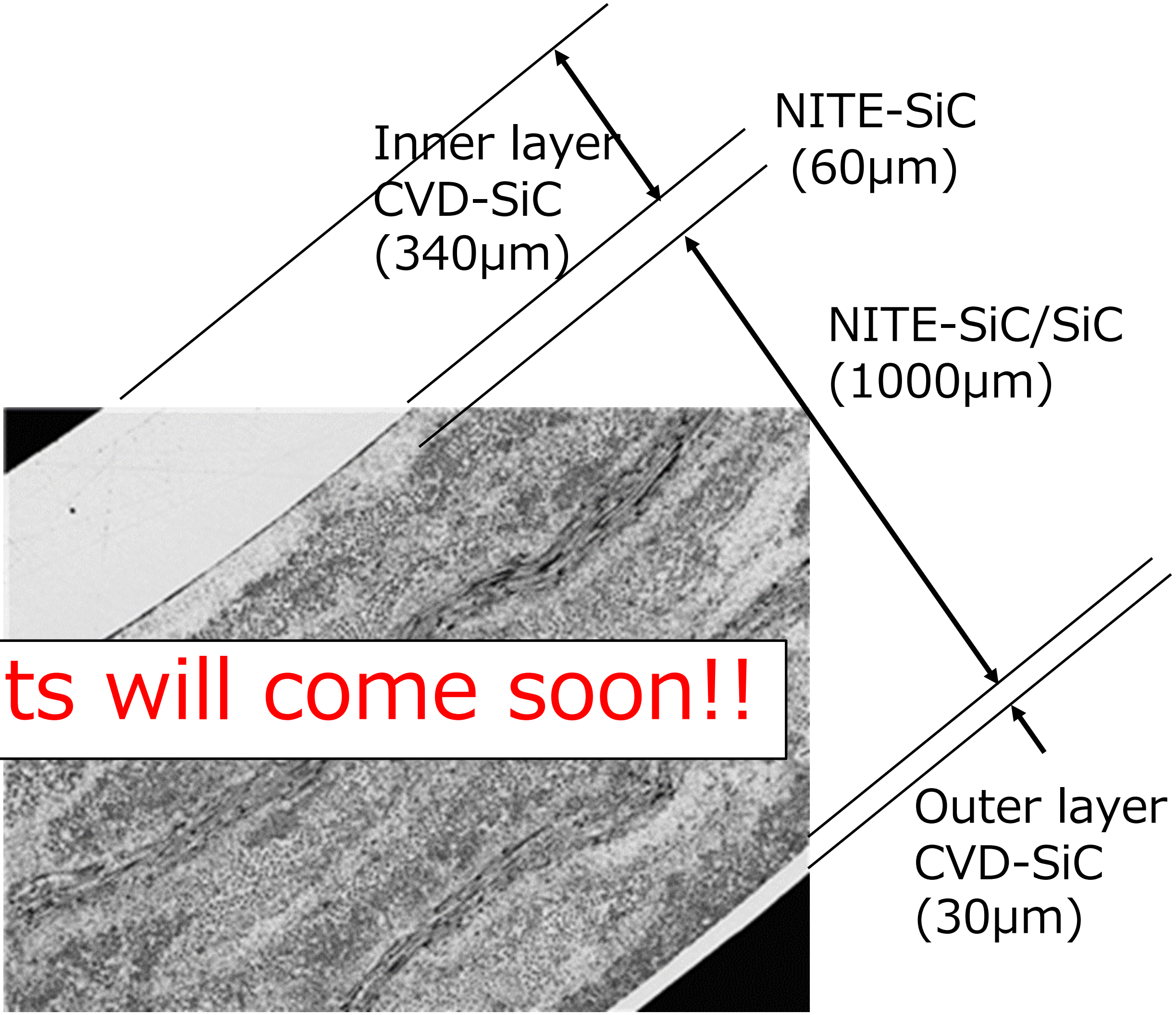
Environmental Barrier Coating (CVD-SiC coated NITE-SiC/SiC tube)

For further improvement of oxidation resistivity of SiC/SiC composites

Side View

Section View





Results will come soon!!

Preliminary PHITS simulations by Matoba

CONS 3
Residual radionuclides of SiC & SiC/SiC

☐ Irradiation tests at RCNP (Low flux)
400 MeV, 1 uA, 1 hour
t= 1 mm, D= 10 mm, plate
☐ Irradiation at MLF beam operation (High flux)
3 GeV, 333 uA, 5000 hours
t = 20 mm, D = 70 mm, plate

Produced radionuclides on simulation for RCNP

Low flux proton beam

PHITS by Matoba

Dose rate @5 cm mSv/h	SiC	SiC comp. material SiC+Al 3%+Y 3%	Graphite
Fresh	3.65	3.80	1.35
After 1 day	0.0417	0.104	0.00104
After 3 days	0.00625	0.0318	0.000938
After 7 days	0.00208	0.0104	0.000833

- Half life

H3 : 12.3 years
Be7 : 53 days
C11: 20 minutes
Na22: 2.6 years
Na24: 15 hours
Ge71: 11 days
Sr83: 1.3 days
Sr87m: 2.8 hours

Radionuclides Bq	SiC		SiC comp. material SiC+Al3%+Y3%		Graphite	
Fresh	Total	4.11E+07	Total	4.11E+07	Total	1.98E+07
	Si27	1.20E+07	Si27	1.25E+07	C11	1.77E+07
	C11	9.90E+06	C11	8.33E+06	C10	1.09E+06
	Al26m	5.73E+06	Al26m	5.73E+06	Be7	2.71E+05
After 1 day	Total	4.01E+05	Total	9.90E+05	Total	2.76E+05
	Na24	1.98E+05	Be7	1.88E+05	Be7	2.66E+05
						+03
Aft						+05
						+05
						+03
Aft						+05
						+05
						+03
	H3	7.29E+03	Sr87m	1.61E+04		

Residual radiation dose of SiC is higher than graphite and is very slowly decayed due to the effect of Na22.
This will be confirmed with low flux proton beam at RCNP.

PHITS by Matoba

- MLF Target:

Irradiation at MLF beam operation
3 GeV, 333 uA, 5000 hours
t = 20 mm, D = 70 mm, plate

	SiC	SiC+Al3%Y3%	Graphite
Loss (W)	5773	5739	3096
Loss rate (W/cc)	75	75	40
DPA	43	48	5.1

Surface dose (5cm)			
	SiC	SiC+AlY	Graphite
Fresh	2.5 kSv/h	2.6 kSv/h	763 Sv/h

Residual radiation dose of SiC is much higher than graphite and is slowly decayed due to the effect of Na22.
Effects of additives for composite material is not so large.
These amounts will be validated at irradiation tests of RCNP.

dominant for actual maintenance.

Plans for irradiation tests of the SiC coated graphite: Under RaDIATE collaboration & BLIP

RaDIATE

Radiation Damage In Accelerator Target Environments

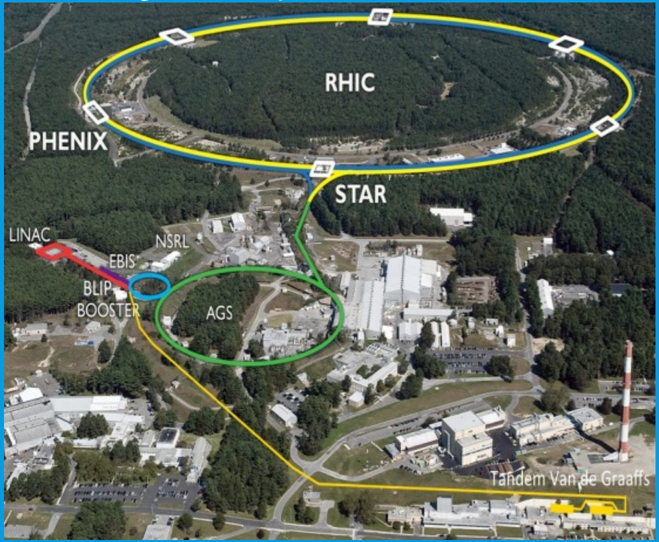
radiate.fnal.gov

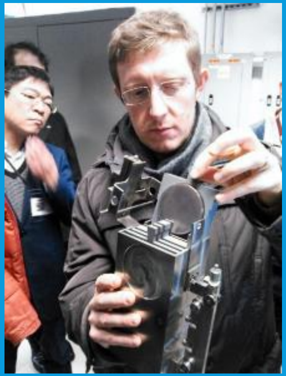
Introduction by P. Hurh in this session

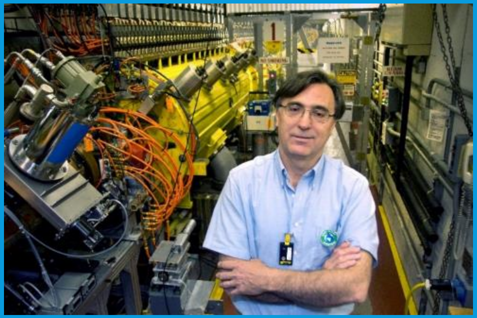
Fermilab
University of Oxford
Science & Technology Facilities Council
Brookhaven National Laboratory
Pacific Northwest National Laboratory
Los Alamos National Laboratory EST. 1943
FRIB
European Spallation Source
Oak Ridge National Laboratory
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
Argonne National Laboratory
CERN

MoU planning (2016~)

- Purpose: Investigation of irradiation effects
- Irradiation at BLIP facility at BNL from next January.







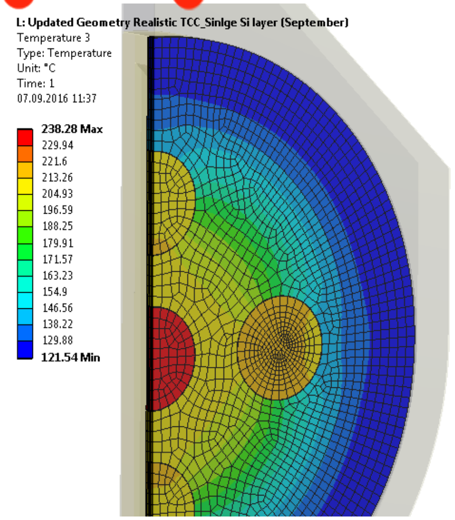
- SiC coated graphite will be included at CERN capsule.
- Confirmation through Microstructural analyses at PNNL whether exfoliation will happen.
- Comparison of three kinds of graphite

Precious opportunity for high-energy proton irradiation

By Claudio. L.T. Martin at CERN

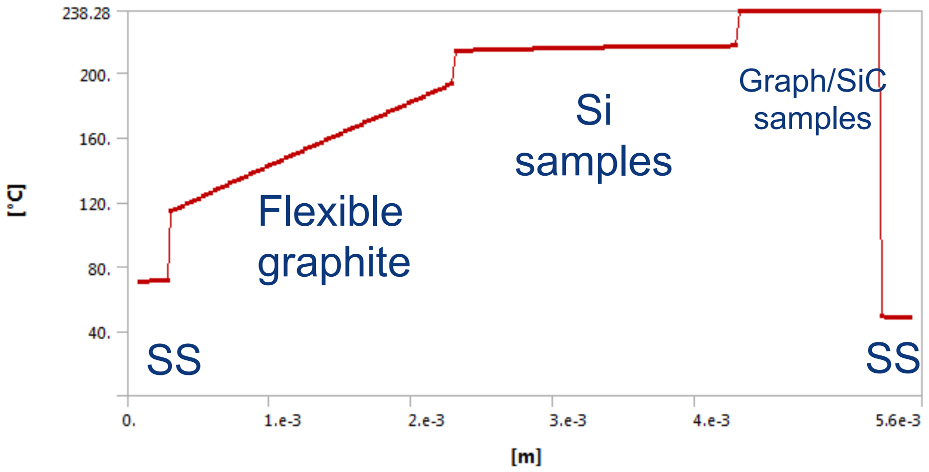
Thermal Analysis – Si Capsule

Temperatures



Max T Si samples:
216 ºC
Max T Graph/SiC:
220-240 ºC
Max T Sigraflex:
193 ºC
Max T SS window:
71 ºC
Max HF SS window-Water:
28 W/cm2

T profile at the center of the capsule



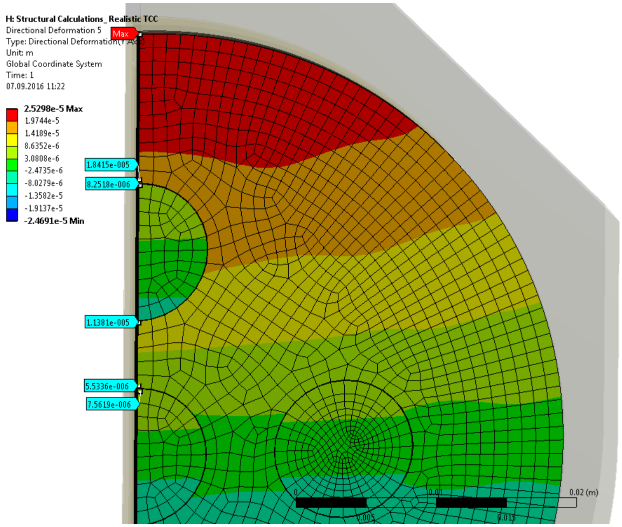
Thermal Expansions:

Initial lateral gaps Samples-Fillers = 0.1 mm
Initial lateral gap Fillers-SS capsule = 0.2 mm

Remaining gap Graph/SiC –Filler: **94 um**

Remaining gap Si samples – Si Filler: **80 um**

Remaining Fillers– SS Capsule: **200 um** (remains the same)

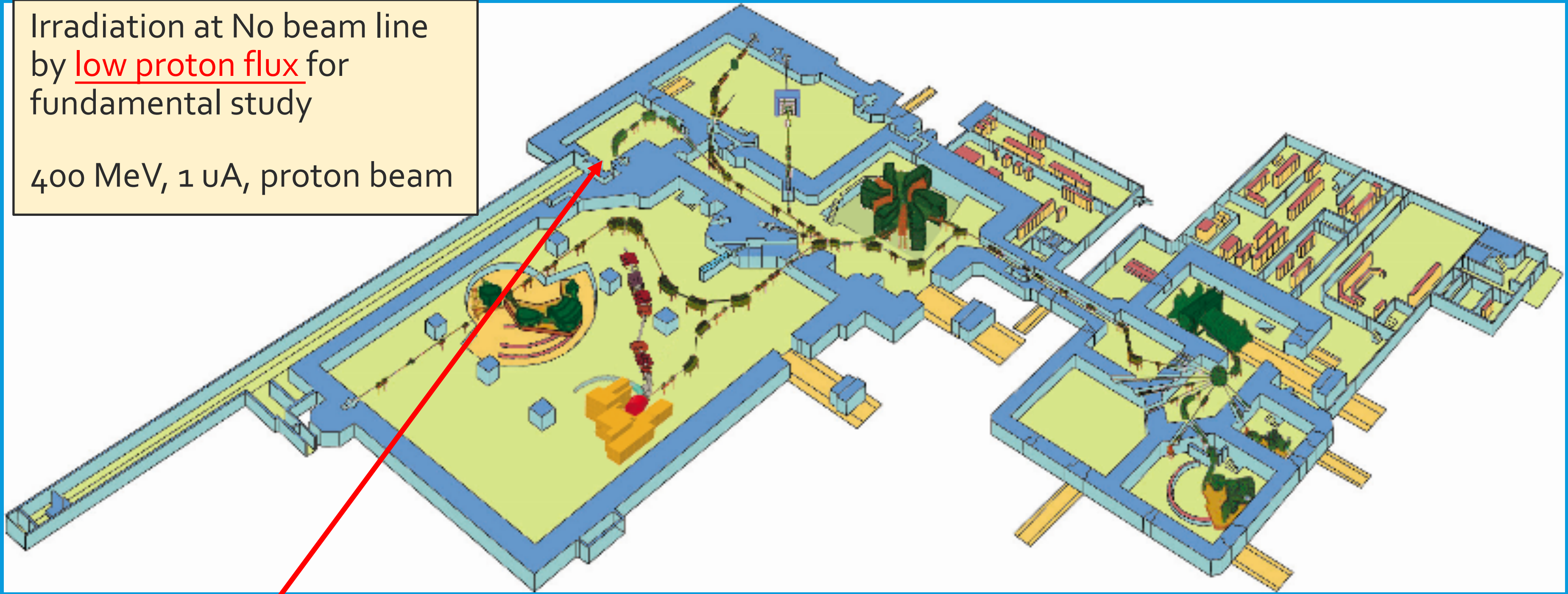


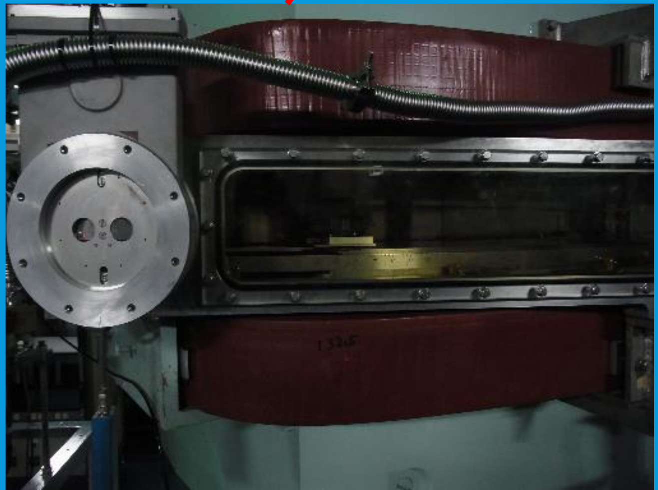
*Assumed TCC in Back-up slides

Plans for irradiation tests of the SiC/SiC composite: at RCNP, Osaka Univ.

Irradiation at No beam line by low proton flux for fundamental study

400 MeV, 1 uA, proton beam



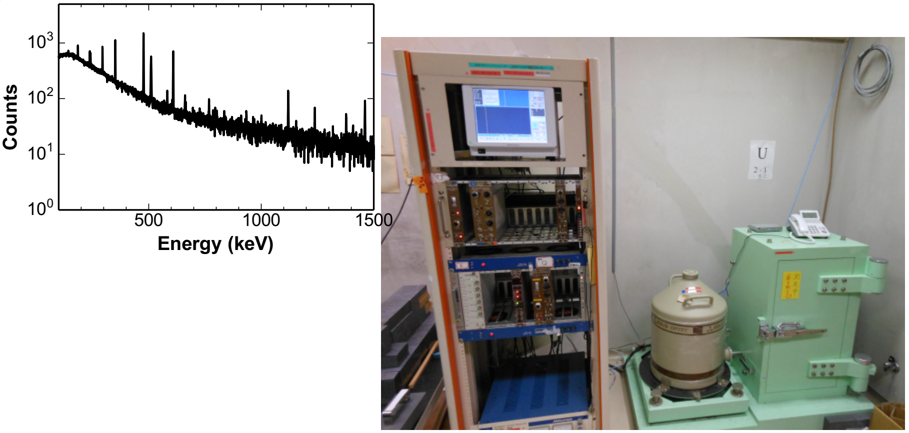


- ☐ Specimens can be handled by hands-on.
- ☐ Chemical analyses is available at RI building of RCNP.
- ☐ Transport from N0 beamline to the RI building, going through only a radiation controlled area
- ☐ Validation of the simulation for residual radionuclides
- ☐ Support by T. Shima and T. Suzuki

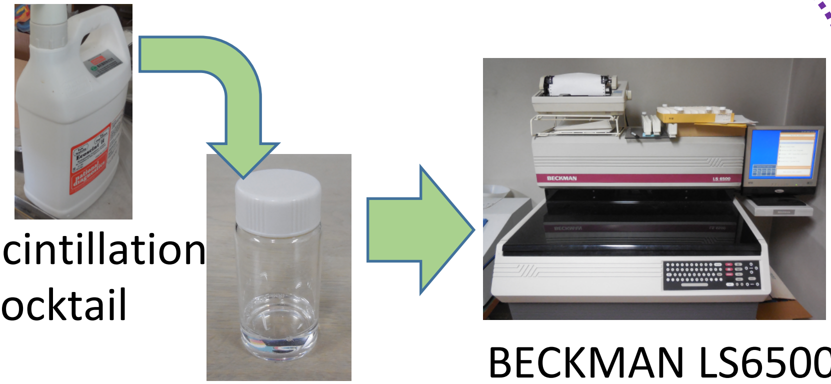
Irradiation tests of Graphite, SiC, and SiC/SiC was approved by PAC with “Grade A”.

Residual radionuclides on graphite sample

By K. Ninomita at Osaka univ.



Gamma-ray counting by HP-Ge detector (^{7}Be: 478 keV)

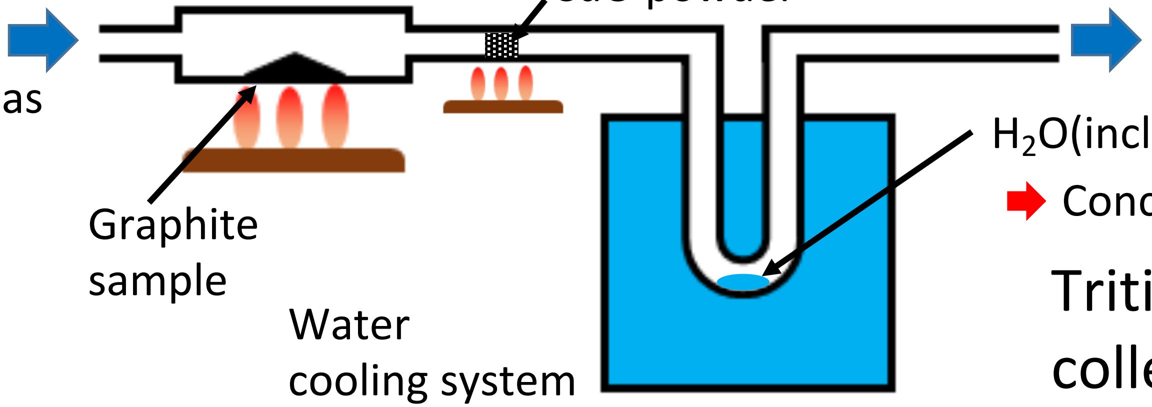


Scintillation cocktail

HTO sample

BECKMAN LS6500

Tritium measurement by liquid scintillation counter



Glass tube

CuO powder

O_2 gas

Vac.

Graphite sample

Water cooling system

H_2O(including HTO)

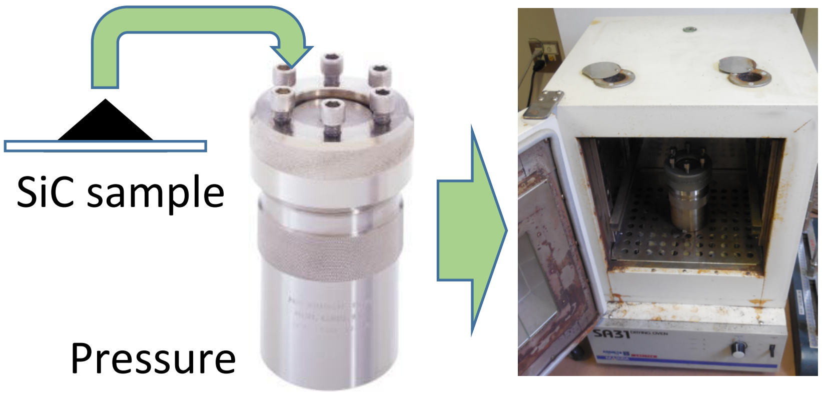
➡ Concentration HTO if necessary

Tritium separation and collection as HTO form

Residual radionuclides on SiC sample

By K. Ninomita at Osaka univ.

After the measurements of gamma-ray emitter

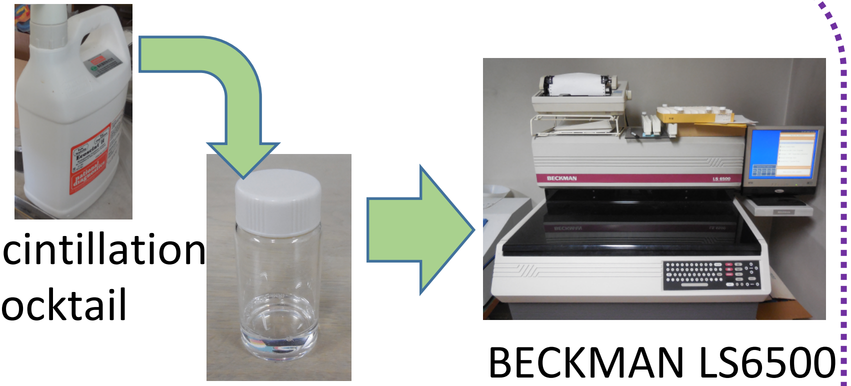


SiC sample

Pressure tight vessel

Oven(~573 K)

Dissolve sample in high-pressure and high-temperature condition

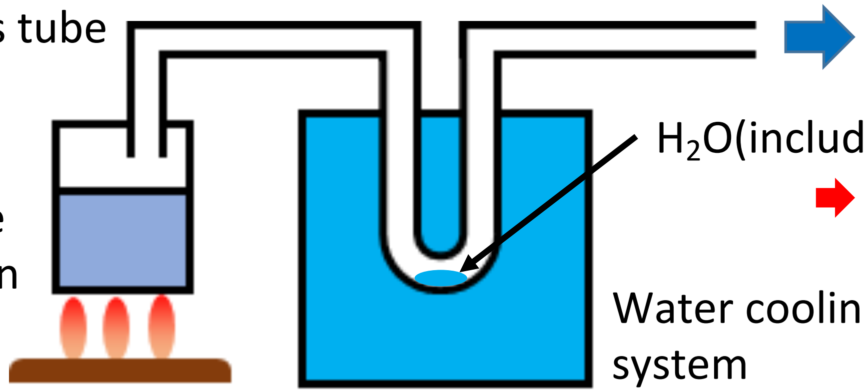


Scintillation cocktail

HTO sample

BECKMAN LS6500

Tritium measurement by liquid scintillation counter



Glass tube

Vac.

H_2O(including HTO)

➡ Concentration HTO if necessary

Sample solution

Water cooling system

Tritium separation and collection as HTO form

Summary and Acknowledgement

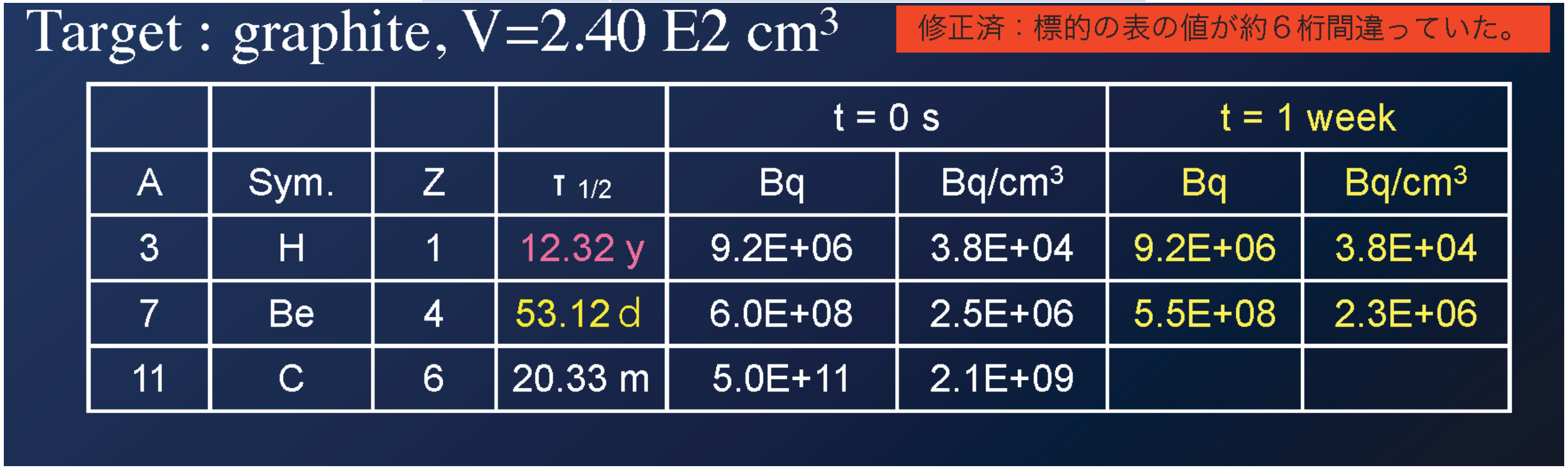
- ☐ Possibility of SiC as Low-Z target material is investigated.
- ☐ SiC coated graphite and SiC/SiC composite are candidates.
- ☐ Higher efficiency of beam transport can be mostly expected at NITE SiC/SiC.
- ☐ Higher oxidation resistance can be expected for both cases.
- ☐ Residual radiation dose will be higher at NITE SiC/SiC.
- ☐ Oxidation tests are on-going.
- ☐ Irradiation tests at BLIP and RCNP are on-going.

Thanks to RaDIATE, Osaka Univ. /RCNP, Muroran Institute Technology /OASIS collaborations

生成放射性核種(Fulka計算との確認用・7時間照射)

- 半減期
  H3 ： 12.3年
  Be7 ： 53日
  C11： 20分
  Na22： 2.6年
  Na24： 15時間

生成放射性核種 /Bq	
照射後	黒鉛
直後	全体: 3.5E11
	C11: 3.2E11
	C10: 1.5E10
	Be7: 5.1E8
	H3: 1.1E7
1週	全体: 4.7E8
	Be7: 4.6E8
	H3: 1.1E7



Target : graphite, V=2.40 E2 cm^3

修正済：標的の表の値が約６桁間違っていた。

				t = 0 s		t = 1 week	
A	Sym.	Z	$\tau_{1/2}$	Bq	Bq/cm^3	Bq	Bq/cm^3
3	H	1	12.32 y	9.2E+06	3.8E+04	9.2E+06	3.8E+04
7	Be	4	53.12 d	6.0E+08	2.5E+06	5.5E+08	2.3E+06
11	C	6	20.33 m	5.0E+11	2.1E+09		

Residual radionuclides for COMET

				Half Life	gamma_energy (MeV)	Bq	Sv/h*mˆ2
SiC/SiC	fresh					6.59E+11	1.23E+05
		C 11	1.02E+11	20m			
		Si 27	8.98E+10	4.2s			
		Al 26m	7.80E+10	6.3s			
		F 18	6.09E+10	1.8h			
		Be 7	5.95E+10	53d	0.478		
	1w					6.84E+10	2.11E+03
		Be 7	5.66E+10	53d	0.478		
		H 3	7.11E+09	12.3y	0.02		
		Na 22	4.67E+09	2.6y	1.27, 0.543(e+)		
		Y 88	1.63E+09	107d	1.86		
		Sr 85	1.40E+09	65d	0.878, 0.514		
		Rb 83	1.08E+09	86d	0.525		
	1y					1.15E+10	1.38E+03
		H 3	6.75E+09	12.3y	0.02		
		Na 22	3.52E+09	2.6y	1.27, 0.543(e+)		
		Be 7	5.16E+08	53d	0.478		
		Y 88	1.99E+08	107d	1.86		
		Rb 83	6.07E+07	86d	0.525		

Residual radionuclides

PHITS by Matoba

Residual radionuckides /Bq

Fresh	C	SiC	SiC+AlY
H3	4.82E+11	6.34E+11	6.37E+11
Be7	3.71E+12	3.33E+12	3.17E+12
C11	1.02E+13	6.57E+12	6.27E+12
Si27		7.39E+12	6.98E+12
Al26m		3.33E+12	3.35E+12
1 week	C	SiC	SiC+AlY
H3	4.82E+11	6.33E+11	6.37E+11
Be7	3.39E+12	3.04E+12	2.89E+12
Na22		3.85E+11	3.72E+11
1 month	C	SiC	SiC+AlY
H3	4.80E+11	6.31E+11	6.34E+11
Be7	2.51E+12	2.25E+12	2.15E+12
Na			
1 y			
H3			
Be			
Na			

- Half life
  H3 ： 12.3 years
  Be7 ： 53 days
  C11： 20 minutes
  Na22： 2.6 years

Residual radiation dose of SiC is much higher than graphite and is slowly decayed due to the effect of Na22.
Effects of additives for composite material is not so large.
These amounts will be validated at irradiation tests of RCNP.

Back-up slides: TCC correlations (1)

- For Metal Interface:

Mikic Correlation*

$$h_m(p) = 1.55\frac{k \cdot m_r}{A_r}\left(\frac{\sqrt{2} \cdot p}{E \cdot m_r}\right)^{0.94}$$

- For Graphite-Metals Interface:

E. Marotta Correlation**

$$h_g(p) = 1.49\frac{k \cdot m_r}{A_r}\left(\frac{2.3 \cdot p}{E_g \cdot m_r}\right)^{0.935}$$

Input Parameters of the materials :
Roughness (RA)
Poisson Ratio
Young Modulus
Thermal Conductivity

“The assumptions included nominally flat contacting surfaces, uniform pressure distribution at the interface, elastic deformation and a vacuum environment...”

*HANDBOOK OF HEAT TRANSFER (Warren M. Rohsenow,James R Hartnett,Young I. Cho), chapter 3, page 3.58.

** E. Marotta and L. S. Fletcher. "Thermal contact conductance of selected polymeric materials", Journal of Thermophysics and Heat Transfer, Vol. 10, No. 2 (1996), pp. 334-342

- Convective Coefficient of cooling water assumed to be: 6000 W/m2K

Back-up slides: TCC Assumed- Low Density Capsule

	Reference Analysis (Realistic Pressures)		
Contacts			
Name	**Pressure assumed (MPa)**	**Ra assumed (um)**	**TCC [W/m2K]**
SS_Graphite Sigraflex	0.2	5	5000
Sigraflex_Si	0.2	10	10000
Si_Makimura Graphite	0.2	5	2000
SS_Makimura Graphite	0.2	50	400
Filler_SS radial Gap	(No contact, just radiation)		20
Sigraflex Thermal Conductivity	5/150 W/mK		

Reference Analysis

	Conservative Analysis (Very low pressure Contacts)	
Contacts		
Name	**Pressure assumed (MPa)**	**TCC [W/m2K]**
SS_Graphite Sigraflex	0.06	3400
Sigraflex_Si	0.01	4500
Si_Si samples	0.04	150
Si_Makimura Graphite	0.01	400
SS_Makimura Graphite	0.06	400
Filler_SS radial Gap	-	20
Sigraflex Thermal Conductivity	5/150 W/mK	
Results		
	Max Temp [C]	**Max Stress [MPa]**
SS Capsule	**64**	180
Sigraflex	**174**	67
Si_1 Samples	**200**	50 in Samples / 35 in
Si_2 Samples	**478**	50
Makimura Graphite	**420**	4 in samples / 9 in fill

Degradation of Sigraflex_Contact loss due to degradation		
Contacts		
Name	**Pressure assumed (MPa)**	**TCC [W/m2K]**
SS_Graphite Sigraflex	0.2	30
Sigraflex_Si	0.2	30
Si_Si samples	0.4	250
Si_Makimura Graphite	0.01	400
SS_Makimura Graphite	0.06	400
Filler_SS radial Gap	-	20
Sigraflex Thermal Conductivit	5/150 W/mK	
Results		
	Max Temp [C]	
SS Capsule	77	
Sigraflex	1250	
Si_1 Samples	1150	
Si_2 Samples	765	
Makimura Graphite	692	
Interfaces	**Expansion [um]**	
Si samples - Si filler	-	
Si filler_SS capsule	-	
Makimura Graphite Samples/F	-	

"Silicon Carbide"

L.L. Snead et al. Journal of Nuclear Materials 371 (2007) 329-377

◆*Major structural material for fusion applications*

◆*Crystal structure*

More than 200 polytypes are currently reported. The fundamental structure unit in SiC is a covalently bonded primary co-ordination tetrahedron (SiC_4 or CSi_4).
The most common polytypes are 3C, 4H, 6H, and 15R. The 3C-SiC are know as β-SiC, and the others are classified as α-SiC.
The β-SiC is believed to be more stable, although some studies dispute this findings.

◆*Fabrication of Silicon Carbide*

Various fabrication techniques; CVD, Reaction bonding, Sintering, Polymer pyrolysis

- CVD– highly crystalline, pure, high density. But Difficulty for fabrication of Large components, and expensive
- Reaction bonding– Mixture of SiC and carbon particles with metallic silicon in the form of vapor or liquid. Severe degradation of bulk performance by Residual silicone.
- Pressureless sintering process– SiC particles with boron and carbon. Flexibility in complex components shape. But degradation of mechanical properties
- Hot-pressing liquid-phase sintering– Robust and dense. But just simple shape and degradation of mechanical properties
- Polymer pyrolysis– Continuous SiC fibers and porus SiC

First candidate of SiC rotating target;
Pressureless sintering process, KYOCERA SC-1000

“Material Properties of Silicon Carbide”

(In parentheses, Graphite)

- Density; 3.2 g/cc (1.82 g/cc)
- Heat generation by proton beam; 8kW (4kW), 2 times larger than Graphite
- Thermal Conductivity; 200W/m/K @ R.T.
  (130W/m/K @R.T., 50W/m/K @1000℃)
  In our case, radiation damage must be considered; 20W/m/K
- Upper temperature limit;
  2000℃ (1700 ℃) on the viewpoint of vacuum
  1000 ℃ on the v.p. of heavy radiation damage, dislocation loop
- Bending Strength; 450MPa (45MPa), 10 times larger than Graphite.
  (By radiation damage; 350MPa @4dpa 500 degC
  280MPa @25dpa 800 degC for typical sin. material [1])
- Young’s Modulus; 440GPa (11GPa), 40 times larger than Graphite.
- Emissivity；0.8-0.9 (0.94; calibrated by T.C.)

Thermal stress depends on Young’s modulus x Heat

[1] G.W. Hollenberg et al. Journal of Nuclear Materials 219 (1995) 70-86

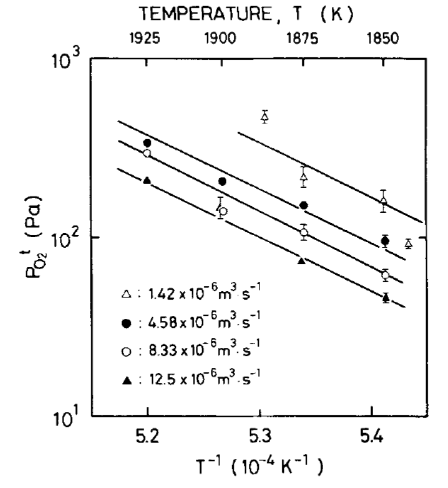
“10 times Strength” vs “80 times Thermal stress”

For thermal stress, 8 times larger risk than Graphite.

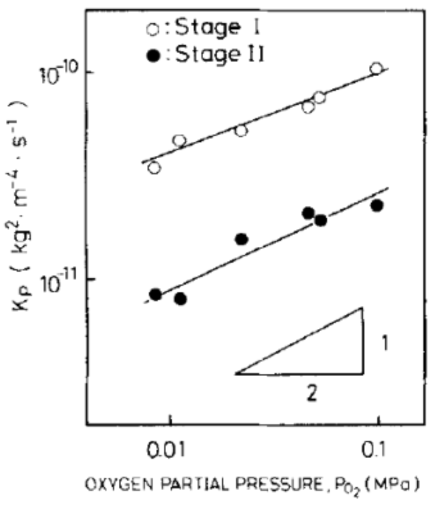
Oxidation resistance of silicon carbide

Active oxidation (low O_2 pressure) VS Passive oxidation (high O_2 pressure)

J. Am. Ceram. Soc., 74 [10] 2583-86 (1991), J. Am. Ceram. Soc., 72 [8] 1386-90 (1989)



Temperature dependence of the transient oxygen partial pressure from active to passive oxidation



Passive oxidation

1500 degC, 1 atm, 5000 h

Thickness gain: 15 mm

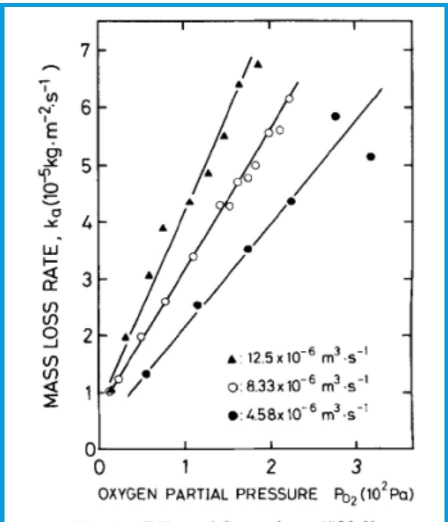


Fig. 6. Effect of P_{O_2} on k_a at 1923 K.

Active oxidation

870 degC, 1Pa, 5000 h,

Thickness reduction: 1.8 mm

870degC, 10^{-3} Pa, 5000 h,

Thickness reduction: 1.8 mm

Resistance to unexpected air introduction

- Oxidation tests of NITE SiC/SiC are on-going by OASIS.
- Oxidation tests of SiC coated graphite are planned by Hitachi co., ltd.