For IAEA ADS-CRP, 2017/09/25

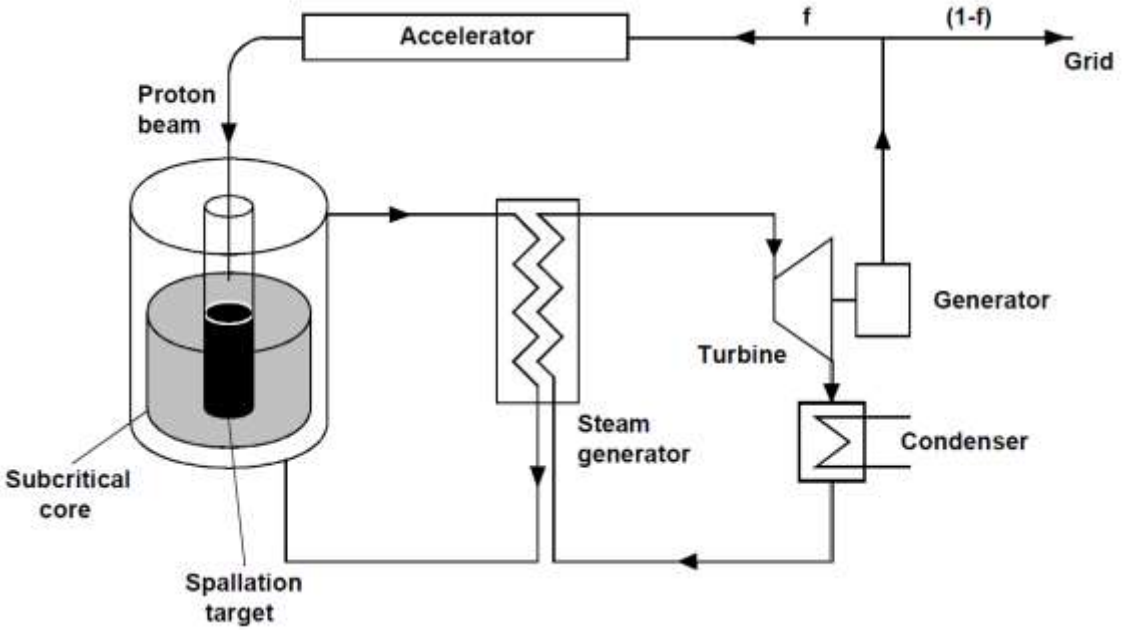
Development of Chinese ADS/ADANES

Lei Yang

Institute of Modern Physics
Chinese Academy of Sciences

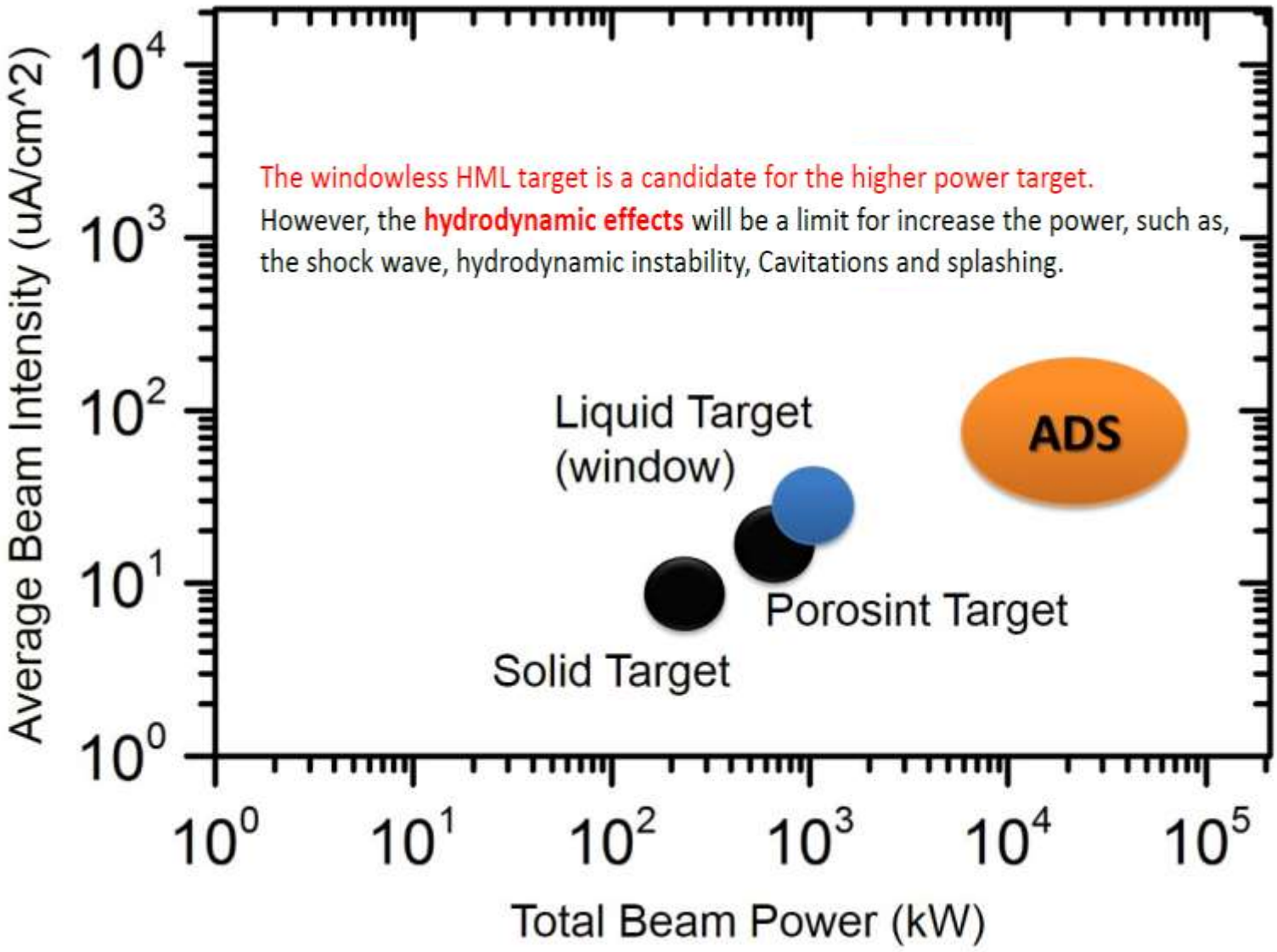
ADS & Motivation

- **Accelerator Driven System was proposed for:**
  - **Nuclear Waste Transmutation （ATW）**
  - **Accelerator Driven Thorium Reactor (ADTR)**
  - **Isotopes Production … (ex. ISOL RIA)**
- **ADS** consists of **High Power Proton Accelerator**, **Spallation Target/Blanket**, **Material & Fuel** mainly.

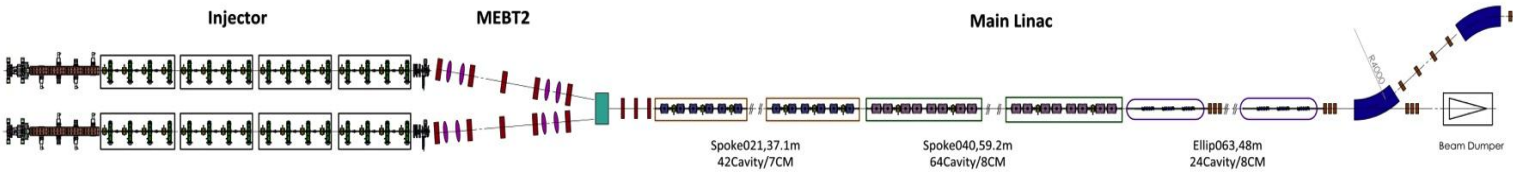


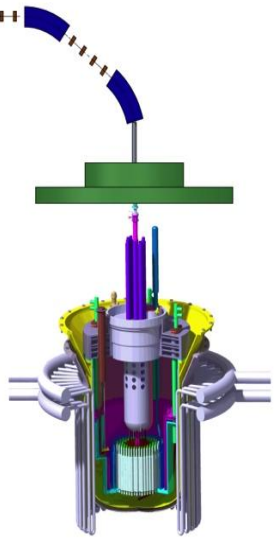
- ✓ ***ADS and FR in Advanced Nuclear Fuel Cycles — A Comparative Study***, NEA/OECD, 2002
- ✓ White paper of ADS in FermiLab. 2010

Higher flux neutron source



CIADS Project (Phase 2)

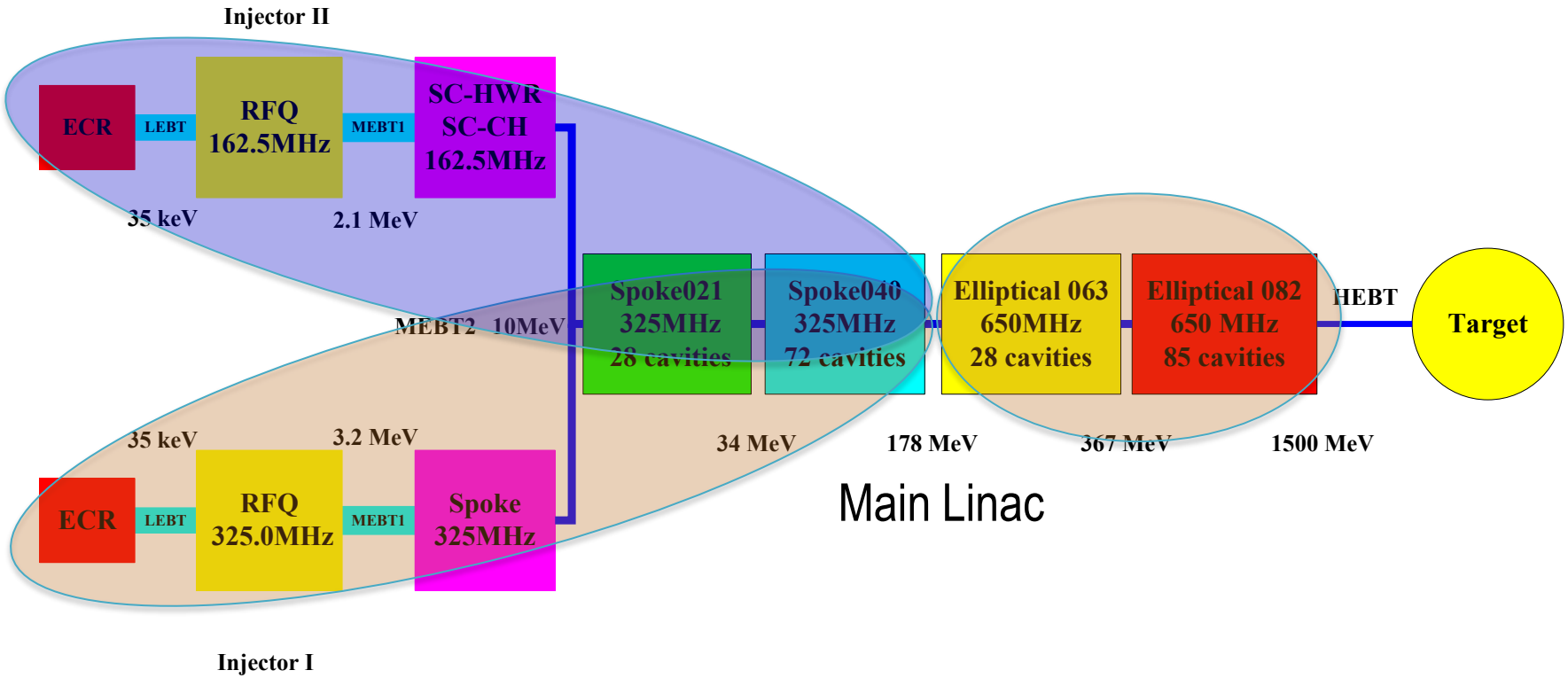




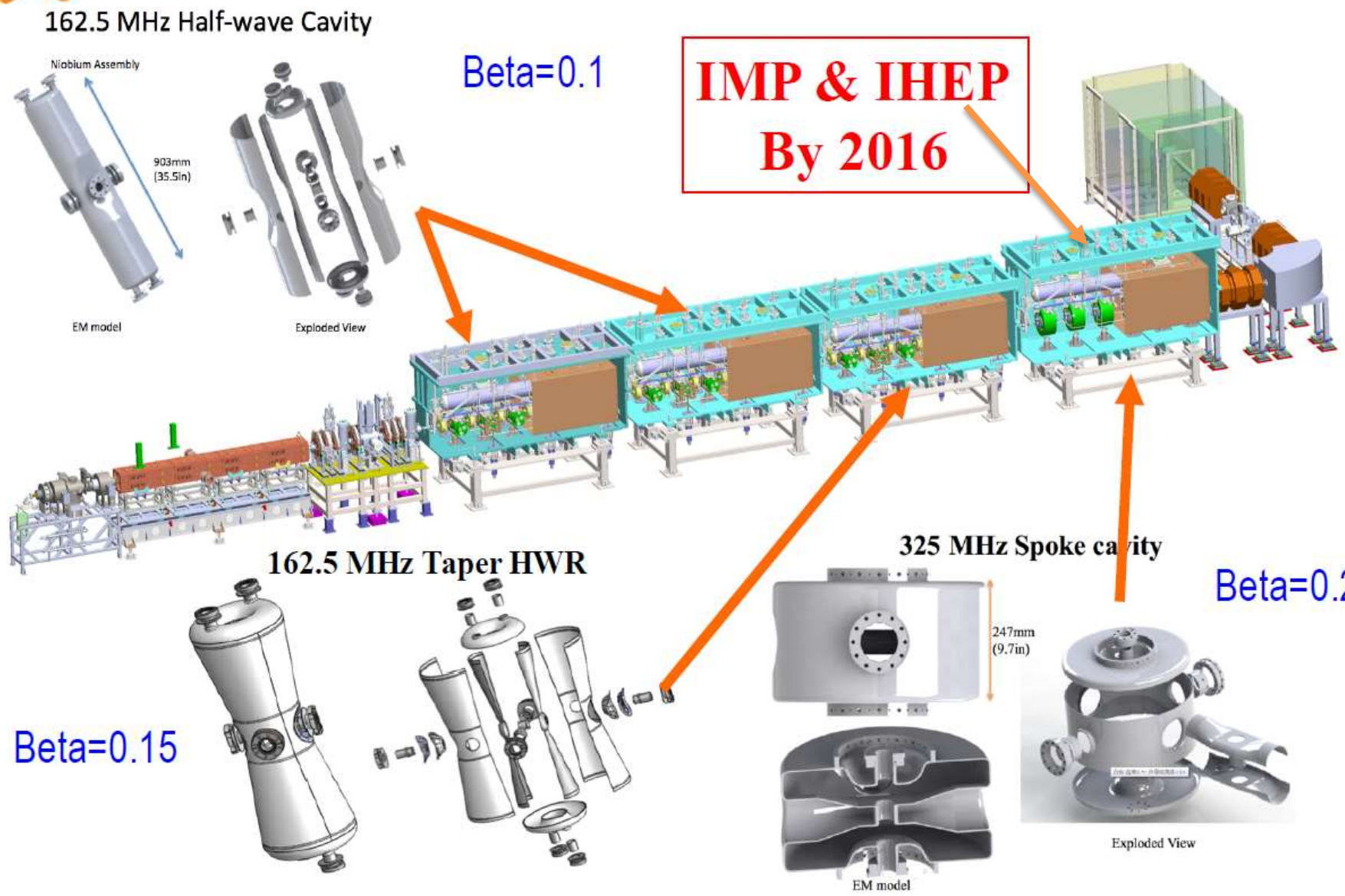
- **CIADS Main Parameters:**
  - **High CW Power (>2.5MW, >500MeV) SC-LINAC**
  - **High Power (>2.5MW) Spallation Target**
  - **Sub-Core (<10MWth)**
  - **Coupling all Components → Full System (~10MW)**
- **CIADS Time Schedule :**
  - **2017—2023**

SC Linac

Configuration of ADS Linac

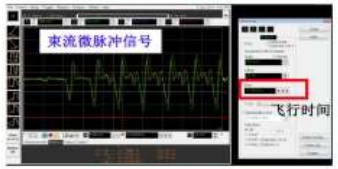


25 MeV LINAC Commissioning in 2016

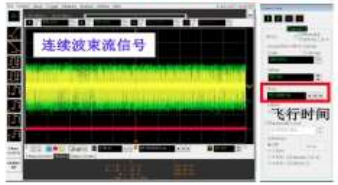


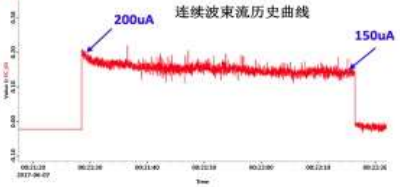
25 MeV SC LINAC

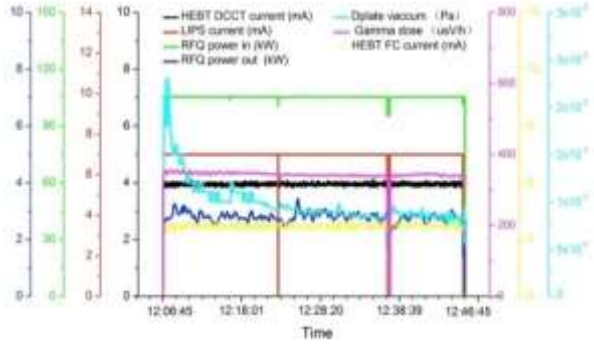
脉冲束流：26.1MeV，12.6mA



连续束流：25.0MeV，150~200uA，5kW功率



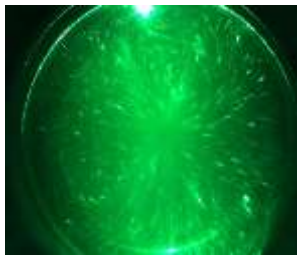
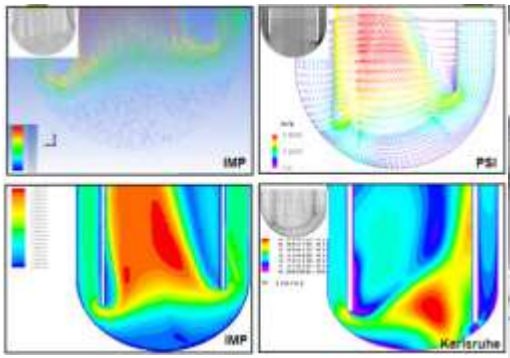


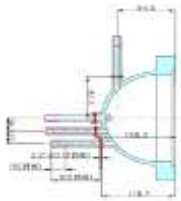


High Power Granular Target

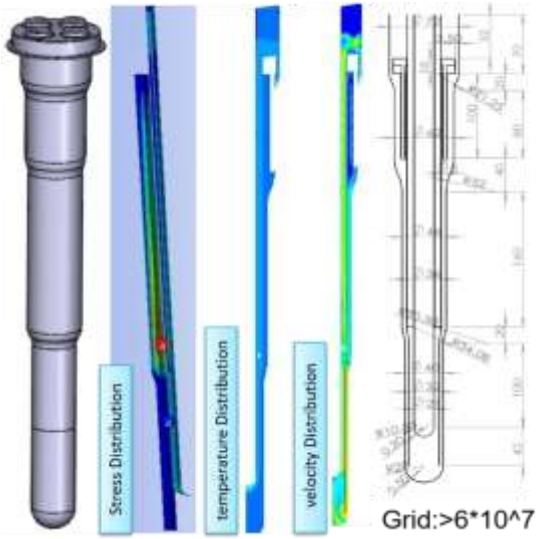
LM Window target research

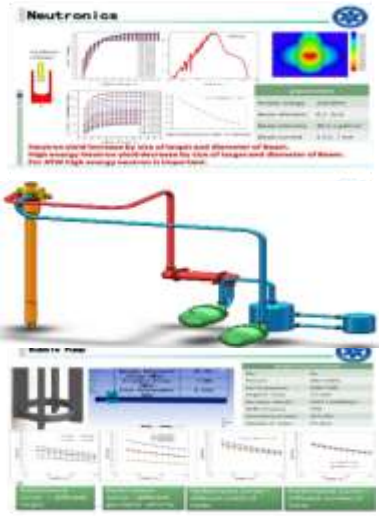


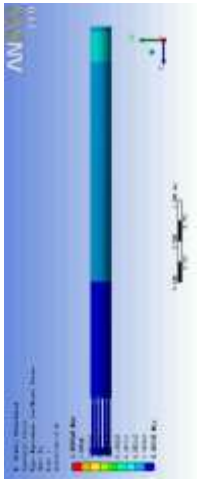


- Average Beam intensity in theory：~30 μA/cm^2. For an ADS, If the diameter of the beam pipe can choose ~30-40 cm, then, the target would be design for severals MW.
- The heat removal of the window will be limited by the heat conduction of the target material and convection-cooling.
- Recently, the materials challenges of windows LMT are shown by PIE, the DPA/Year -> 8.

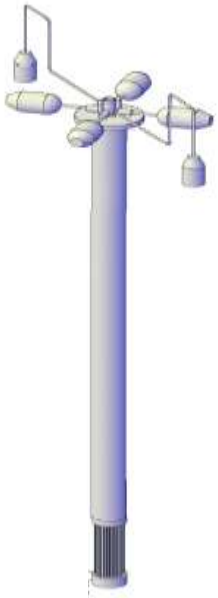


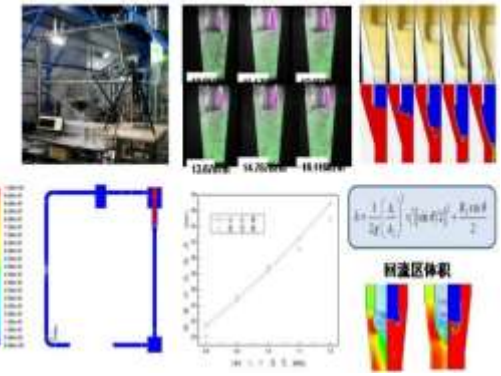


LM Windowless target research

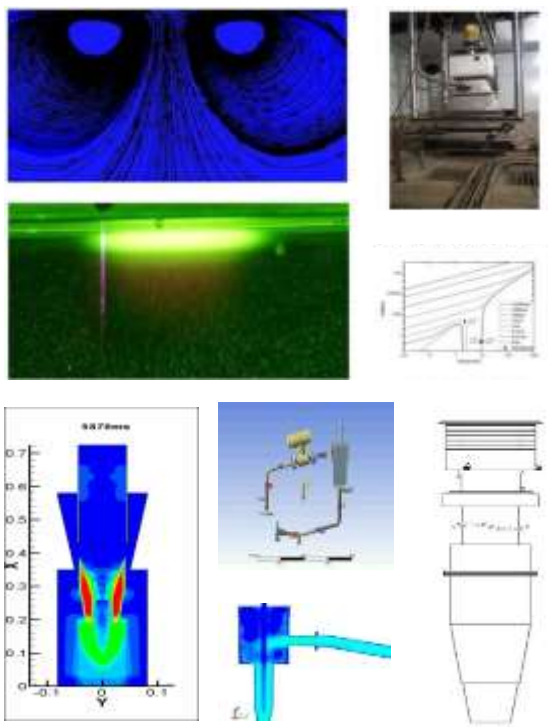


Stress Distribution

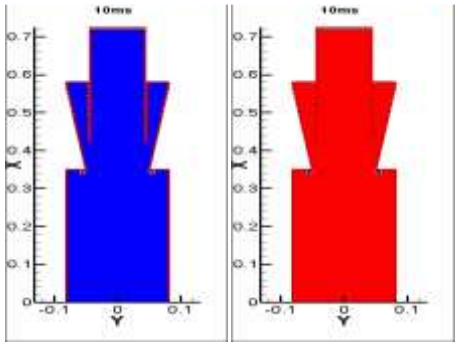




loop test for windowless HML target

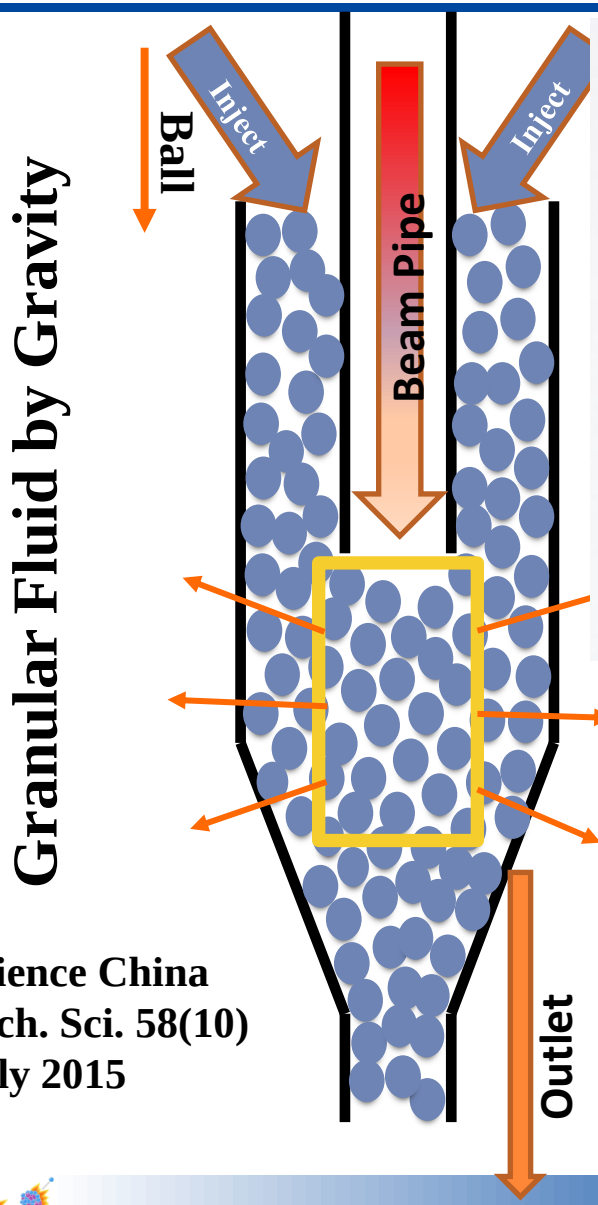


DNS Parallel CFD (GPU) for Beam-Target-Coupled



- The hydrodynamic instability of system will be increase by the flux of the inlet.
- The region of the **e**ddy could be design, so the annular beam can be used to avoid eddy, the control of stability is not an easy task.

Principle of Granular Fluid Spallation Target

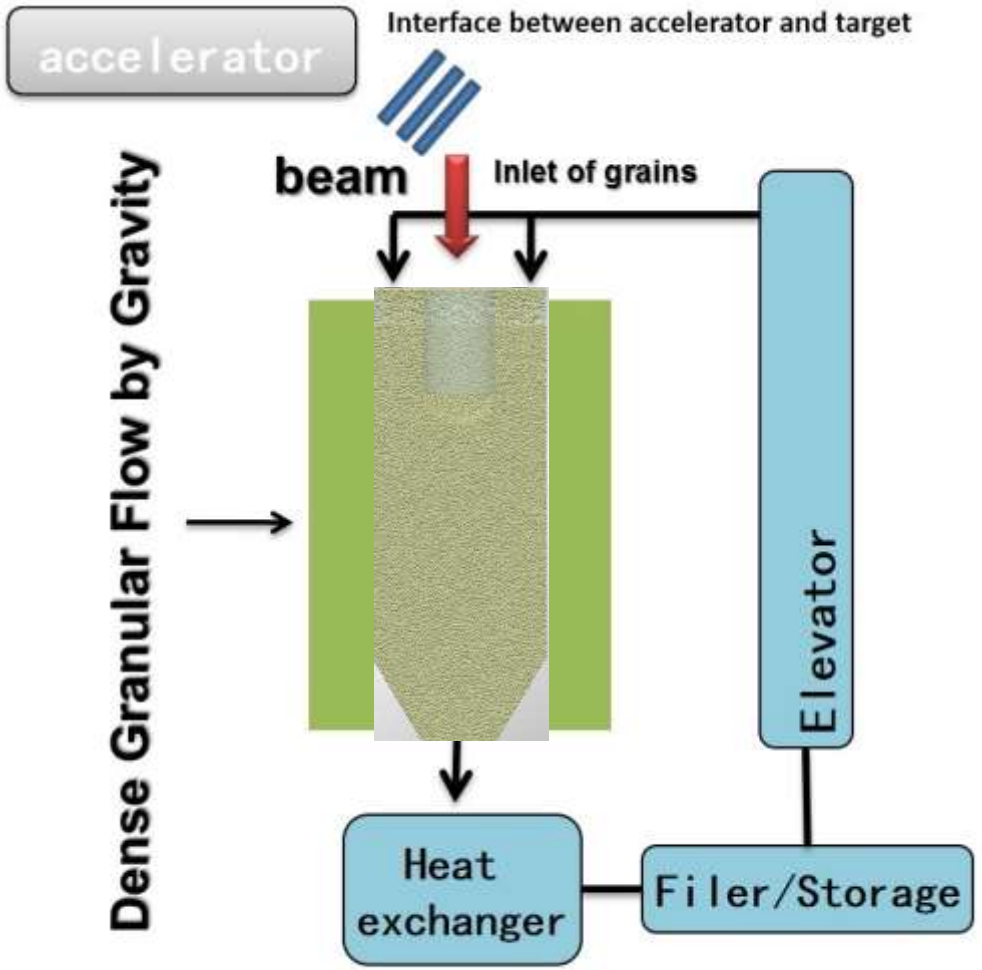


Science China
Tech. Sci. 58(10)
July 2015

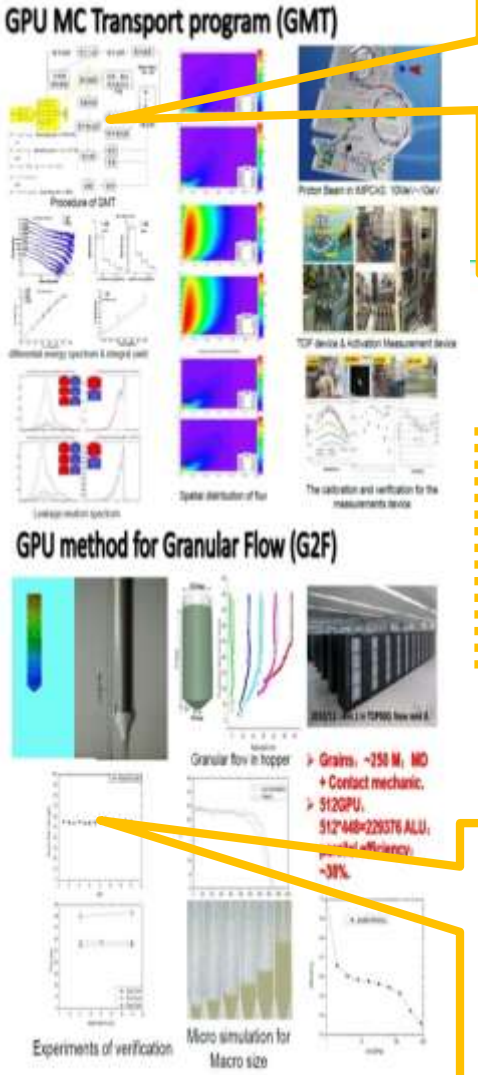
Spallation neutron

- Granular fluid operate stable as sand clock
- Target heat removing off line
- Grain update on line
- Higher target power capacity: 10~100 MW
- Dissipation the shock wave induced by beam trip
- Relieve short beam trip (<10s) requirement as discrete medium in target
- Target material selectable
- Dust handling require
- High cost effective

Concept of Granular target of windowless

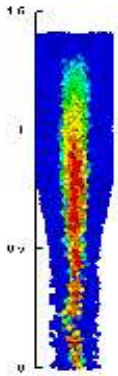


Yang L, Zhan W. *Sci China Tech Sci* October (2015) Vol.58 No.10 P1705



Stochastic many-spheres geometry for random packing grains

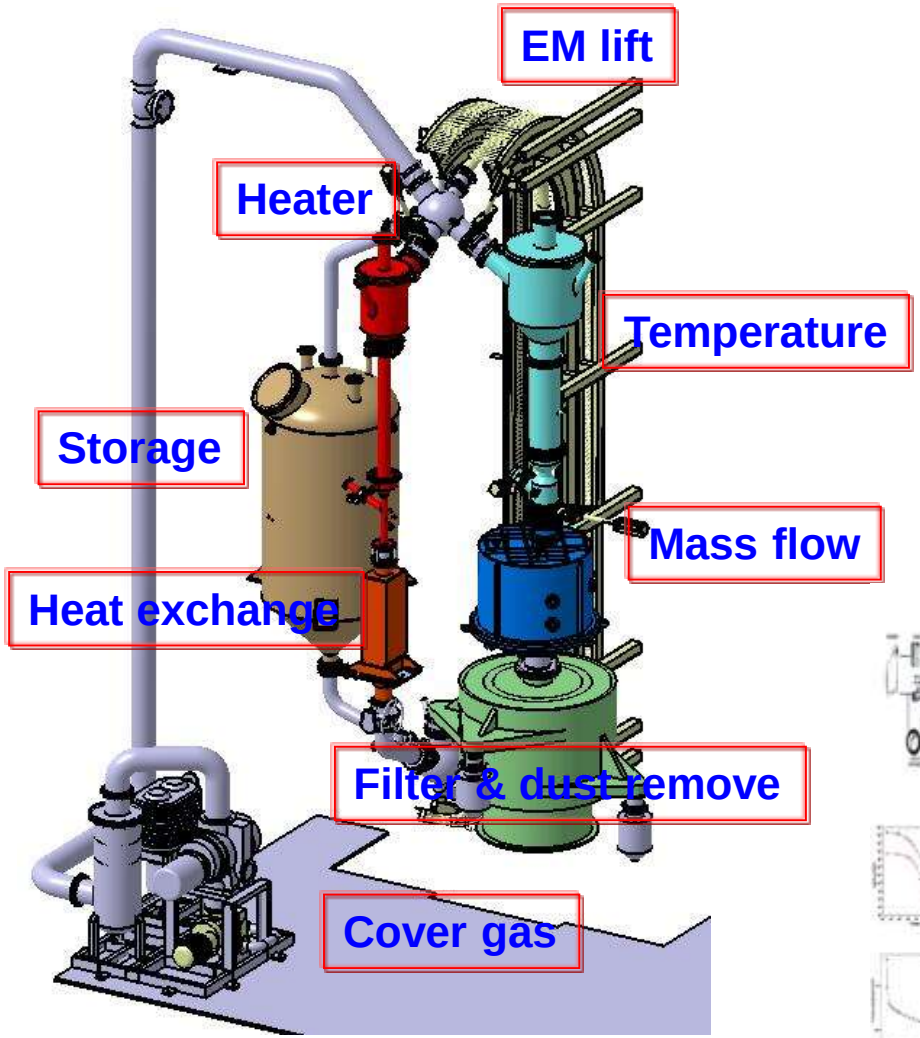
Beam coupled granular target

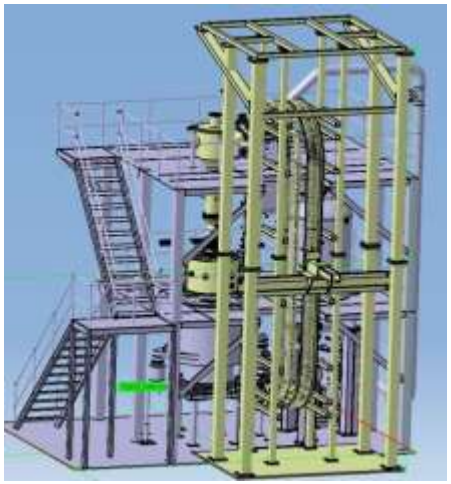


Dense granular flow, Heat transfer & Intermedia fluids

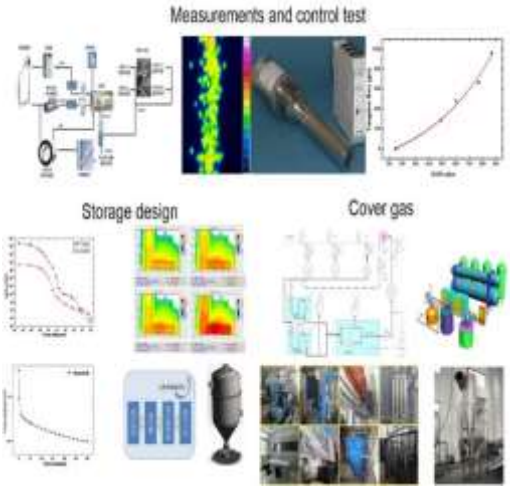
Motivation: Fusion of solid & liquid target advantages & Avoiding the weak points.

Prototype of granular target





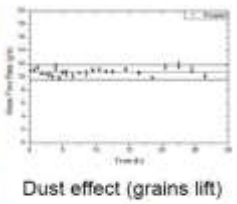
Construction design



Development of key sub-systems

Mechanical granular lift: Pipe/Plate-chain

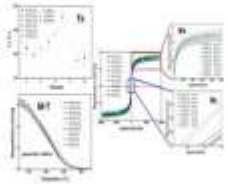
Large scale test loop



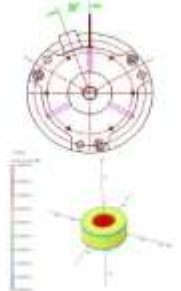
Dust effect (grains lift)

NOTE: Maximum capacity 300m³/h,Maximum length 80m,Maximum height 50m,product temperatures up to 750. More than 500 sets tube chain conveyors is being used in the global.

EM lift test: new concept



Curie point measurements



Small scale prototype

Heat exchanger and prototype

Countercurrent water corrugated plate heat exchanger to be cooled W alloy particles since the force of gravity under the direction of flow, and the corrugated plate upward flow of the cooling water absorbs the heat carrying particles derived.

Filter test & developing: high temperature

Max flux：≥40 kg/s

Temperature：0-300℃

Geometry size：2×1.6 m

before after

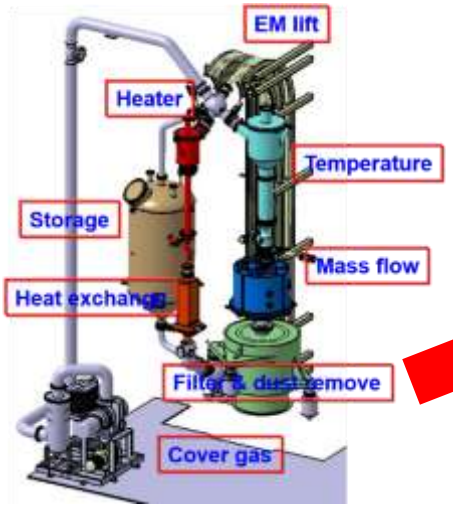
Prototype of granular target

（Pipe Chain Lift）

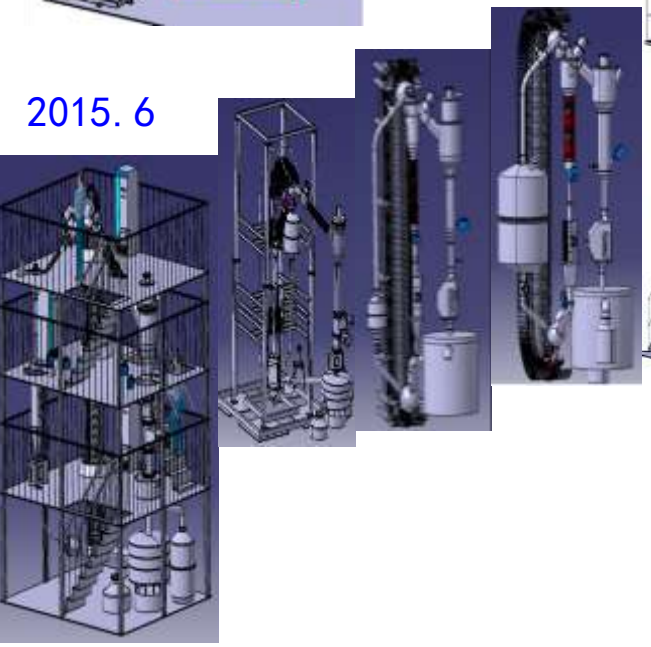
（Magnetic Travelling Wave Lift）

10Tons, 1mm W Alloys Grains

Prototype of granular target



2015. 6



2015. 11

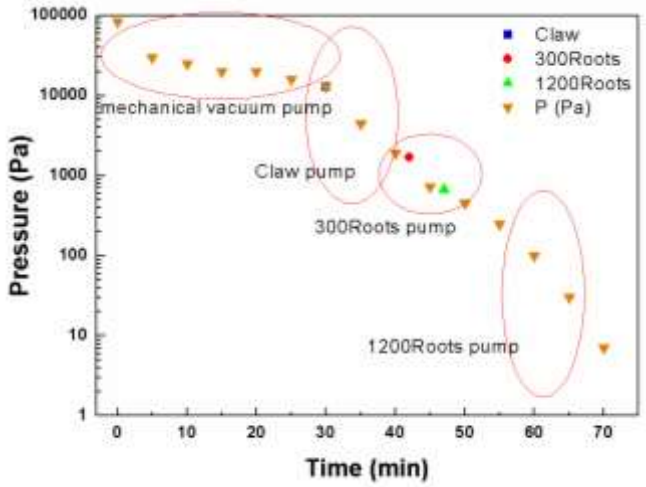
2016. 3

2016. 6

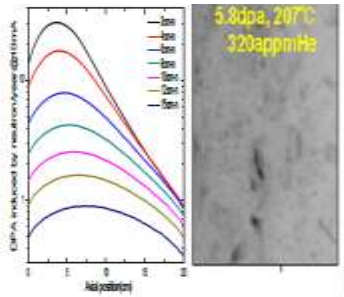
2016. 9

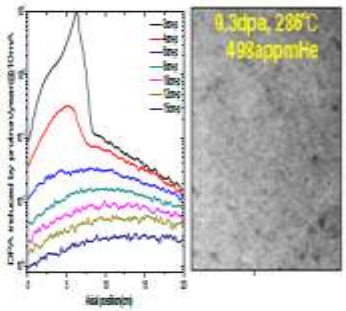
2016. 12

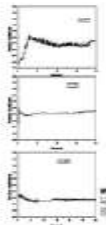
Air tightness test

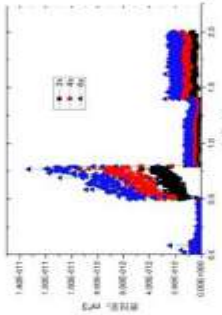


Target container & grains erosion research







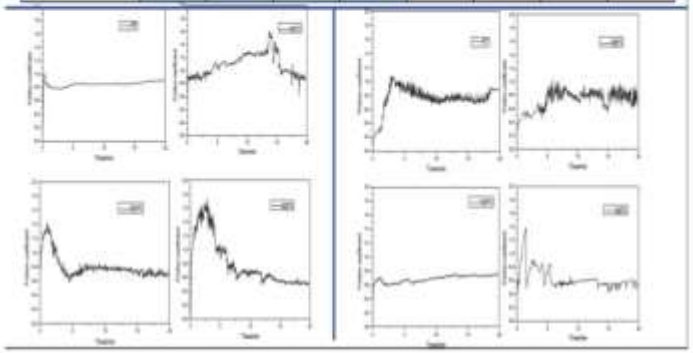


Maximum erosion estimation distribution

316L

SiC

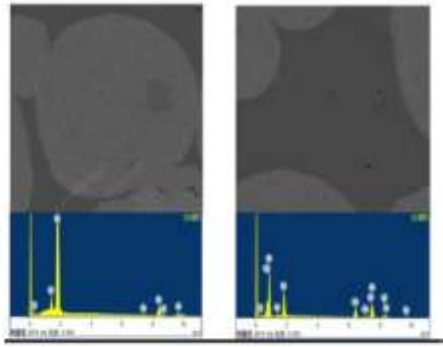
磨损/℃	RT	300	500	800	RT	300	500	800
	钨球（SiC）磨损率				钨球（SIMP钢）磨损率			
比磨损率mm³/Nm	-4.62E-6	-6.47E-5	-3.78E-5	-3.78E-5	-4.62E-6	-9.25E-6	-4.62E-6	-1.85E-5
	SiC块磨损率				SIMP 钢磨损率			
比磨损率mm³/Nm	-4.21 E-7	-2.01 E-6	-1.43 E-6	-8.86 E-7	-5.92 E-6	-7.17 E-6	-1.32 E-4	-5.62 E-4



W	RT	300℃	500℃	800℃	1000℃
min	30	30	20	20	20
Specific wear rate mm³/Nm	-4.92E-5	-7.08E-5	-4.62E-6	-9.24E-6	+1.29E-4

SiC	RT	300℃	500℃	800℃	1000℃
min	30	20	20	20	20
Specific wear rate mm³/Nm	-3.56E-7	-2.41E-6	-1.56E-6	-9.63E-7	

Microscopic structure of dust 1 - XX um



1000 hours test: <100 um

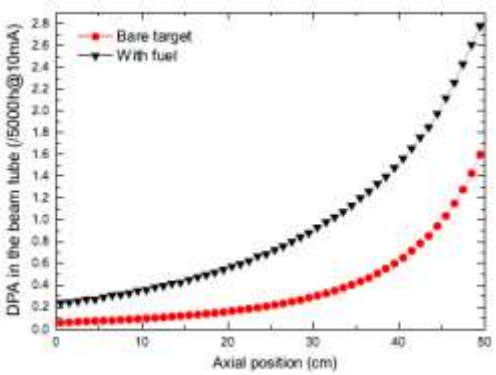
->2000 hours test: <40 um

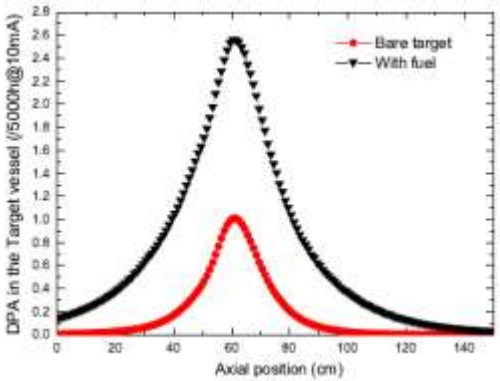
In the RT-1000 ℃ temperature range, W granular, SiC is excellent in wear resistance, wear amount of <1mm.

Target container & grains radiation damege

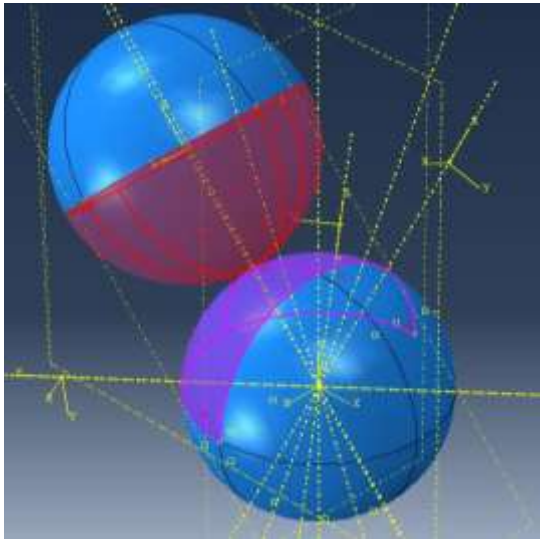
Proton energy	250 MeV
Power	2.5 MW
Profile	Uniform distribution, beam diameter is 10 cm
Target material	Tungsten
Density	11.55 g/cm^3
Displacement threshold	90 eV
Fuel	UO_2
Structural material	316L
Density	7.916 g/cm^3
Composition	Fe (64.7 at%), Ni (11.3 at%), Cr (18.1 at%), Mo (1.4 at%), Mn(2.0 at%) and Si (2.0 at%)
Displacement threshold	40 eV

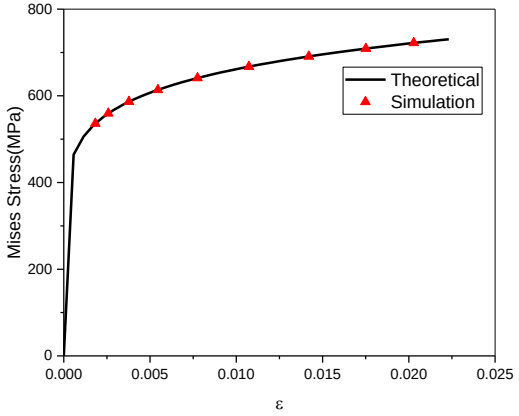
Compared to the solid target and the static granular target, the DGT has an advantage in radiation damage since the irradiation time of the flowing grains in the region of high flux protons and neutrons is significantly reduced. In our calculation model, the grain flow rate is about 0.6 m/s [4] in target hopper, therefore the time that the tungsten grains flow in the main part of the spallation area is merely 2.5 seconds. The loop time of grain movement is about 200 seconds, therefore the exposure time of the tungsten grains in the radiation field is about 62.5 hours in an operating year of 5000 hours. Moreover, from our present calculation, the results show that the average DPA induced by neutron for the tungsten grains are 0.0033 DPA/y and 0.0065 DPA/y for bare target and coupling target with subcritical core respectively, and the average DPA induced by proton for the two cases are both 0.0047 DPA/y. The average helium and hydrogen production for the tungsten grains are 0.1 and 6.76 appm/y respectively, which are a relatively low value.

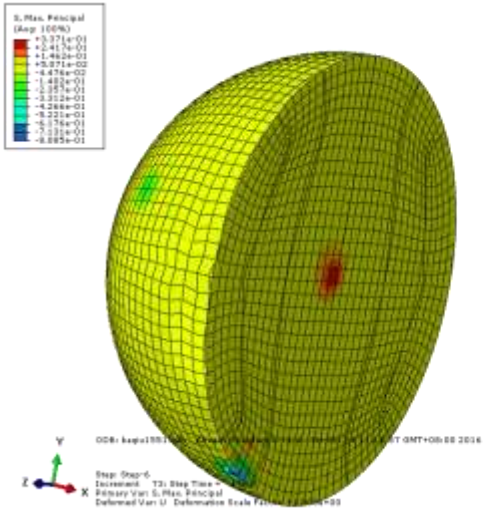




W Alloy Grains:
<0.01 DPA/y (5000h) for 250MeV@10mA
<0.1 DPA/y (5000h) for 1GeV@10mA



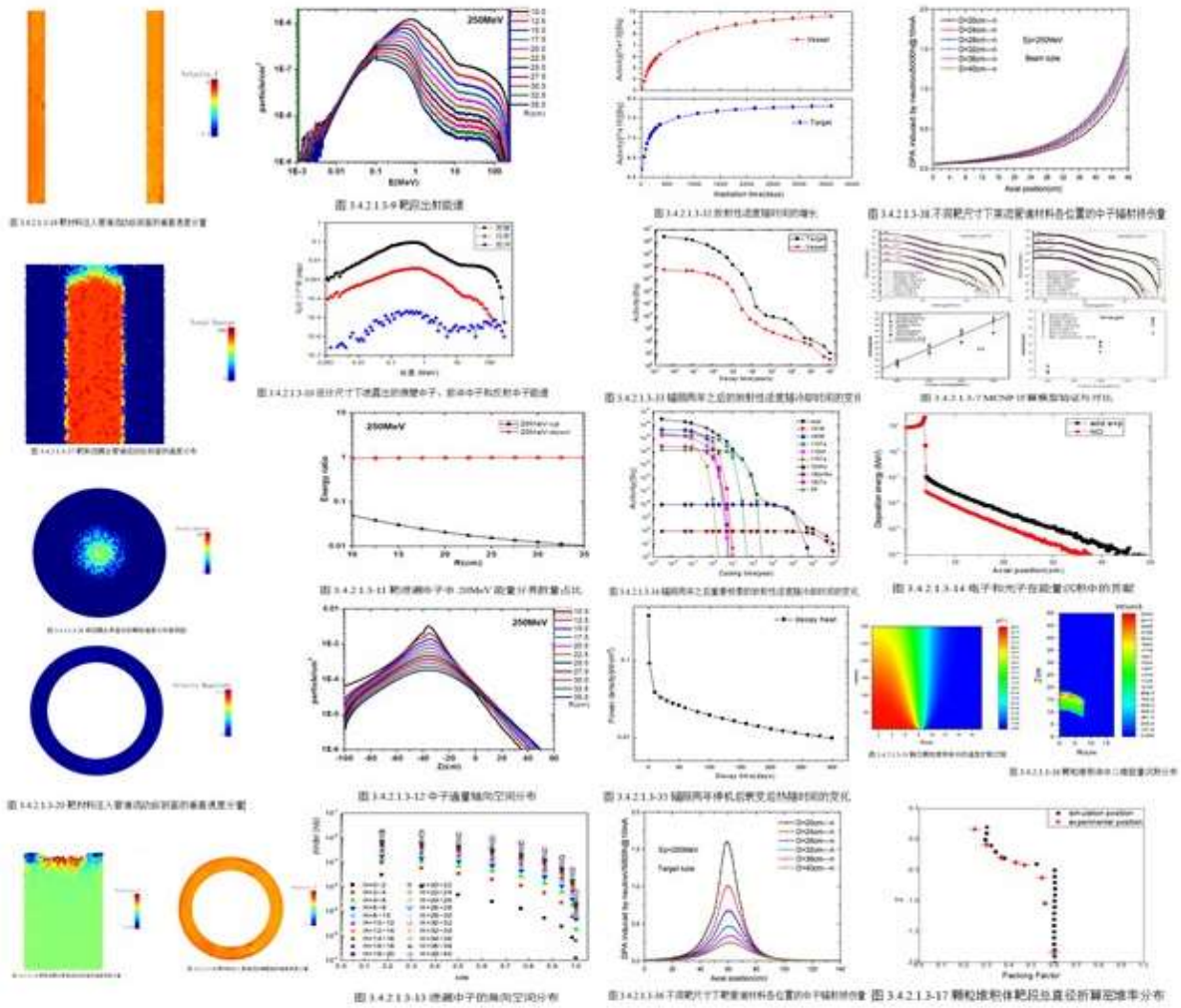




Physical Design for Granular Target of CIADS

项目	数值
总流量	200kg/s
束流能量	250MeV
束流强度	10mA
束流耦合区平均流速	~0.18m/s
靶材料加注平均流速	~0.40m/s
束流耦合区平均密堆率	0.57
颗粒流靶管内径	260mm
束流管道外径	170mm
靶入口温度	250℃
靶出口平均温度	330℃
束斑直径	>12cm

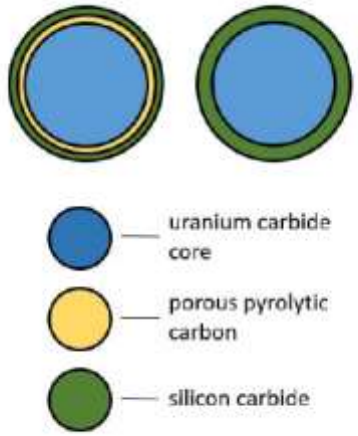
- 靶颗粒流结构
- 中子学效果
- 束流沉积热
- 放射剂量
- 辐照损伤
- 热扩散影响
- 颗粒体系评价方法



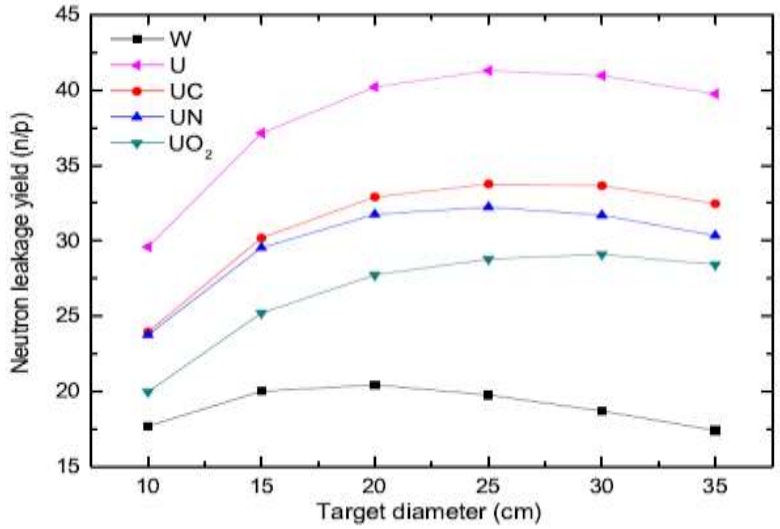
250MeV@10mA

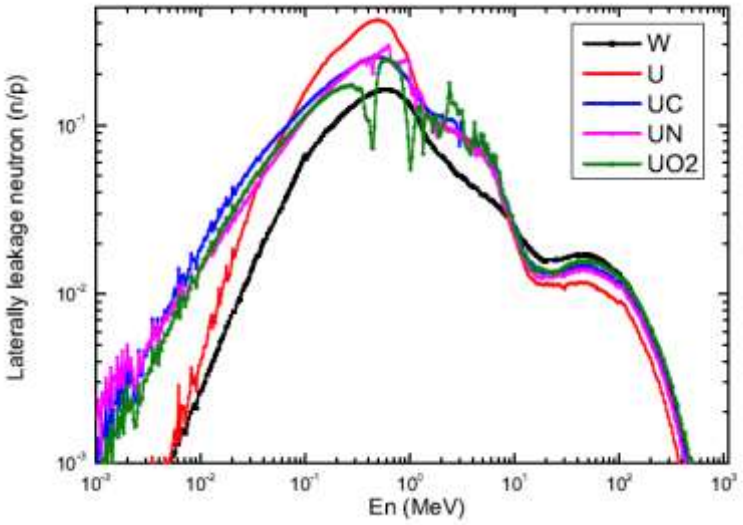
Granular target as a candidate of HPT?

- ✓ The higher beam power can be optimized
- ✓ **High neutron yield**, low radiation toxicity can be optimized
- ✓ Heat capacity, high thermal conductivity can be optimized
- ✓ No corrosion and low chemical-toxicity can be optimized



The schematic plot of TRISO type pellets target.





Coolant of core

Coolant for ADS (ATW)

Lead/LBE Cooling Fast Reactor

Strong points

- Unpressurized reactor vessel
- High boiling tempe
- High thermal inert
- Good passive safe convection)
- Transmutation
- Compatible with w
- Some experience (Russia)

Weak points

- High melting temperature (lead)
- Corrosive and toxic
- Problematic cleaning and decontamination
- Activation of Pb and Bi → ^{210}Po
- Nitride fuel: ^{14}C contamination

Gas Cooling Fast Reactor

Strong points

- Resistant fuel barrier
- Thermal negative fee
- Inert coolant (He)
- Transmutation capab

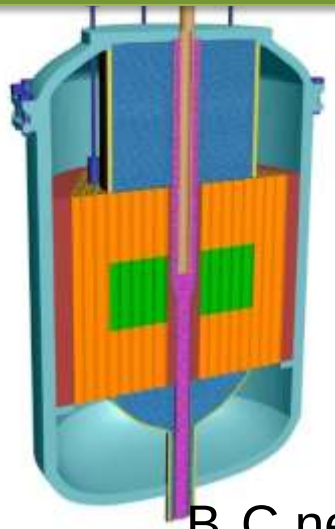
Weak points

- High power density (100 MW/m^3)
- Low thermal inertia (gas)
- No operating experience
- High coolant flow → vibrations
- Decay heat removal and depressurisation → high pump power

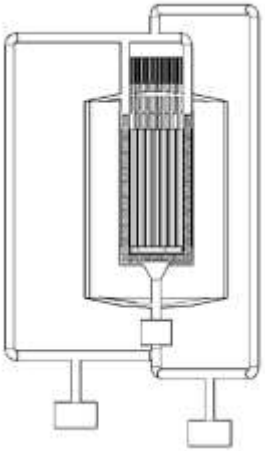
Concept of the granular coolant reactor

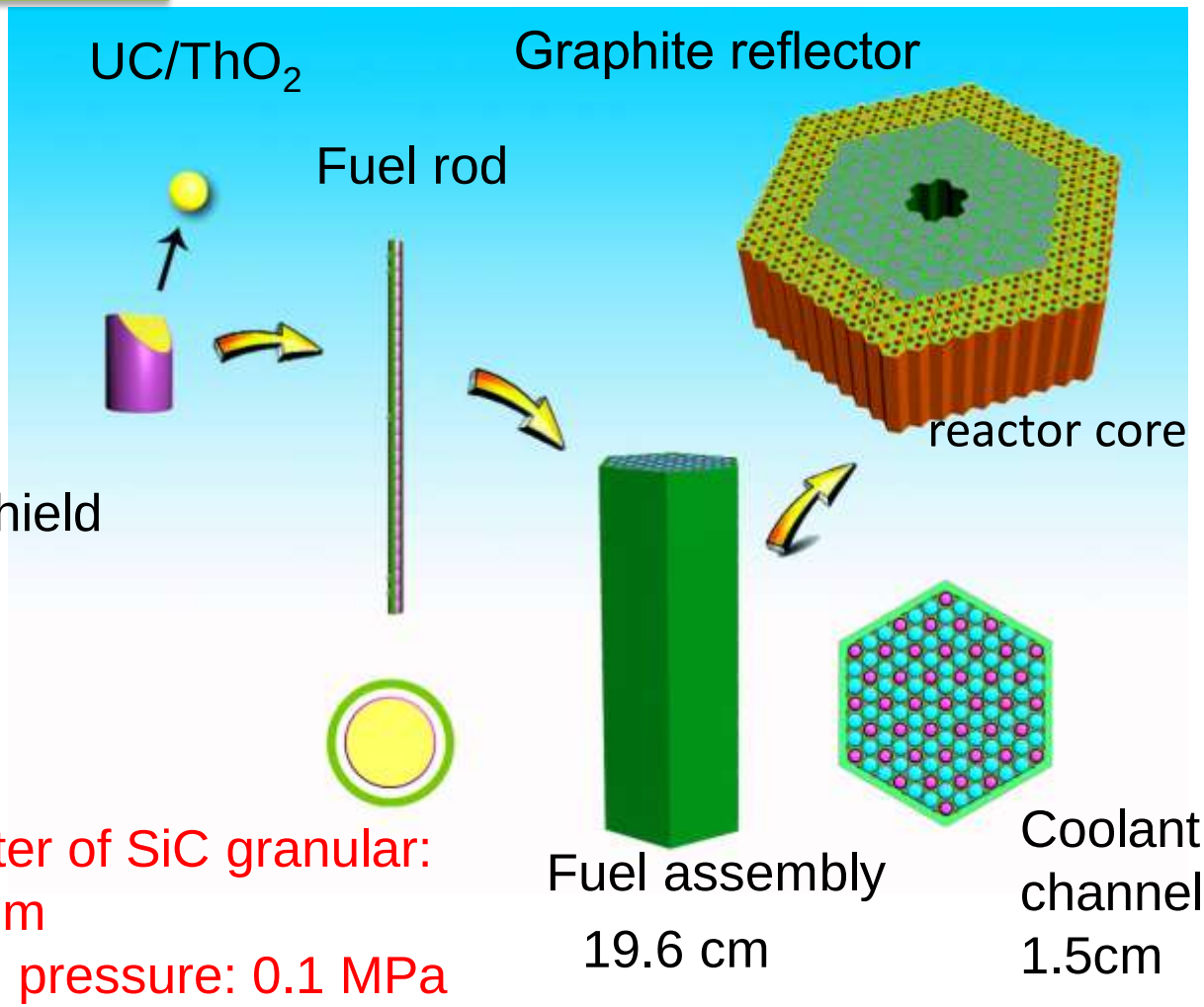
Granular coolant

Two phase coolant: Solid grains + Gas



B_4C neutron Shield



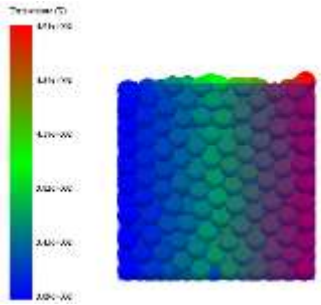


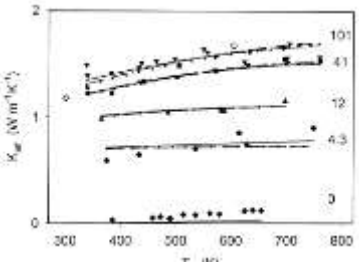
Diameter of SiC granular: ~0.5 mm

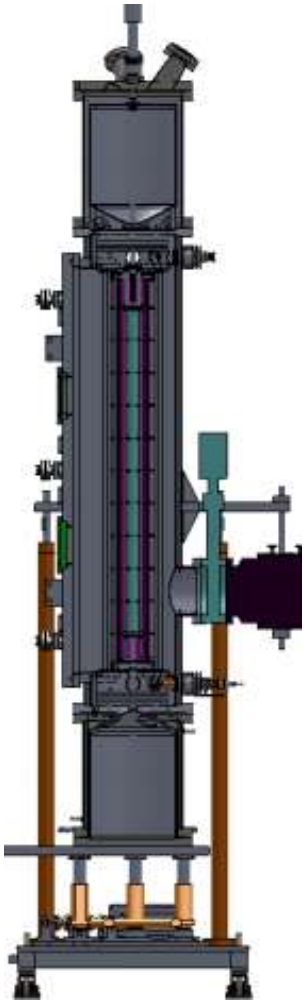
Helium pressure: 0.1 MPa

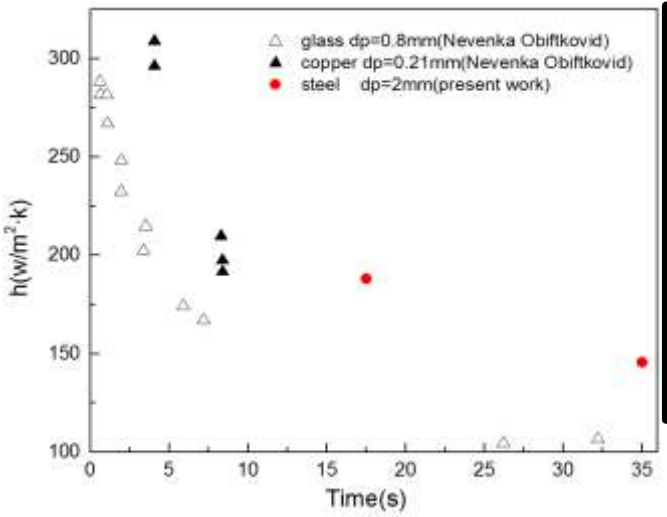
Heat transfer by granular flow coolant

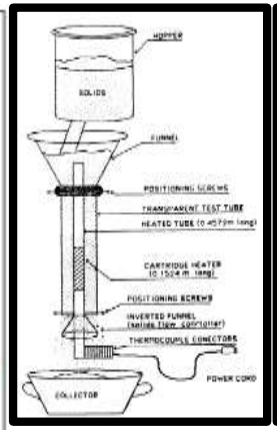
Granular coolant





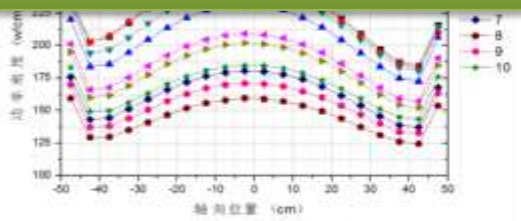


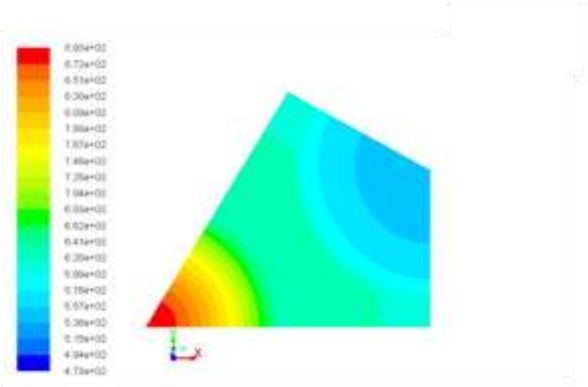


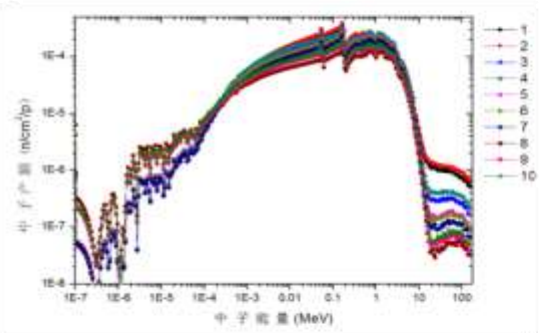


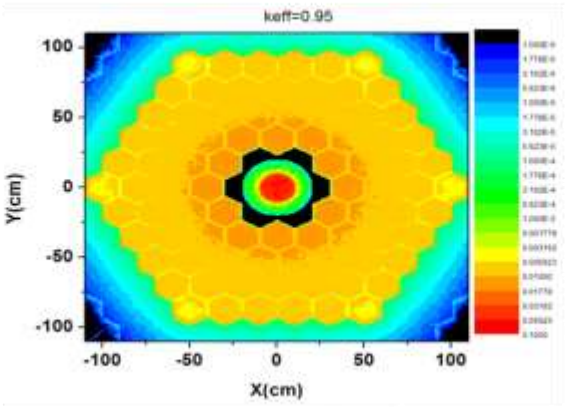
Concept design for granular flow coolant

Granular coolant

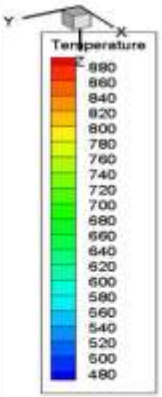


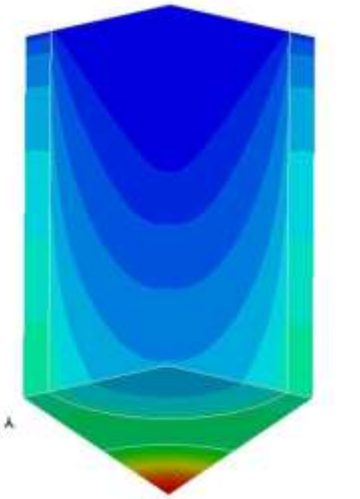


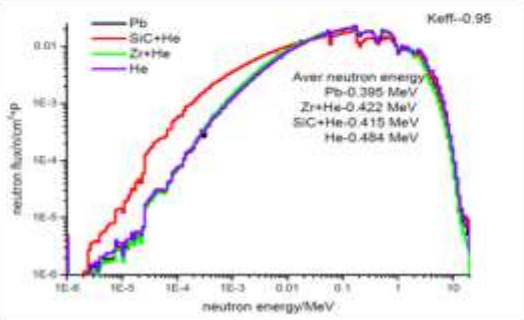




Density of Power distribution







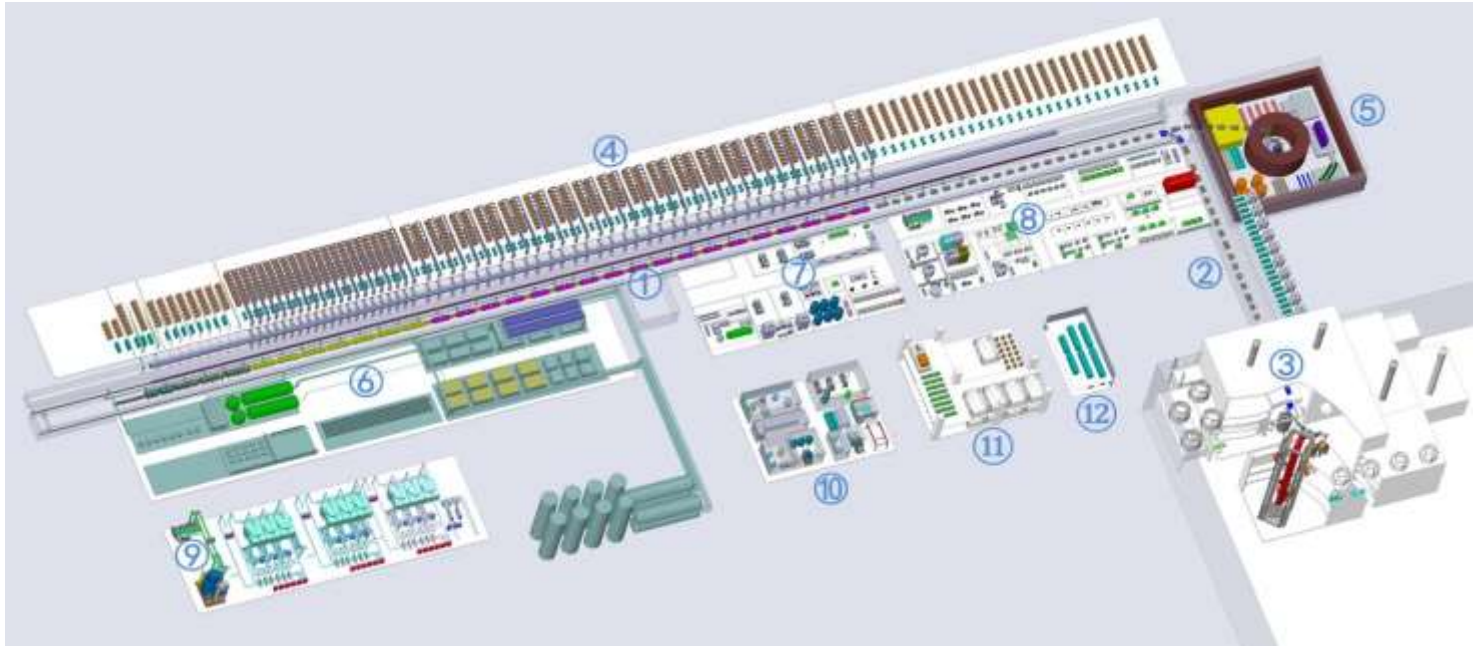
- ✓ Specific heat is similar to LBE coolant
- ✓ No corrosion & Less radio/chemical toxicity

Comparison Options of Coolant

	LBE/LPb	Water+Steam	He+Grain
Temperature (°C)	~600	~600	~900
Pressure	>1atm	~10MPa	~1atm
Corrosion	Stronger >500°C	Adequate ~ 600°C	Low
Long Burnup	Difficult（material）	Yes	Yes
Radiation/live time	Higher/Long	Minimum/Shortest	Low/Short
Relative toxicity	Stronger	Minimum	Weaker
Density（MW/m^3)	>50	~50	30~50
Core Safety	Passive	Passive	Passive
Thermal Quality	Good	Adequate	Best
Material improving	Corrosion/Erosion	Corrosion >500°C	Erosion
Tech. Diff./mature	Diff./Spec. Op.+R&D	Simple/R&D	Adequate/R&D
Cost Constr. / Op.	High / High	Lower/Lower	Adequate/Lower

- LBE/LPb：Diff., Short Refueling, Lower in cost effective
- Water+Steam：Low electricity efficiency, Middle in cost effective
- He+Grain：Better cost effective, New, need more R&D

CiADS系统总体布局



①超导直线加速器
②器靶耦合段
③反应堆与散裂靶装置区
④加速器设备厅
⑤束流收集终端及散裂靶热态实验区
⑥低温中心设备厅
⑦加速器装配调试及工艺实验厅
⑧超导综合测调与加速器维修厅
⑨冷却水设备厅
⑩散裂靶及堆芯热工测调维护厅
⑪放化与材料厅
⑫中心变电站

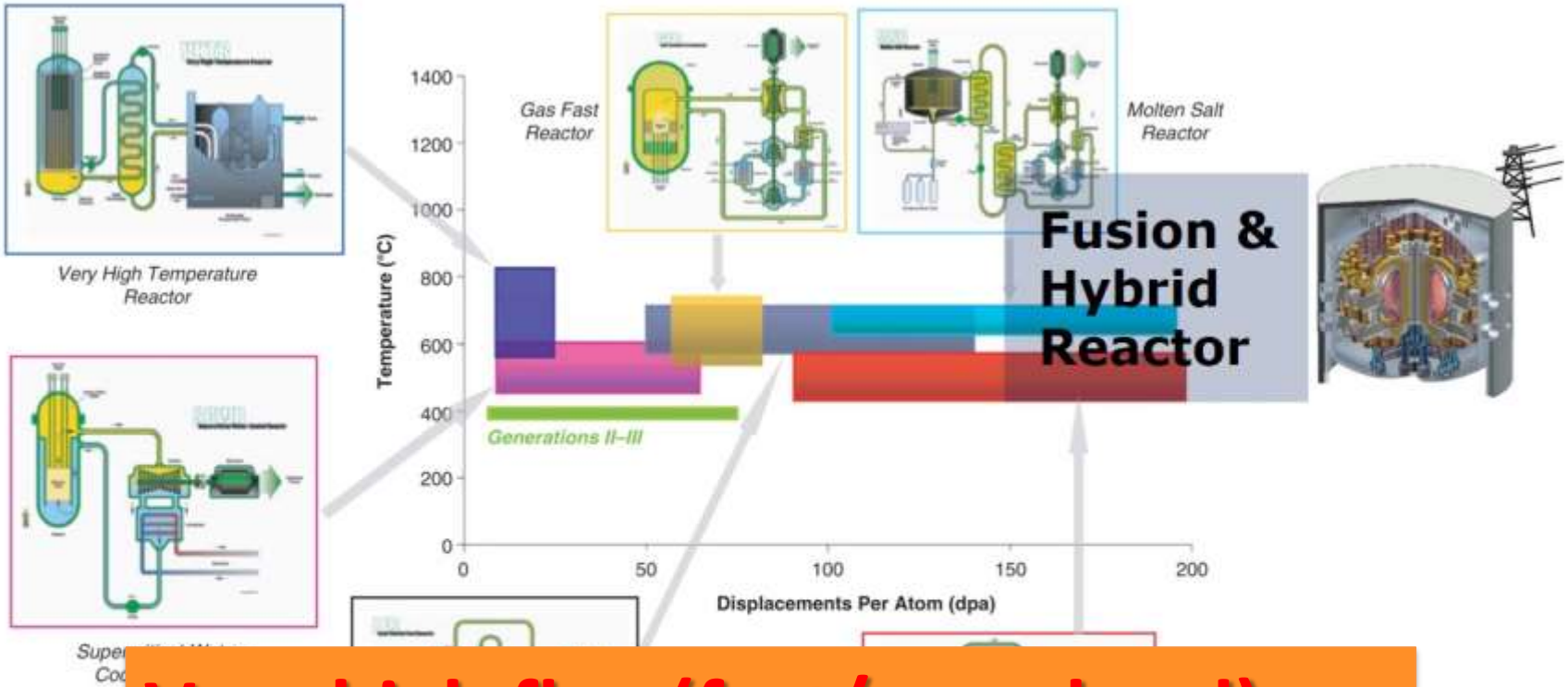
园区


冷却设备大厅
散裂靶及
堆芯热工
大厅
射频超导和
加速器综合大厅
中心
变电站
反应堆与散裂靶
装置区
低温中心
设备厅
束流收集终端
职工宿舍

Materials & CMIF

Material Irradiation Facility (MIF)

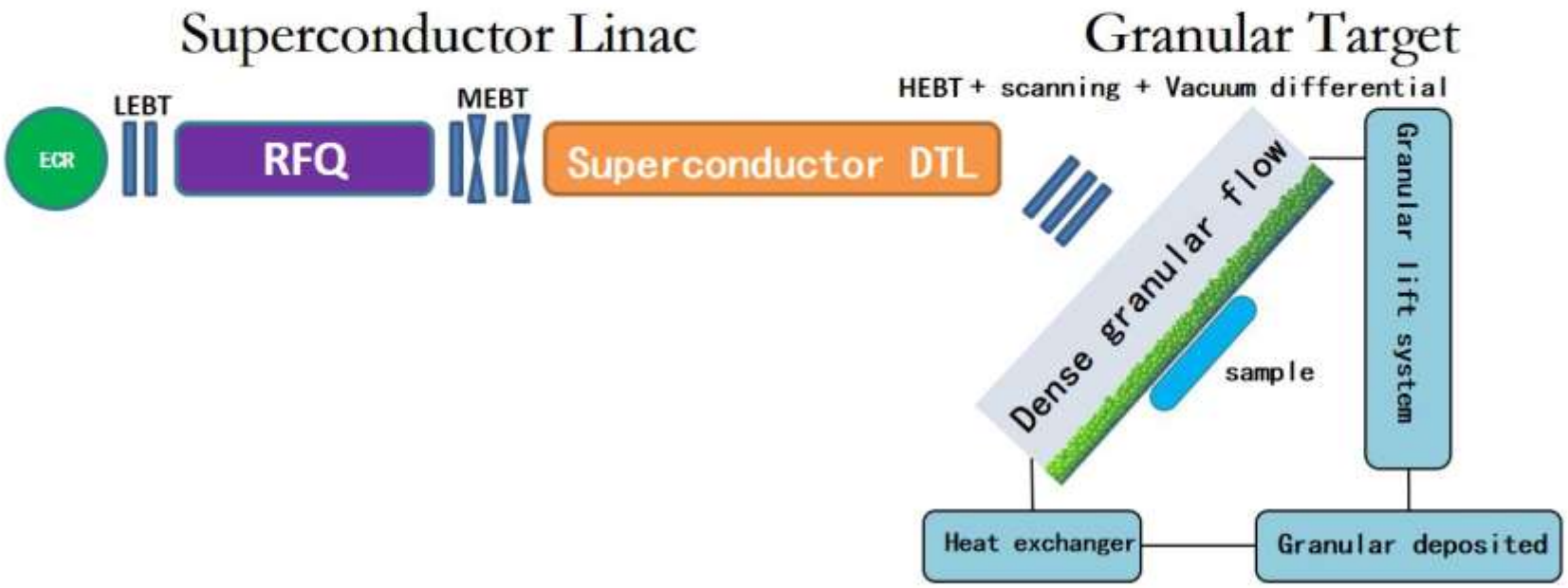
MIF for Nuclear Energy



Very high flux (fast/even hard) neutron source is enthusiastic requirement.

Granular target (windowless) for Compact-MIF

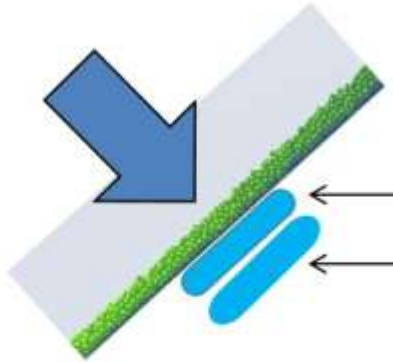
Project name: Compact Materials Irradiation Facility (CMIF)	
Target	**High Neutron Flux; Low Total Neutron Yield; Small Sample Size beryllium alloy grains; dense granular flow target**
Beam	**50~100MeV@(5~15)mA (CW); ~1MW heat removal**
Cost	**Low; Based on techniques of Chinese ADS project**



Low Pressure Helium environment <1 atm.

User Facility of Compact-MIF

50 MeV@10mA Deuton beam

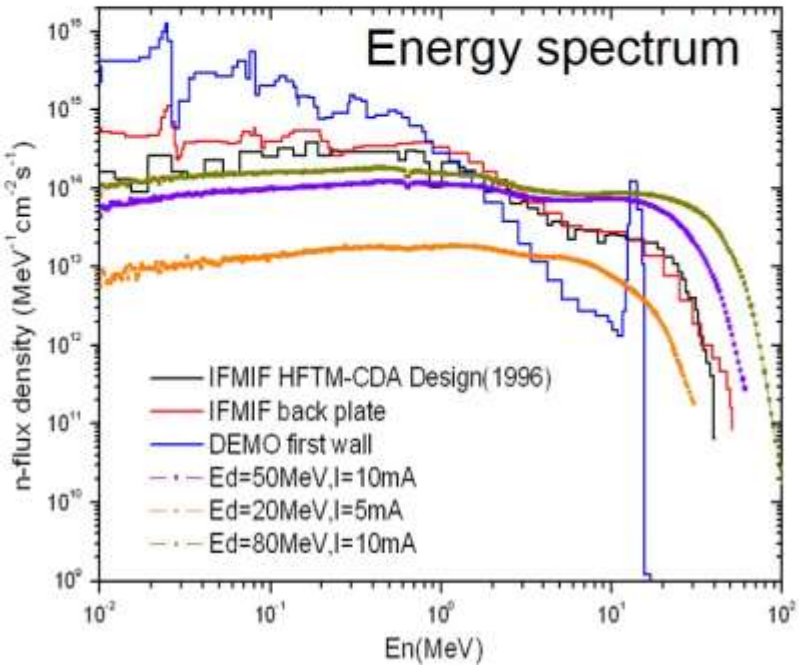


Sample 1 from back 1 mm

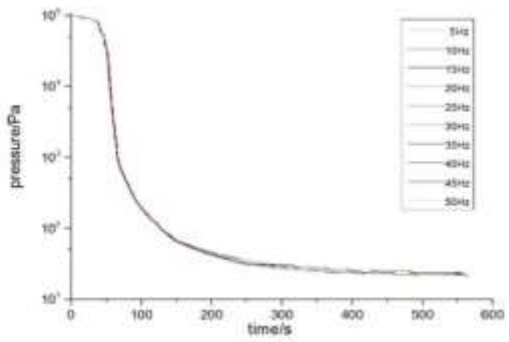
Sample 2 from back 10 mm

	DPA	Flux
1	1*1*1 ~80DPA	~$2*10^{15}$
2	3*3*1 ~20DPA	~$8*10^{14}$

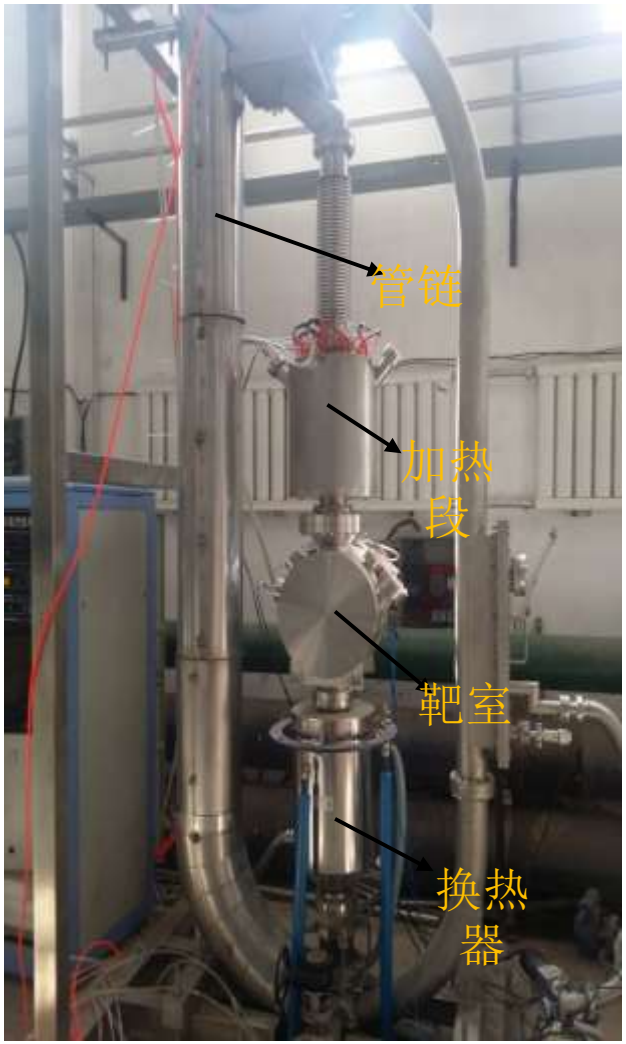
decided

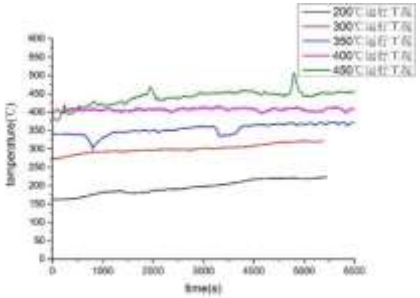


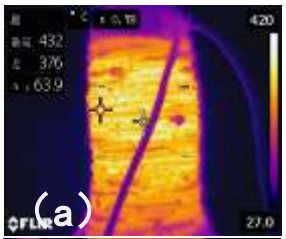
Test for Target Prototype target

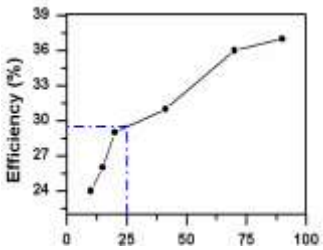


High temp. Test for Target Prototype of Demo. CMIF



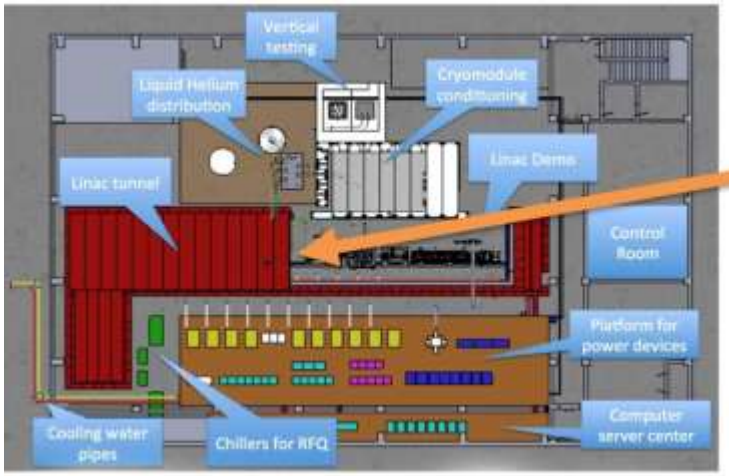






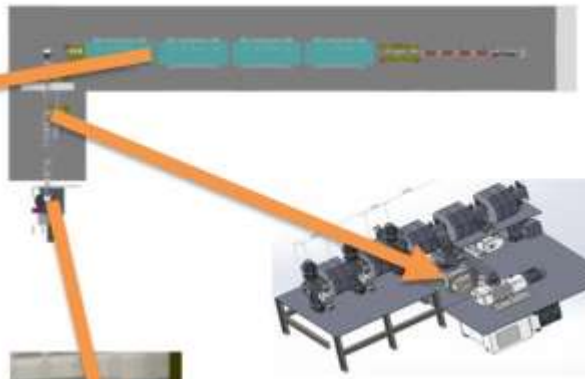
radio frequency induction heating

Beam Target coupling test for 25MeV



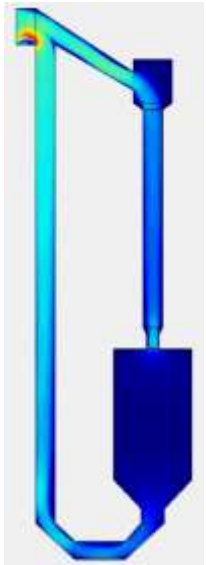
Setup for installation site

Linac



Difference vacuum system

Granular target

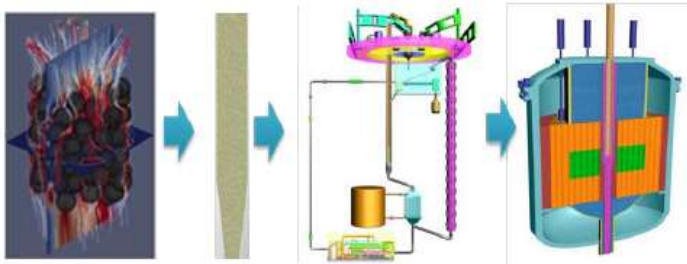


Next plan: Test without beam (end of 2016); Test with beam (end of 2017)

Super computing design system and V&V

Super-Computing, Simulation & Design System

Mass parallel simulation method (GPU)



- Radiation transport computation in stochastic granular and neutronic analysis, etc.
- Granular flow and fluid flow simulations and thermal-hydraulic analysis.

250 S1070 GPUs
~300 Tflops(S)

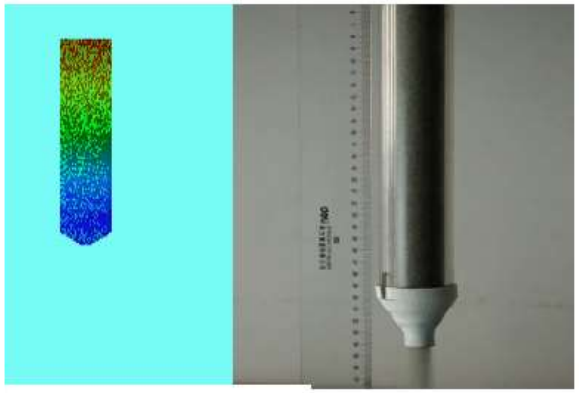
128 K20 GPUs
~150 Tflops(D)

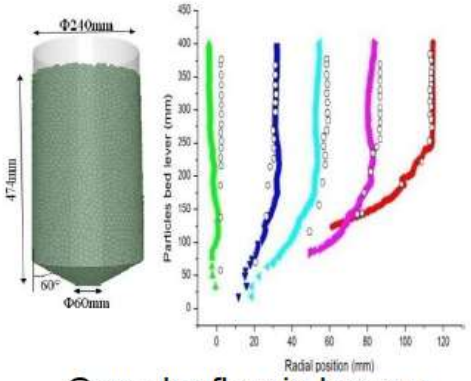
Software Copyrights

End of Last year, we have 1P Flops for Simulation & Design

Super-Computing, Simulation & Design System

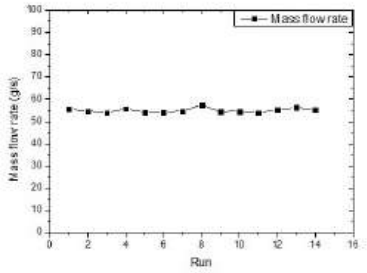
GPU method for Granular Flow (G2F)

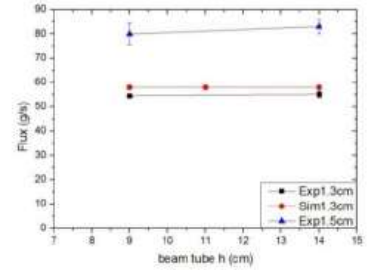




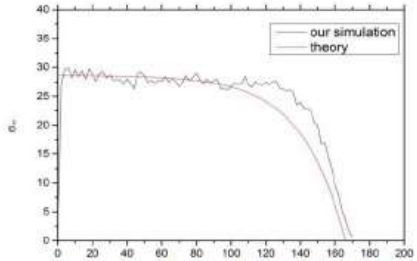
Granular flow in hopper

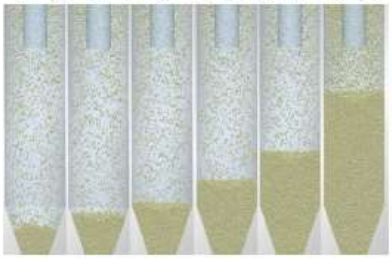
- **Grains：~250 M；MD + Contact mechanic.**
- **512GPU, 512*448=229376 ALU；parallel efficiency：~38%.**



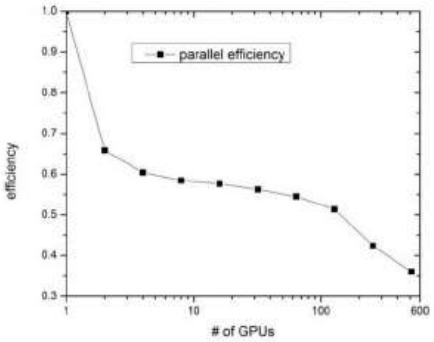


Experiments of verification



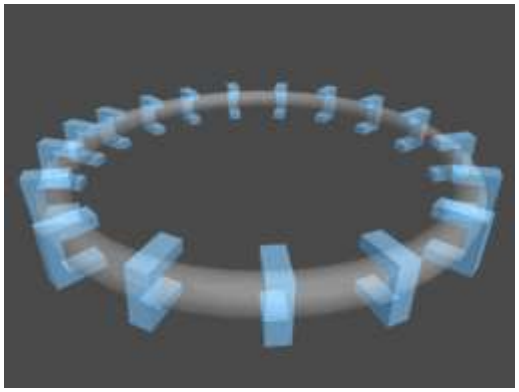


Micro simulation for Macro size

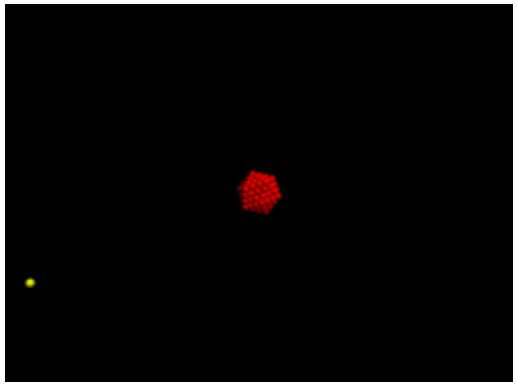


Super-Computing, Simulation & Design System

Hydra dynamical & PIC simulation by GPU

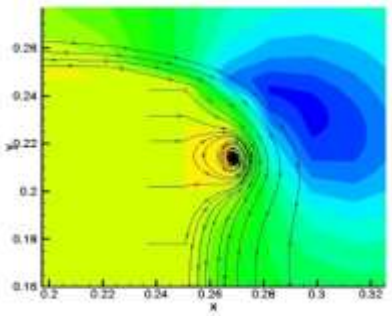


束流动力学模拟

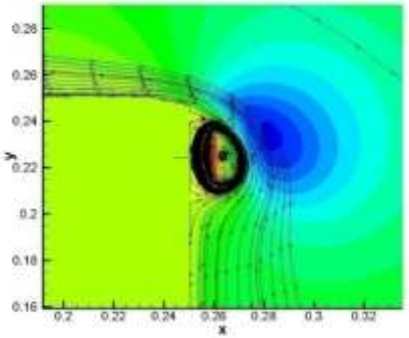


束流与物质相互作用快过程模拟

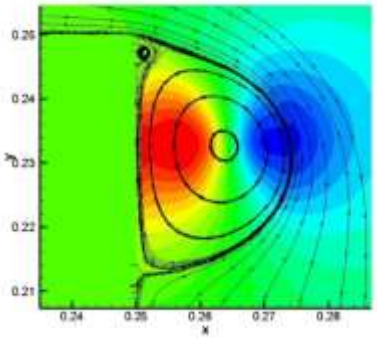
计算时间0.1s
雷诺数Re=3000



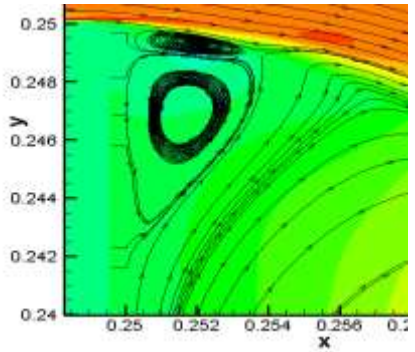
网格数目为6.5万



网格数目为26.2万



网格数目为1677.7万

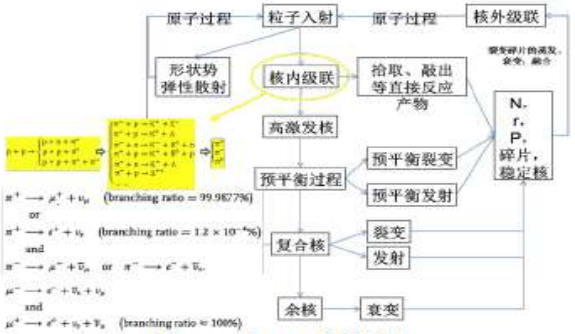


网格数目为6656.92万

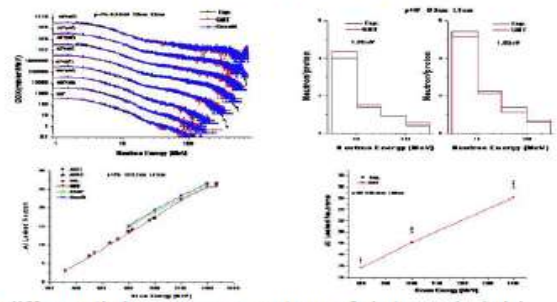
流体力学的DNS

Super-Computing, Simulation & Design System

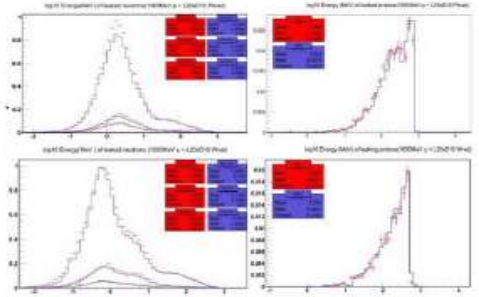
GPU MC Transport program (GMT)



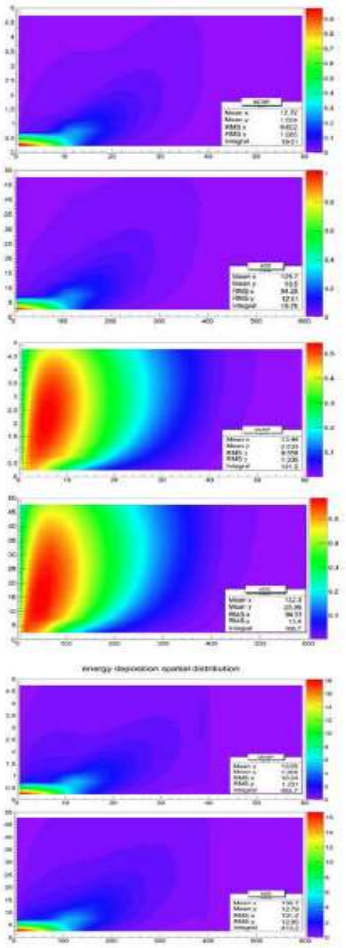
Procedure of GMT



differential energy spectrum & integral yield



Leakage neutron spectrum



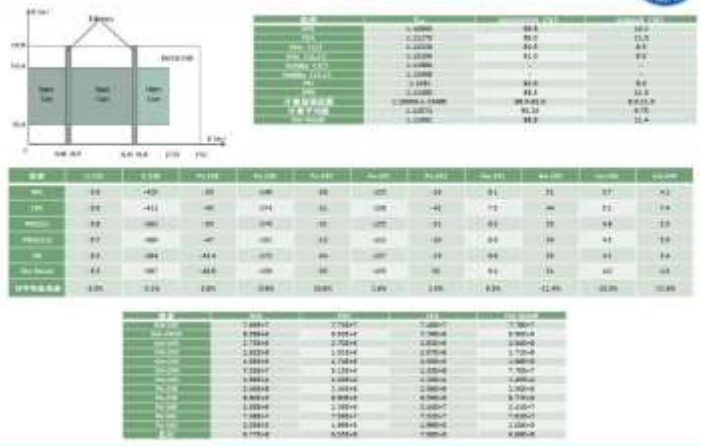
Spatial distribution of flux

OECD/NEA (PWR) benchmark testing

Based on the Monte Carlo simulation method, the use of particle transport code of MCNP and burn-up module LITAC coupled a procedure MCADS. The coupling procedure can be used for complex three-dimensional geometry of nuclear reactors and target of burn-up and decay calculations and isotope analysis.

Radiotoxicity analysis of LBE target and reactor by the code.

Fast reactor benchmark testing



Thank you!

谢谢！