Development of granular target for CADS

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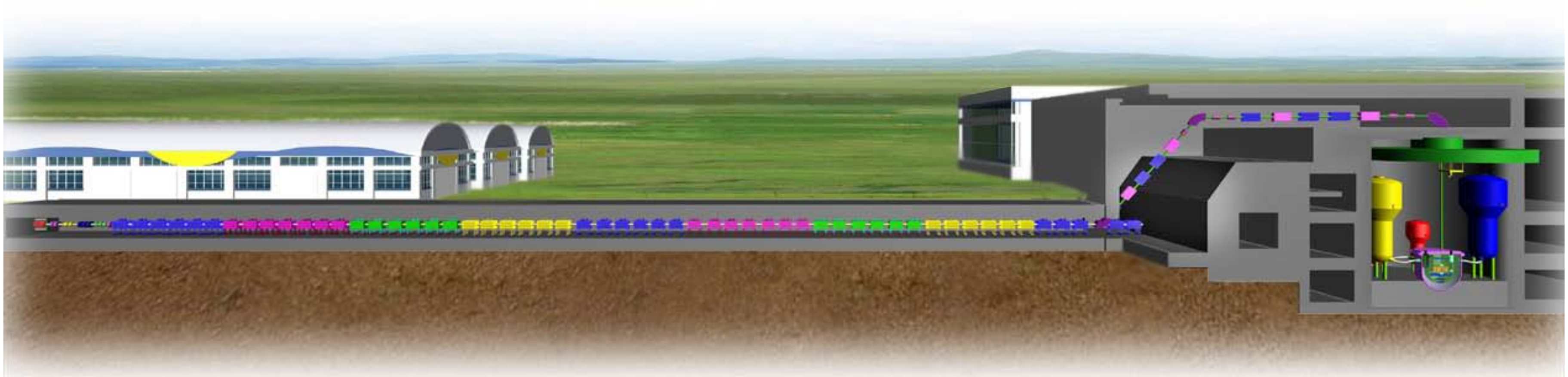
ADS（Accelerator Driven System）

accelerator

Industrial facility ~50MW=2.0GeV@25mA

Subcritical core/blanket

Industrial facility ~500MW



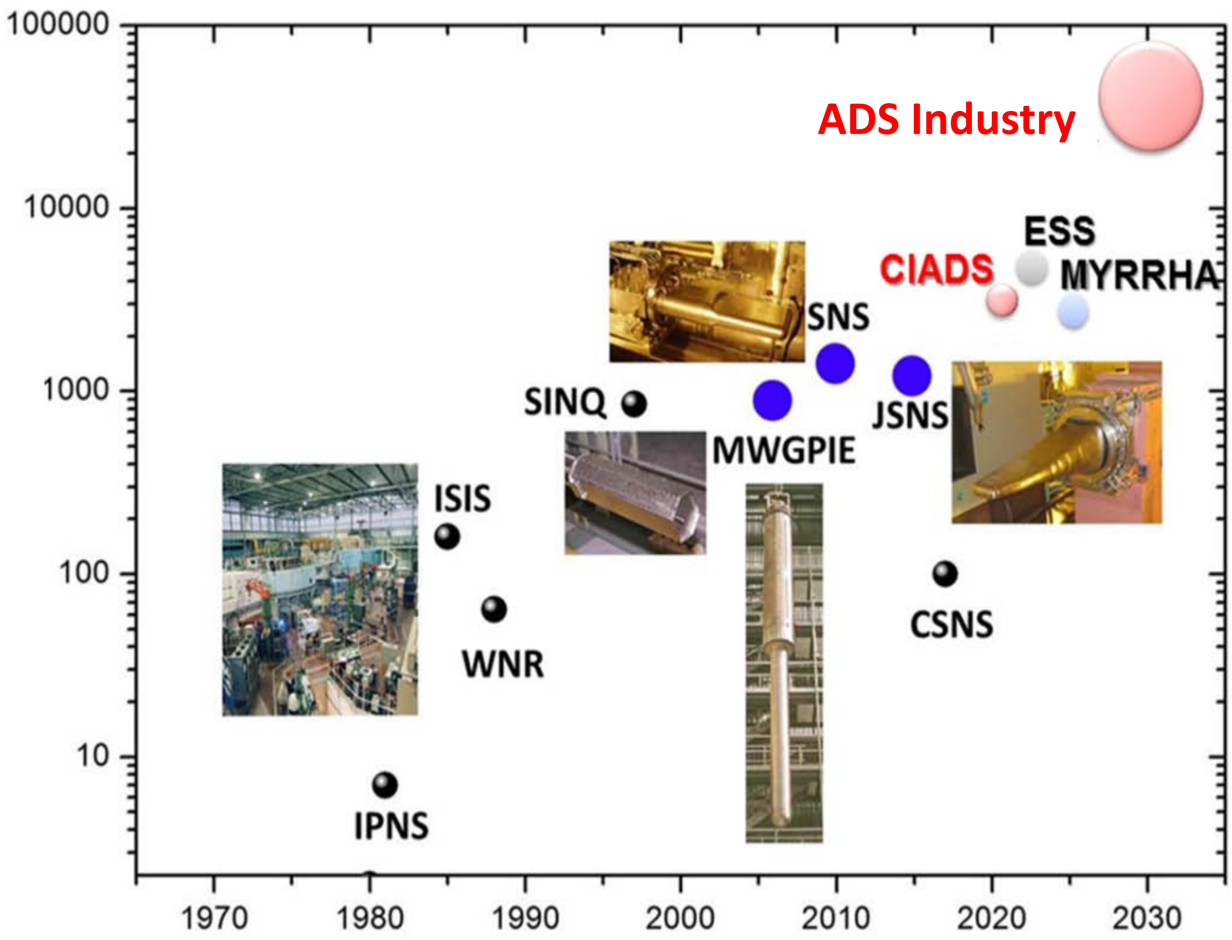
Spallation target

Density of heat deposited by proton beam： ~ X kW/cm^3

	Transmutation Demonstration	Industrial Scale Transmutation	Industrial Scale Power Generation with Energy Storage	Industrial Scale Power Generation without Energy Storage
Beam Power	1-2 MW	10-75 MW	10-75 MW	10-75 MW
Beam Energy	0.5-3 GeV	1-2 GeV	1-2 GeV	1-2 GeV
Beam Time Structure	CW/pulsed (?)	CW	CW	CW
Beam trips (t < 1 sec)	N/A	< 25000/year	<25000/year	<25000/year
Beam trips (1 < t < 10 sec)	< 2500/year	< 2500/year	<2500/year	<2500/year
Beam trips (10 s < t < 5 min)	< 2500/year	< 2500/year	< 2500/year	< 250/year
Beam trips (t > 5 min)	< 50/year	< 50/year	< 50/year	< 3/year
Availability	> 50%	> 70%	> 80%	> 85%

	Transmutation Demonstration (MYRRHA [5])	Industrial Scale Facility driving single subcritical core (EFIT [10])	Industrial Scale Facility driving multiple subcritical cores (ATW [11])
Beam Energy [GeV]	0.6	0.8	1.0
Beam Power [MW]	1.5	16	45
Beam current [mA]	2.5	20	45
Uncontrolled Beamloss	< 1 W/m	< 1 W/m	< 1 W/m
Fractional beamloss at full energy (ppm/m)	< 0.7	< 0.06	< 0.02

High Power Spallation target



- Solid target options, which consist of a solid material in the form of rods, spheres, or plates to produce the neutrons, and coolant flowing between the elements for heat removal.
- Liquid target options where a flowing liquid metal acts both as the source of neutrons and the heat removal media.

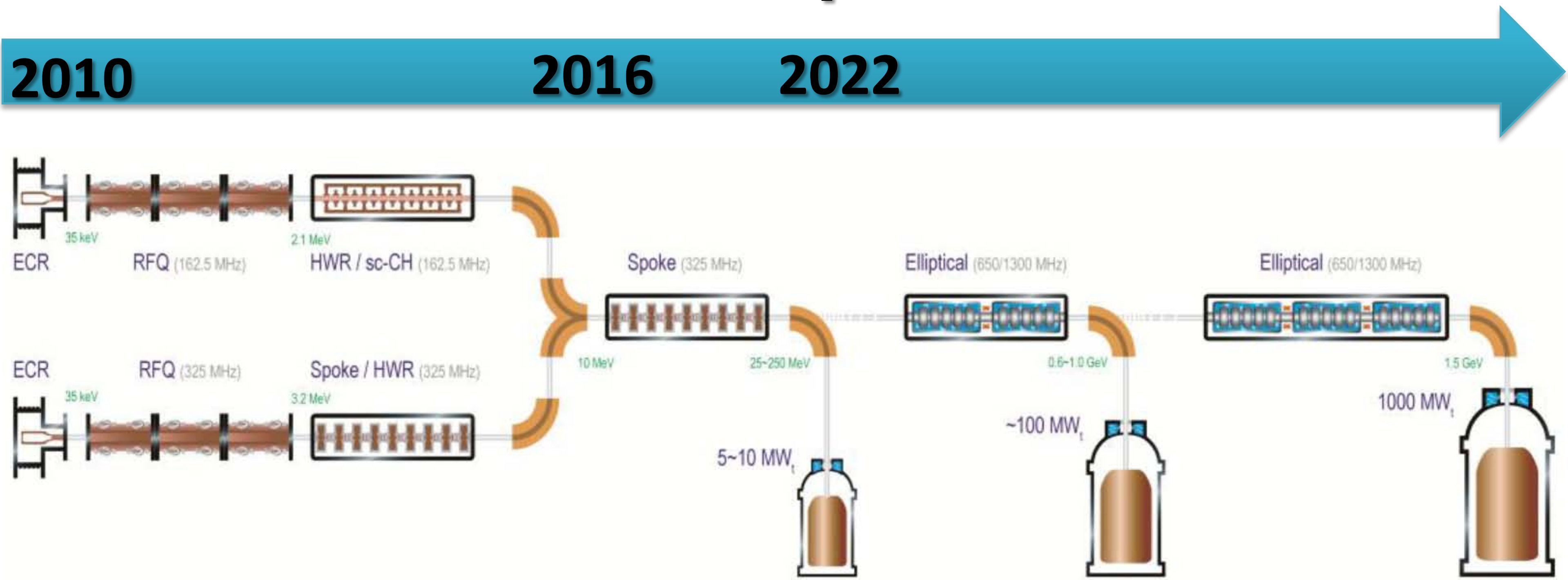
➢The heat removal (Solid target/beam window) will be limited by the heat conduction of the target material and convection-cooling;

➢The life time of the target will be limited by the radiation damage, heat shock and al.

➢Safety, operation, complexity, al.

Fluid target will be likely used for tens of MW.

Chinese ADS roadmap



CIADS: INITIAL FACILITY

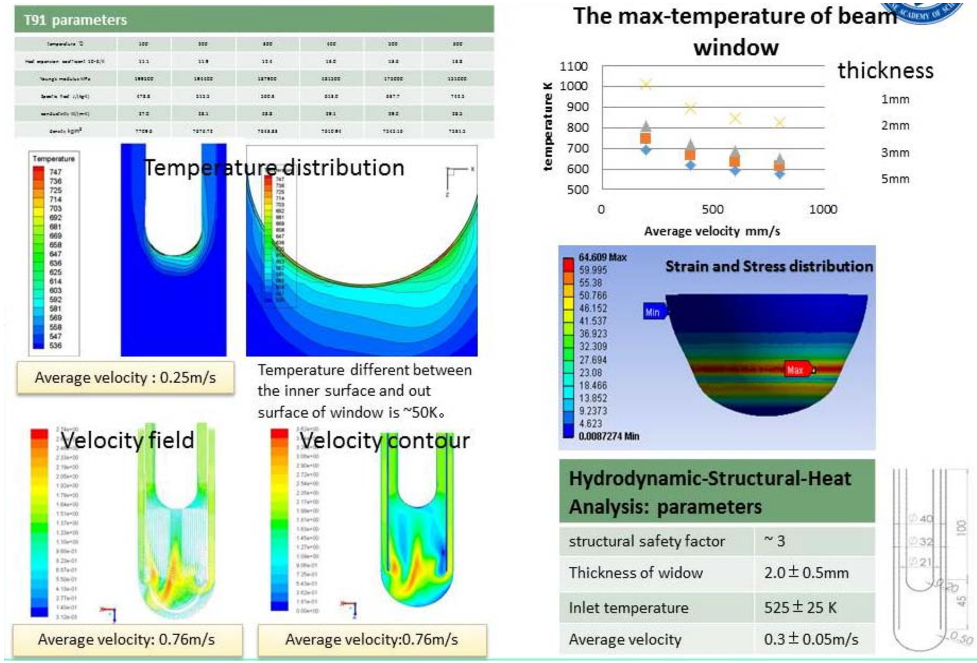
DEMO FACILITY

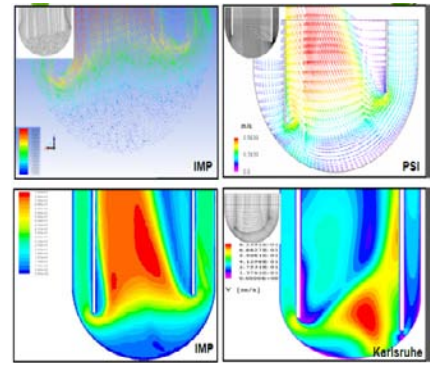
INDUSTRY FACILITY

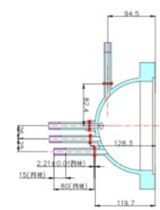
250MeV@10mA
5-10MW

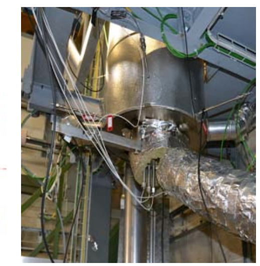
Design goals: For CIADS, the target can accommodate 2.5MW=250MeV@10mA; the target system can update to ~50 MW=2.5GeV@20mA.

LM Window target research

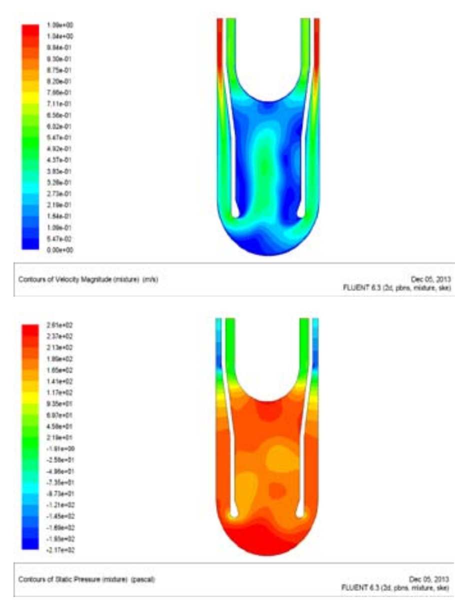


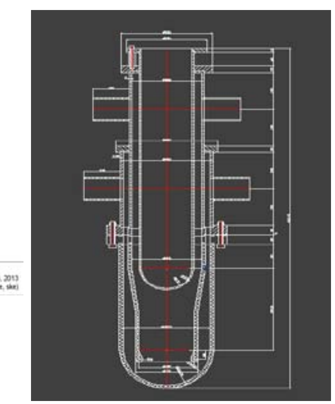




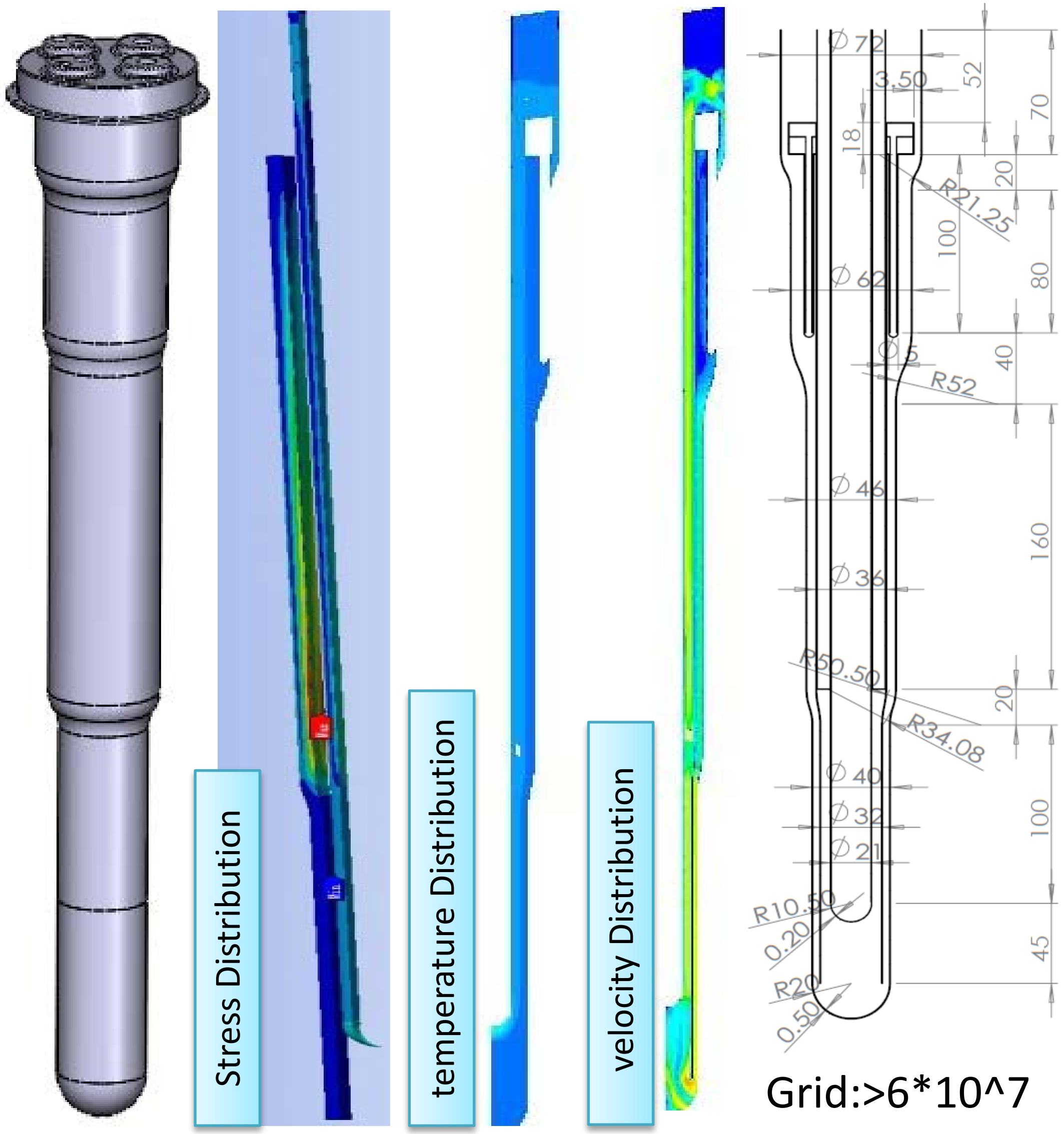


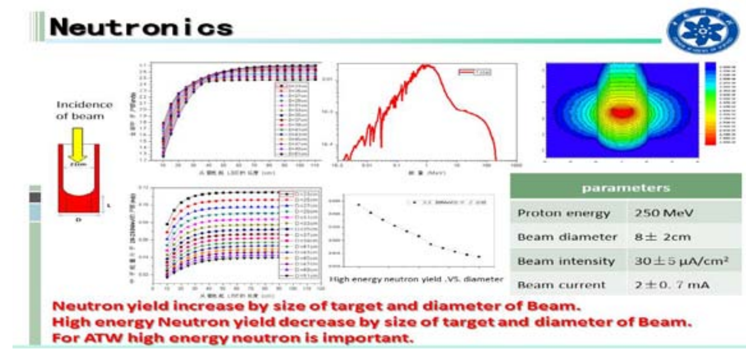
- ➢Average Beam intensity： ~30 μA/cm^2. For an ADS, If the diameter of the beam pipe can choose ~30-40 cm, then, the target would be design for >10MW.
- ➢The heat removal of the window will be limited by the heat conduction of the target material and convection-cooling; the life time of the window will be limited by the radiation damage and al.

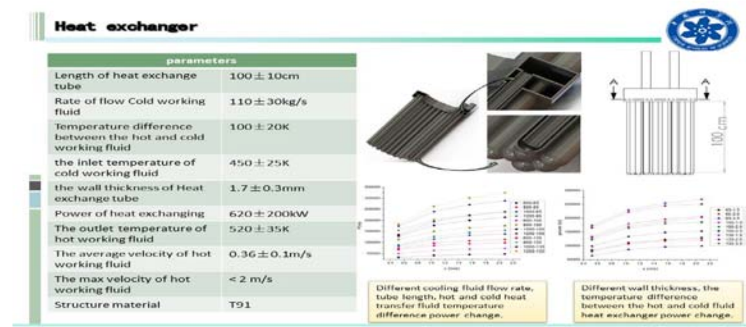




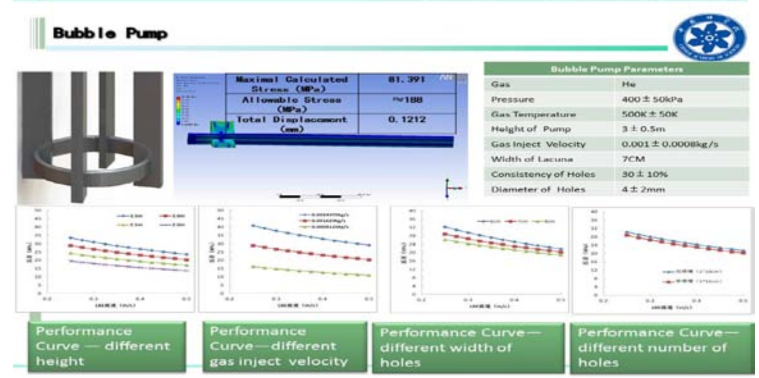
LM Window target design for CIADS







parameters	
Length of heat exchange tube	100±10cm
Rate of flow Cold working fluid	110±30kg/s
Temperature difference between the hot and cold working fluid	100±20K
the inlet temperature of cold working fluid	450±25K
the wall thickness of Heat exchange tube	1.7±0.3mm
Power of heat exchanging	620±200kW
The outlet temperature of hot working fluid	520±35K
The average velocity of hot working fluid	0.36±0.1m/s
The max velocity of hot working fluid	< 2 m/s
Structure material	T91

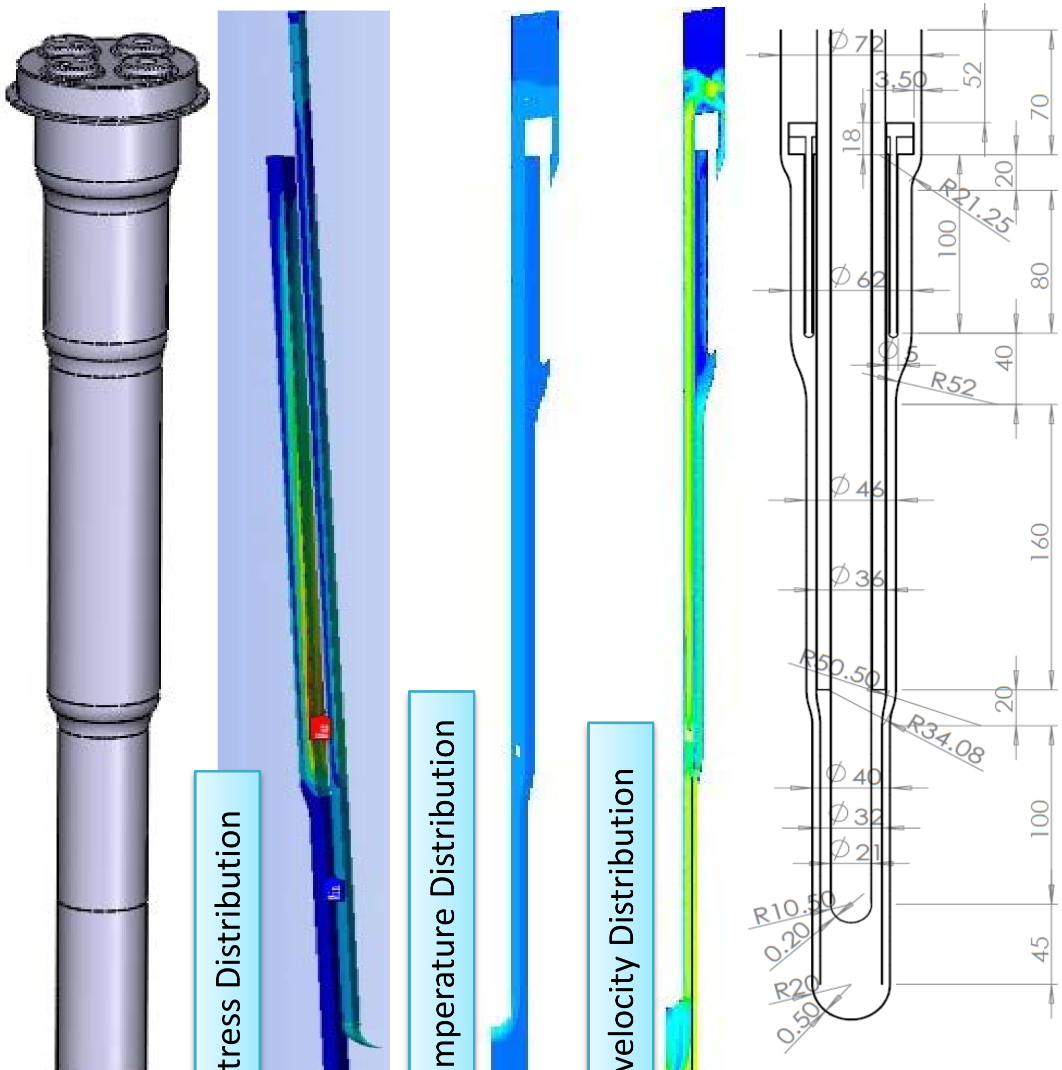


Maximal Calculated Stress (MPa)	81.391
Allowable Stress (MPa)	~188
Total Displacement (mm)	0.1212

Bubble Pump Parameters	
Gas	He
Pressure	400±50kPa
Gas Temperature	500K±50K
Height of Pump	3±0.5m
Gas Inject Velocity	0.001±0.0008kg/s
Width of Lacuna	7CM
Consistency of Holes	30±10%
Diameter of Holes	4±2mm

3D coupled analysis: temperature, hydrodymics and structure

LM Window target design for CIADS

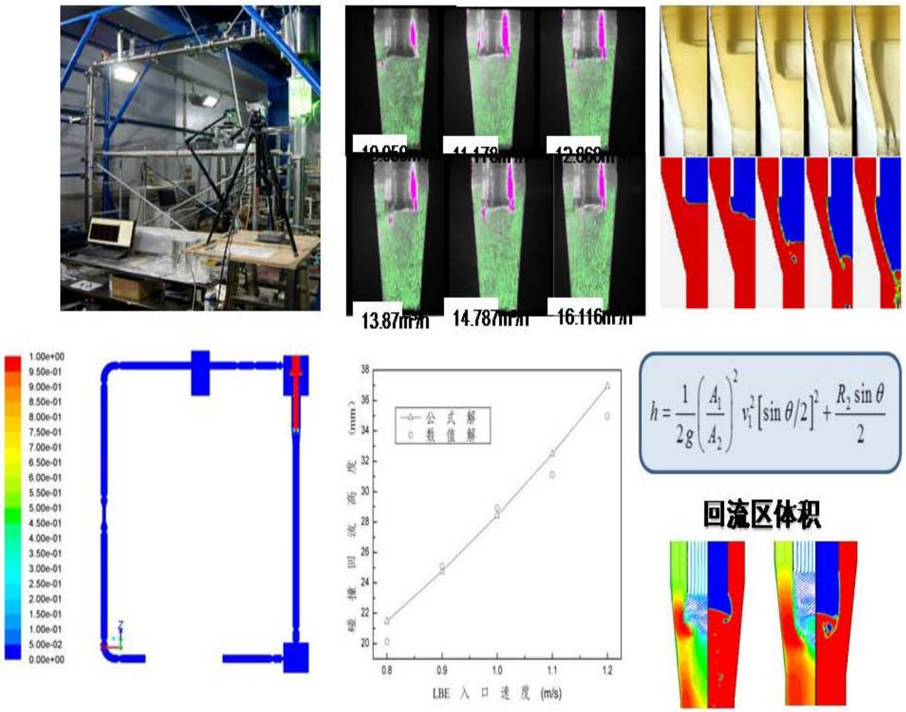


Grid:>6*10^7

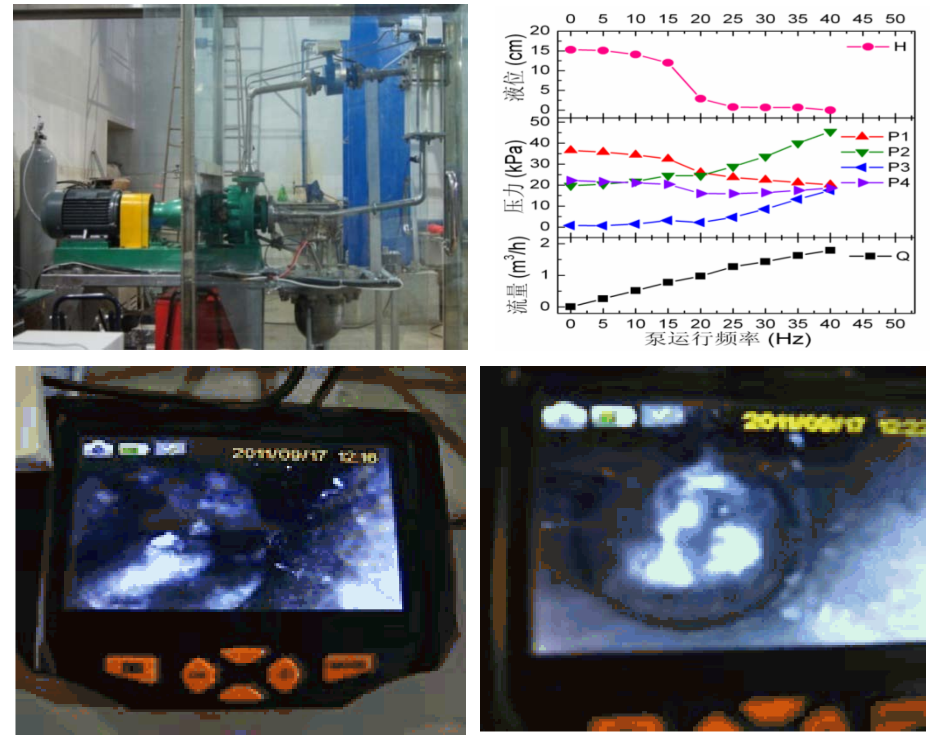
Physical Design Parameters	
Neutron Yield	3.2 n/p
Diameter of Beam	8cm
Beam Energy	**250MeV**
Beam Current	**2.5mA**
LBE average velocity	0.21~0.49m/s
LBE max velocity	1.29m/s
Window Thickness	2mm
Temp. Difference of Heat Exchanger	90K
Max velocity of cold fluid	1.52m/s
Wall Thickness of Heat Exchanger	1.75cm
Flux of Gas inject	5L/s
Width of Lacuna	7cm

3D coupled analysis: temperature, hydrodymics and structure

The free surface in windowless target



Water loop test for full scale windowless HML target

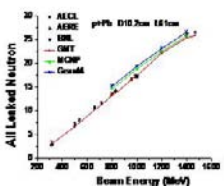


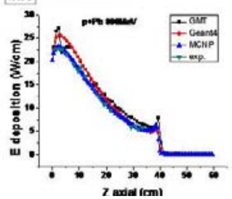
HML loop for Small scale windowless HML target

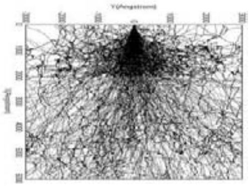
➢The hydrodynamic instability of system will be increase by the flux of the inlet.

➢The region of the eddy could be design, so the annular beam can be used to avoid eddy, but the control of stability is not an easy task.

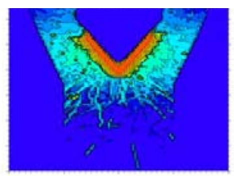
The Beam-Target-Coupled in windowless HML target by Mass-Parallel CFD (GPU)





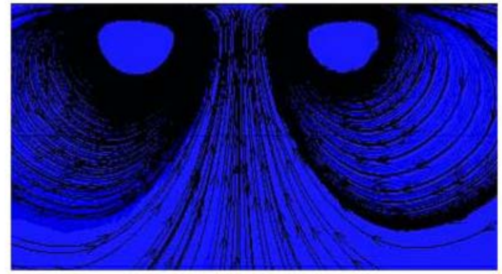


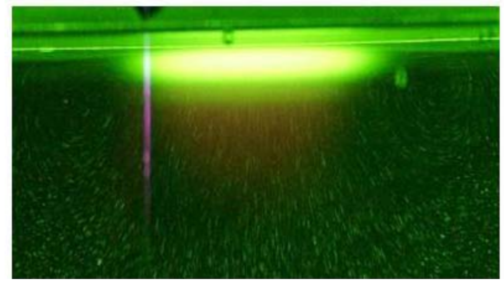
MC proton trace

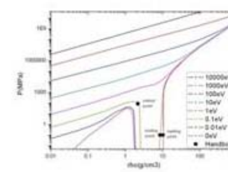


Energy deposition

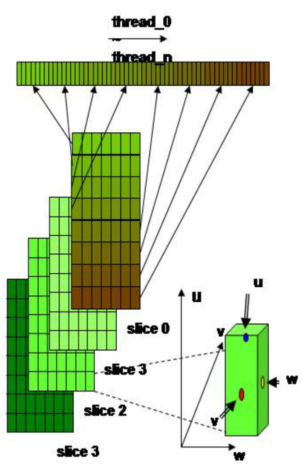
MC proton transport code for energy deposition

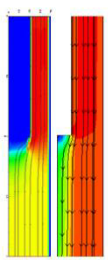


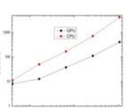


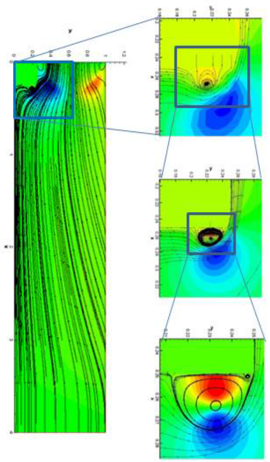


Test by the electron beam coupled with water





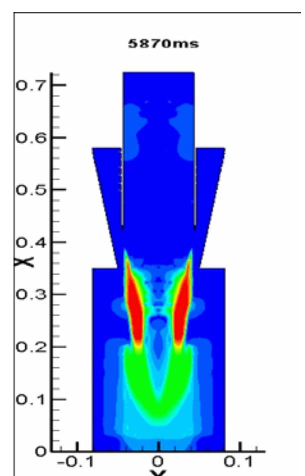




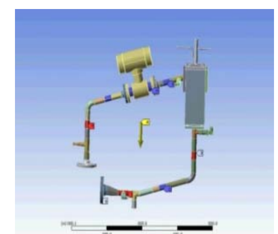
10^5

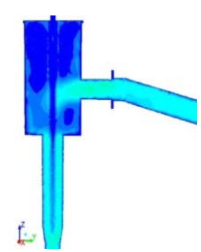
10^6

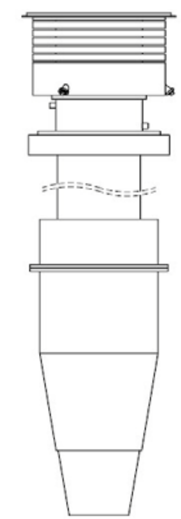
10^8



Annular beam to avoid eddy

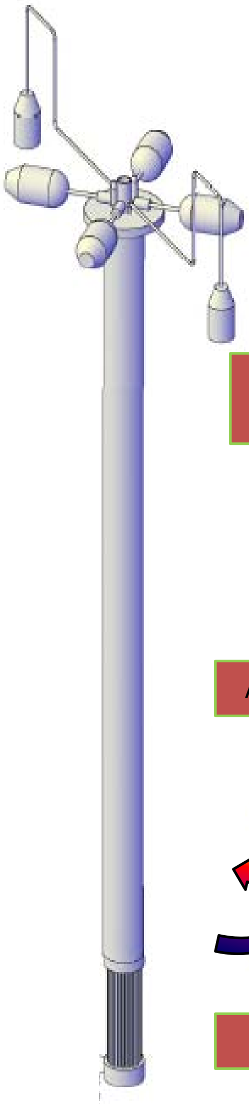


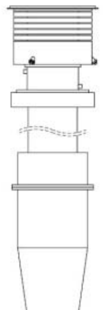




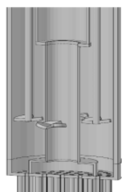
Mass-Parallel CFD (GPU) for **Beam-Target-Coupled**

Windowless Target Design for CIADS

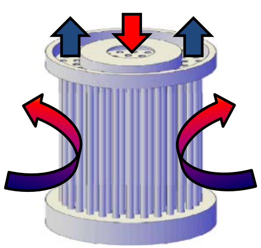




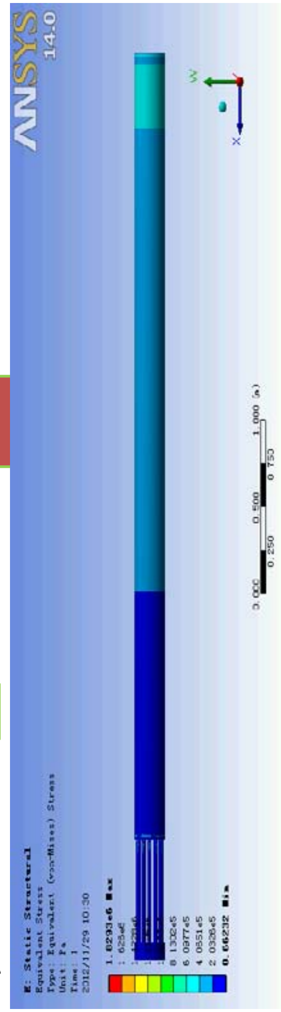
Beam coupling segment



Axial flow pump

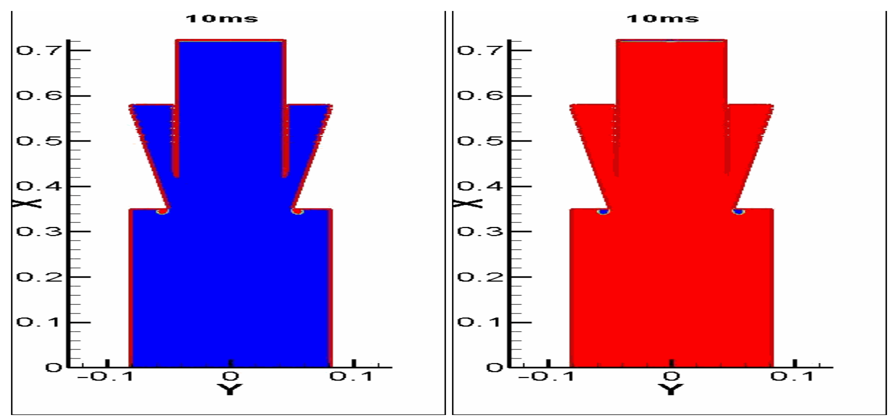


Heat Exchanger



Stress Distribution

Compacted Windowless Target	
Target Material	LBE
Structure Material	316L
Beam Pipe Diameter	20cm
Height of Target	500cm
Coupling Zone Outer Diameter	45cm
Coupling Zone Height	100cm
Proton Beam Energy	250MeV
Proton Beam Current	5mA



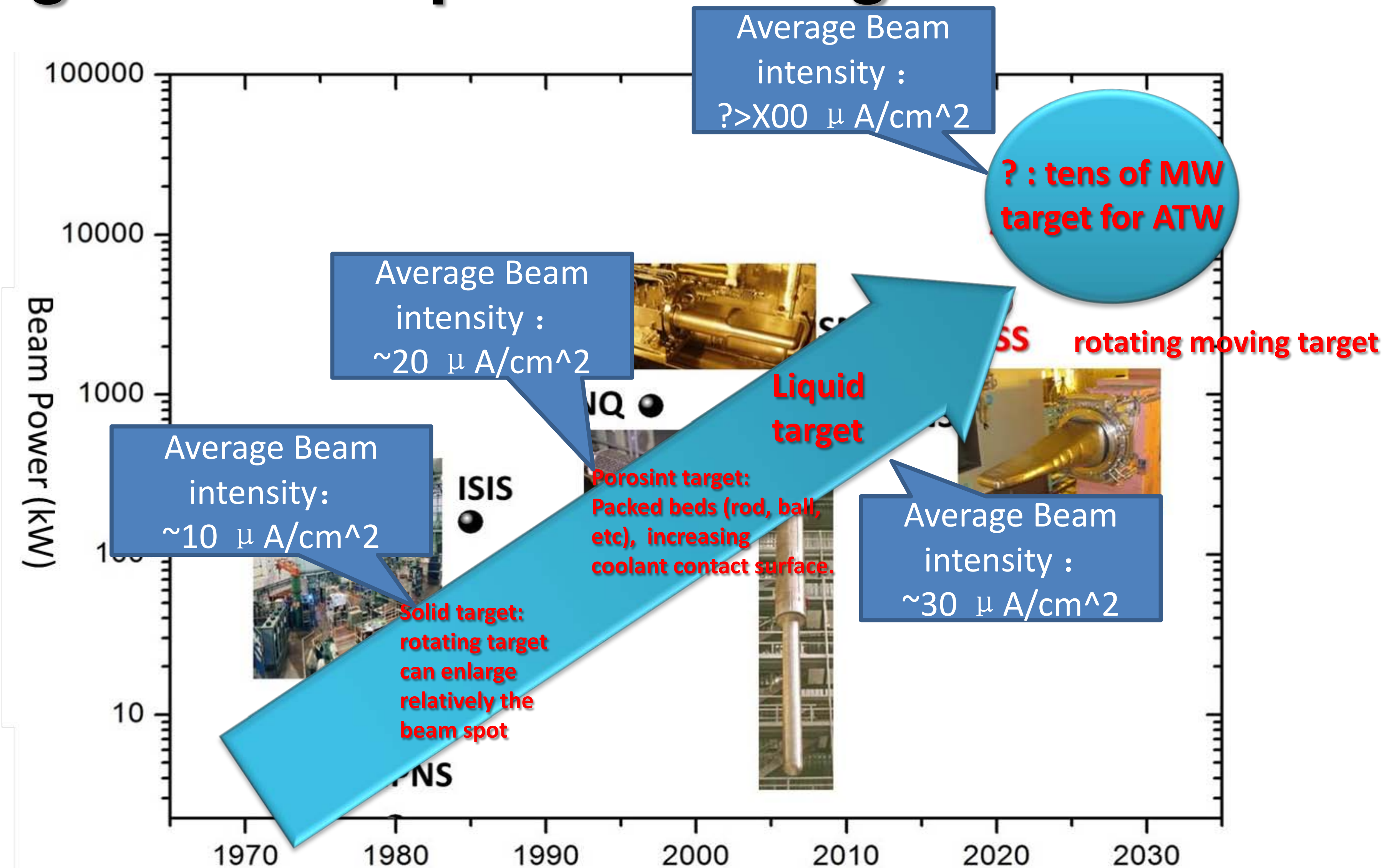
Rotation of liquid for stabilization of the free surface, but the hydrodynamic effects remain to deal with carefully.

3D coupled analysis: temperature, hydrodymics and structure

The system of LBE target will be complex; the challenges of techniques for LBE target.

- **Heat removal:** heat deposition in LBE would be limited
  - LBE's corrosion and erosion of material (now, temperature ~< 550C, velocity ~< 2m/s): The beam power will limited by different of temperature and flux of LBE, because of the corrosion and erosion of the structure material. Beam window material and structure will be a limitation for the beam power increase. **Oxygen control in an LBE environment**
  - Hydrodynamics: Cavitation, Shock waves, Splashing. For window target, the window structure will be damaged. For windowless target may increase beam power, but the system is not essential stable .
- **Radio-toxicity:** operation and decommission
  - Operation: the production of α-radioactive 210Po having 138 days half-life undergoes α-decay, 210Po is volatile, so that the leakage from the cover gas poses some hazard to operate.
  - Polonium release from LBE, To support safety analyses, measure Po release fractions from LBE as a function of LBE temperature and concentration of trace contaminants.
  - LBE cleanup chemistry. To limit corrosion of steels in contact with LBE, develop LBE cleanup chemistry techniques. Plate out of spallation products throughout the circulating LM system (piping, heat exchanger(s), filters) is likely with an LM target. The impact on personnel dose and ways to ensure RAMI (Reliability, Availability, Maintainability and Inspectability) and ways to mitigate adverse consequences should be explored.
  - Decommissioning: α -activity of the typical lead - bismuth coolant is defined by 210mBi (half-life = 3.6×106 years, 209Bi (n, γ) 210mBi) and β-activity of 208Bi (half-life = 3.65×105 y, 209Bi (n, 2n) 208Bi). Thus, the residual activity of lead-bismuth coolant is expected to be as high as millions of years. That purification of lead-bismuth from the long-lived radionuclides should be discussed.
- **Other problem:**
  - The intermediate circuit : In principle, lead-bismuth cooled system would not have to have an intermediate circuit separating the primary coolant and water/steam. However, there have been incidents with lead-bismuth cooled reactor.

High Power Spallation target

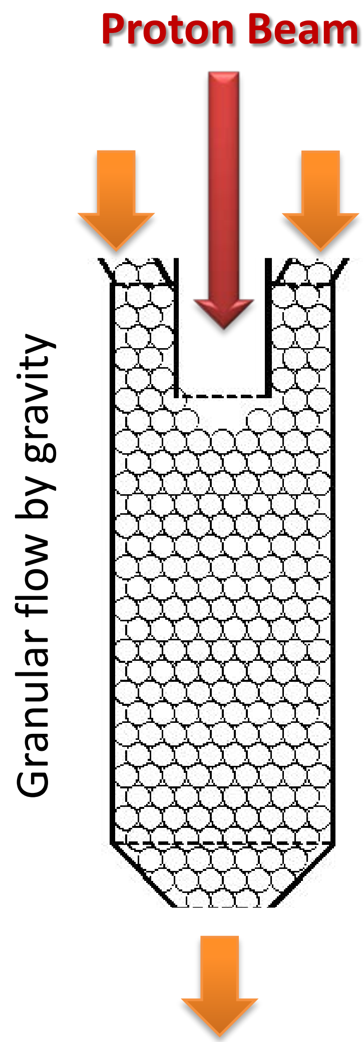


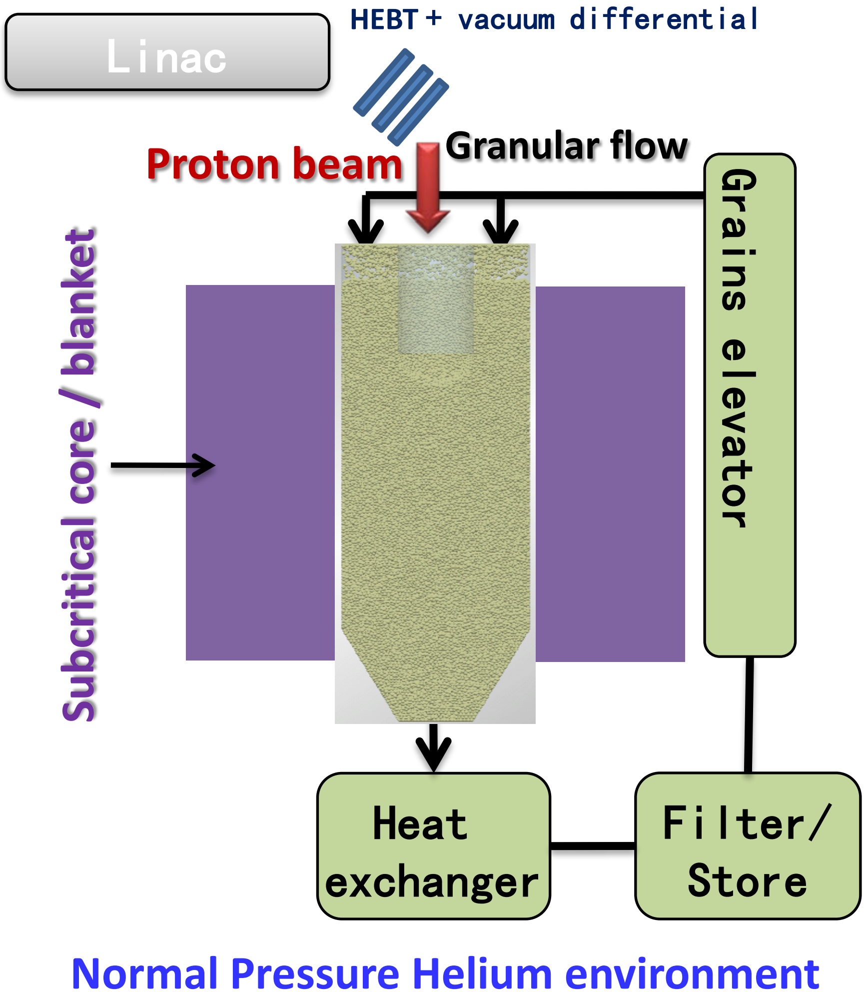
The windowless HML target is a candidate for the higher power target.

However, for heavy metal liquid, the **hydrodynamic effects** will be a limit for increase the power, such as, the shock wave, hydrodynamic instability, Cavitations and Splashing.

Granular target (windowless) system concept: Dense Granular flow target by gravity

Sand Clock: domed interior is sand sand bucket, sand and time is proportional to the amount of outflow relationship, based on the stock of sand and sand can know the time.



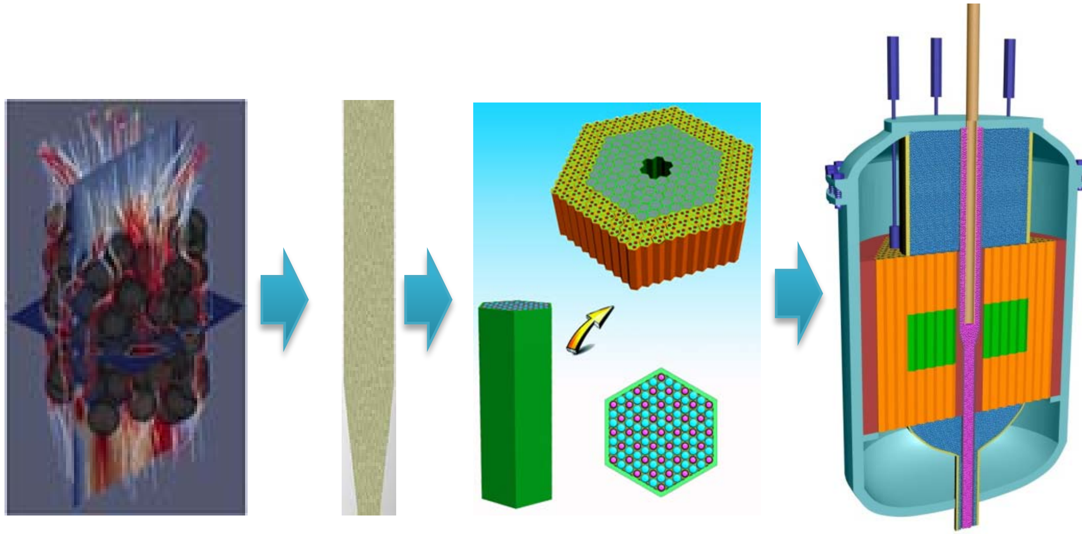


Challenges for Granular target

Time	
2013/4	PSI
2013/4	KIT/ESS
2013/7	International Workshop on “Accelerator Driven System with Thorium” /Korea
2013/10	PSI
2013/10	13th Thorium Energy Conference /CERN
2013/11	Argon
2013/11	MSU
2013/11	GA
2013/11	Berkley
2014/2	KTH
2014/3	KAERI

	Comments	Research
Principle feasibility	Blockage	Empirical regularity: more than 6 times the diameter can not plug, the current design is more than 20 times the diameter
	Hydraynamical stability	Empirical regularity: P = C, macro-scale micro-simulations and testing.
feasibility device	erosion	Wear test; design dust remove system
	Heat exchanger	Heat exchanger with jointly developed
	Dust effect (grains lift)	Small lift test
	Protype loop	Next month
	Beam coupled test	Next month
Operational reliability	Lifetime	Irradiation data to estimate tungsten carbide
	Operation complexity	preparing at the venue, permits, etc., for proton beam coupling

Mass parallel simulation method (GPU) for granular target



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

Coupled computations

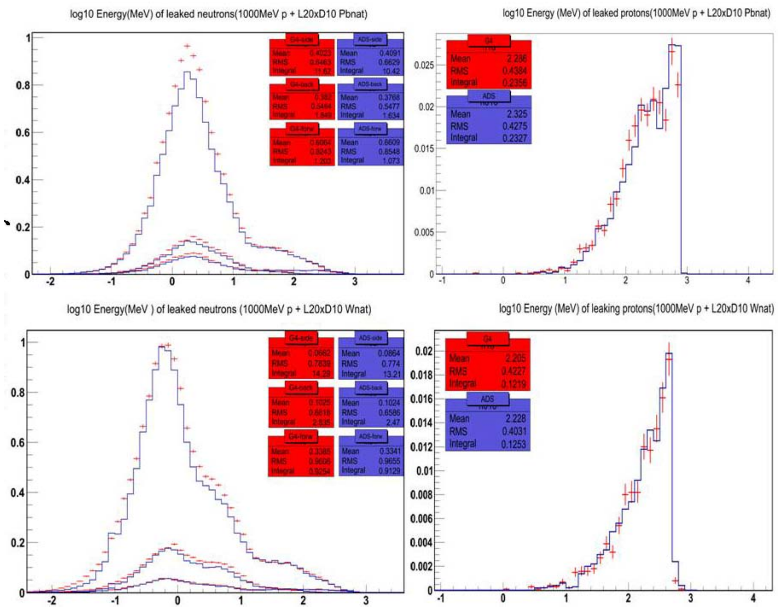
GPU hardware

250 S1070 GPUs
~300 Tflops(S)

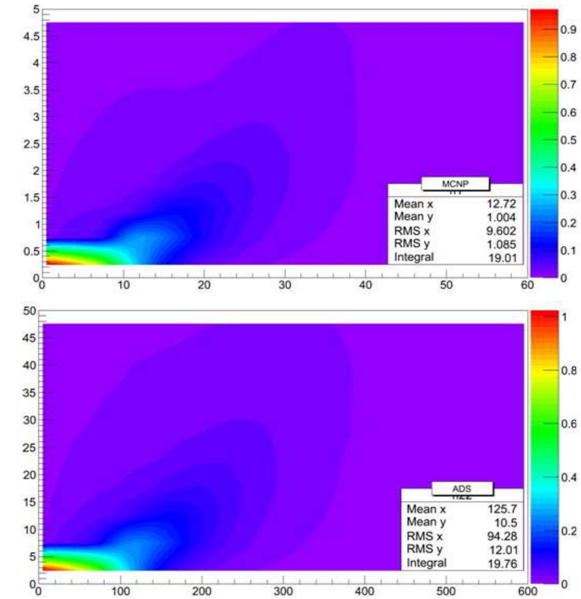
128 K20 GPUs
~150 Tflops(D)

2010/11: rank 1 in TOP500; Now rank 8.

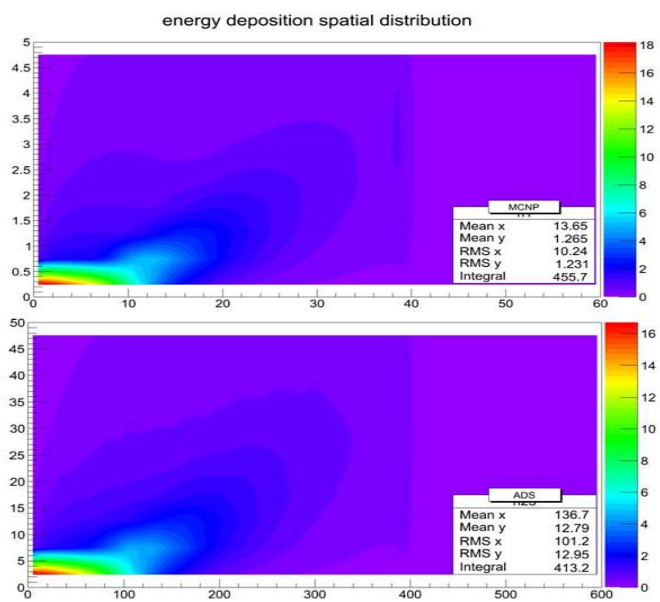
GPU MC Transport program(GMT)

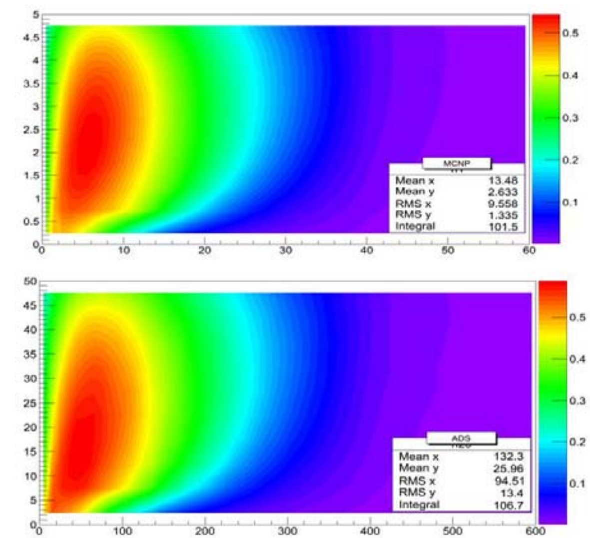


Leakage neutron spectrum for thick spallation target



Spatial distribution of Proton flux

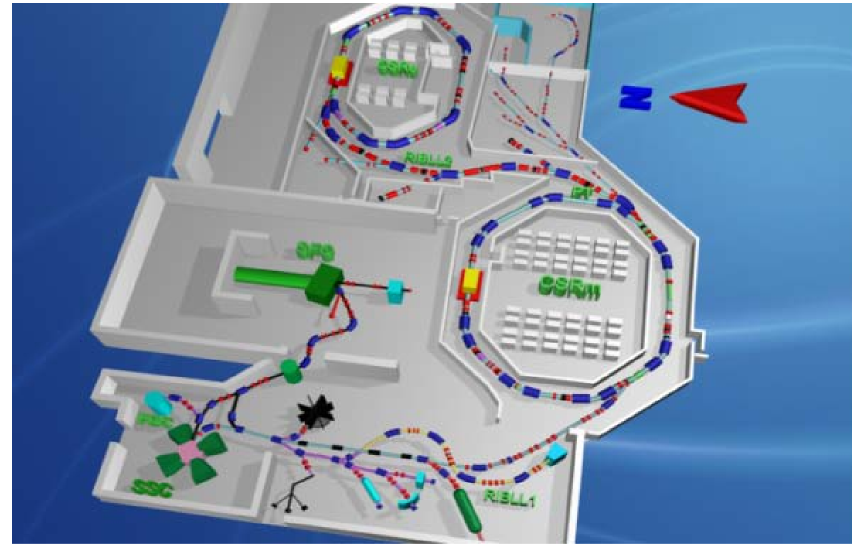




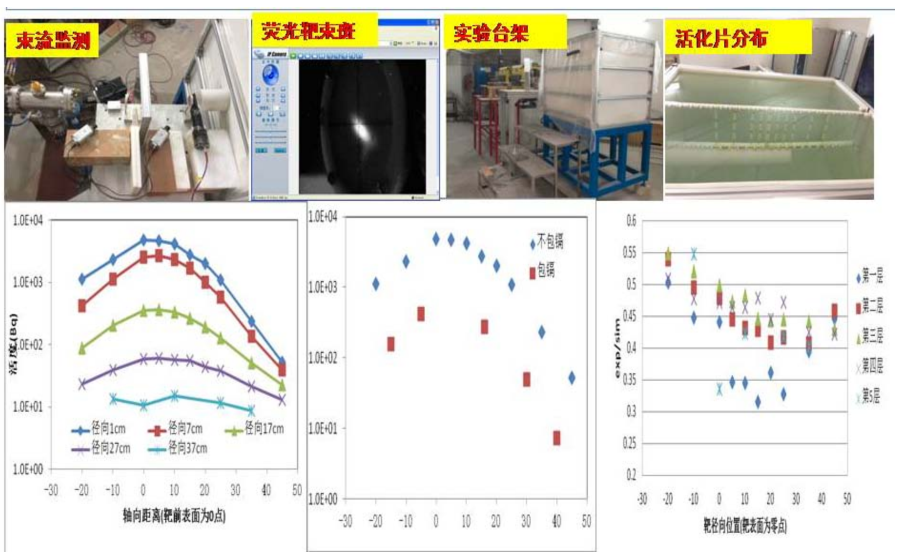
Spatial distribution of Neutron flux

GMT-verification

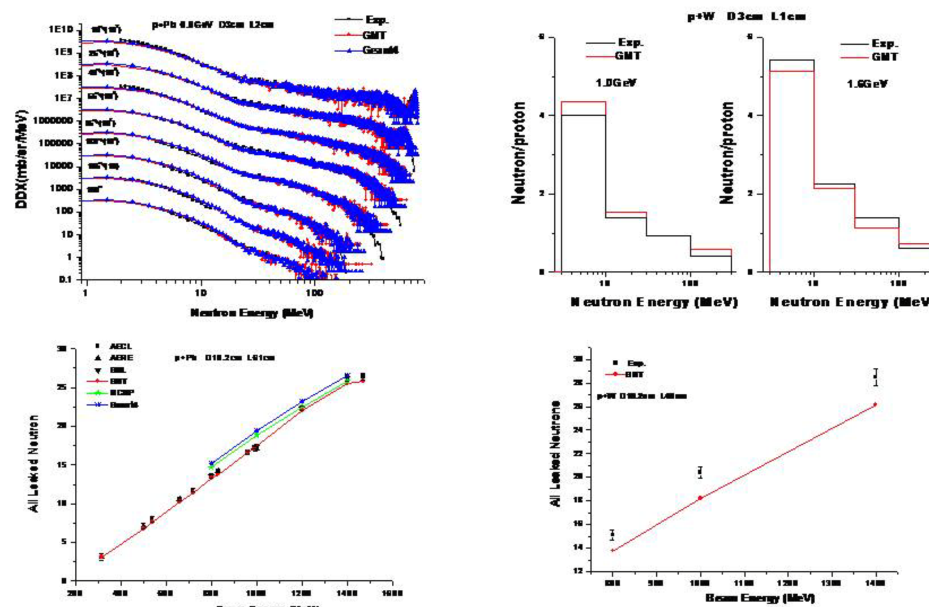
TOF device & Activation Measurement device



Proton Beam in IMPCAS: 10MeV~1.5GeV

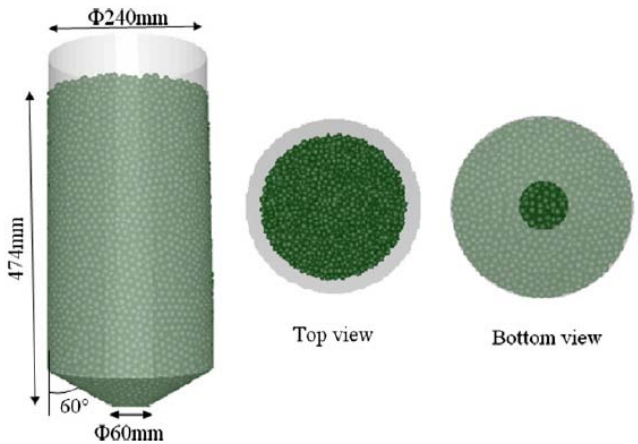


The calibration and verification for the measurements device

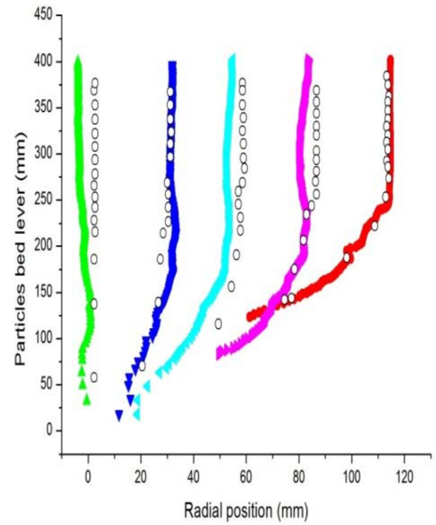


differential energy spectrum & integral yield

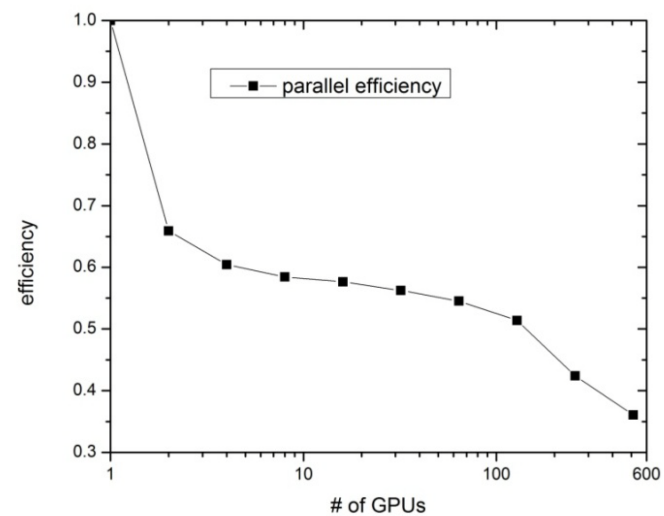
GPU method for granular flow

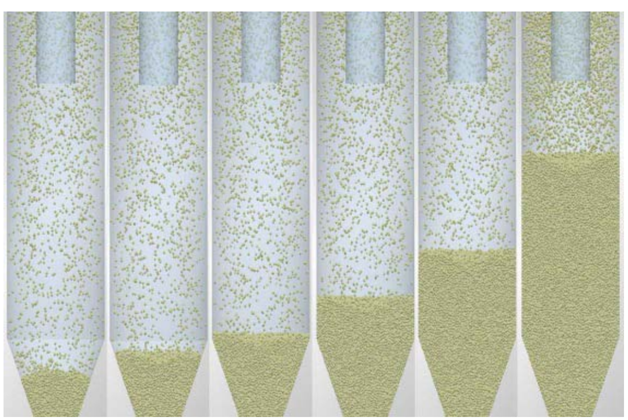


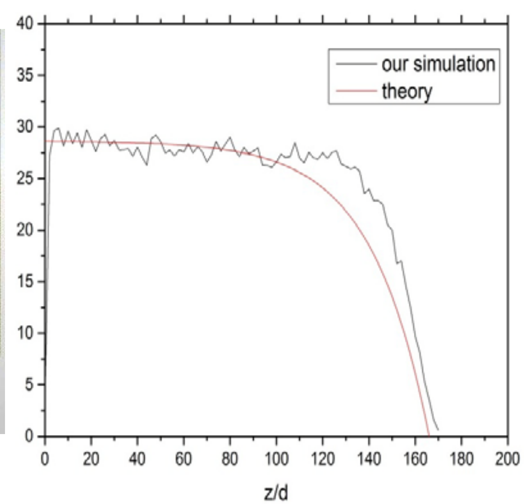
Granular flow in hopper



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

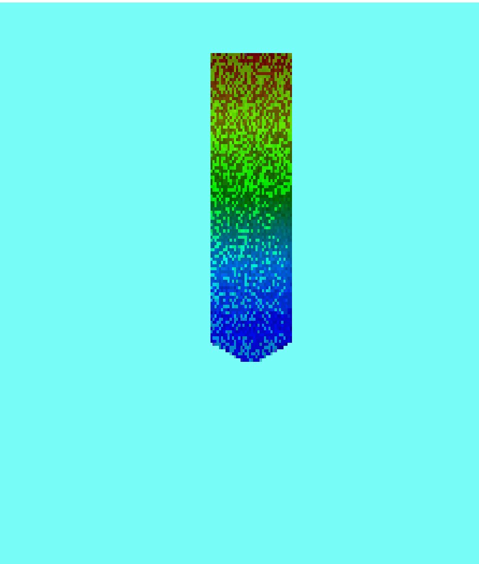


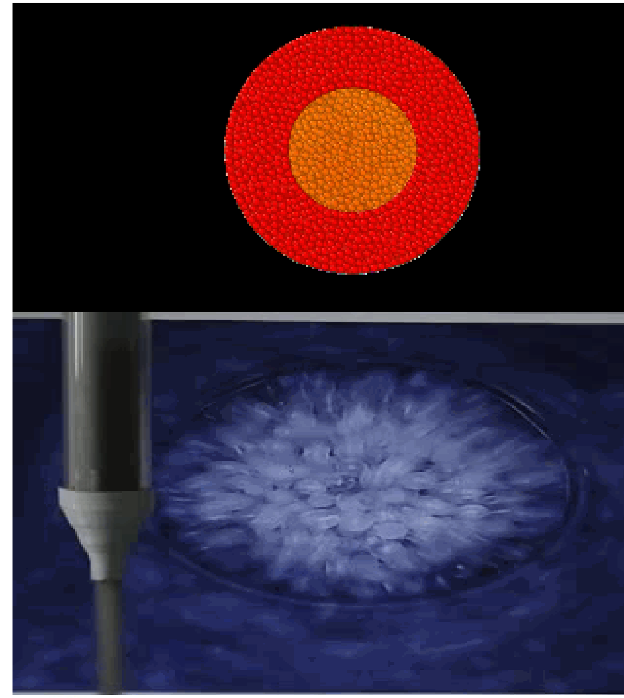


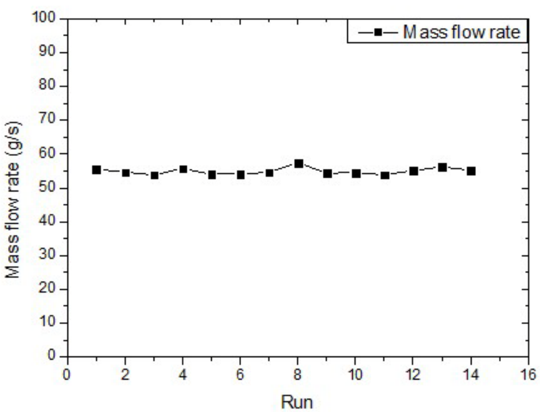


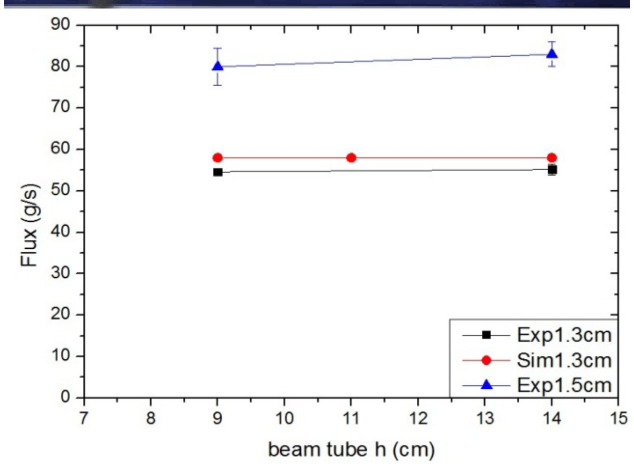
Micro simulation for Macro size

Physical principle experiments



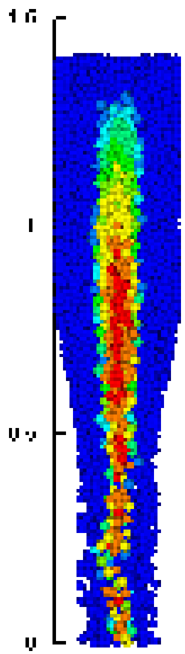




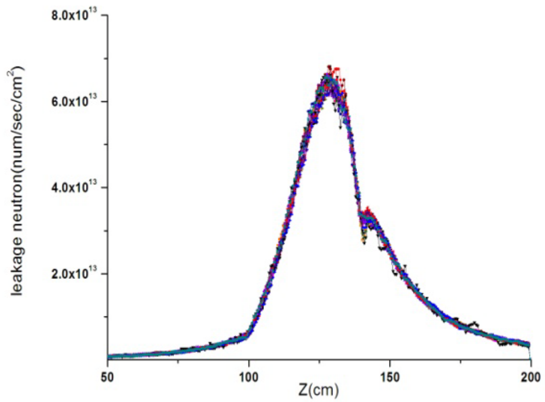


Granular target physical design & experiments

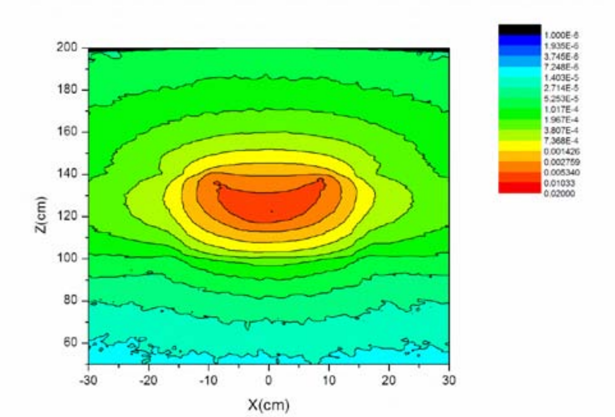
10MW=1GeV@10mA



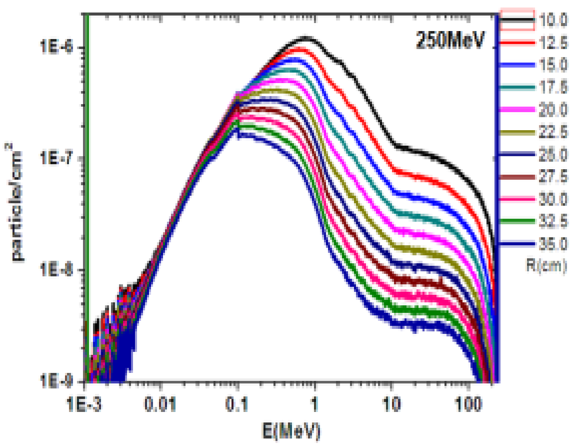
Mass parallel Simulation:
Contact mechanism + MD +
MC transport
Number of particles: 0.5 M



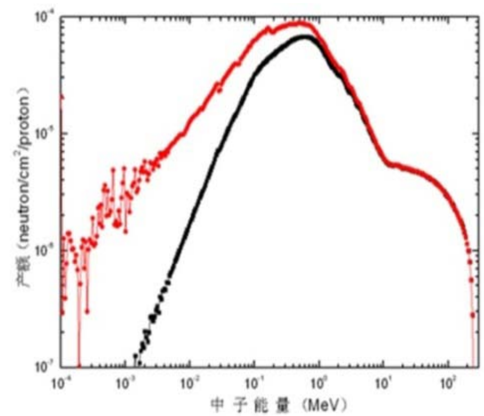
sidewall distribution at different times



Neutron flux distribution



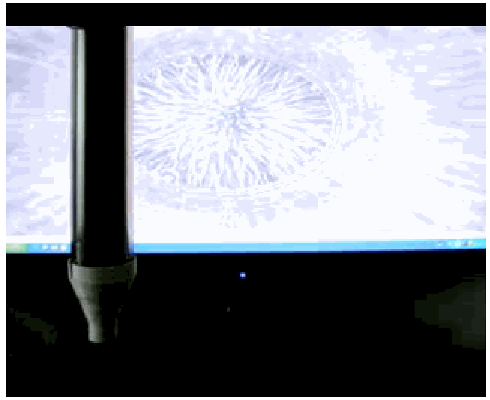
Sidewall leakage neutron spectrum

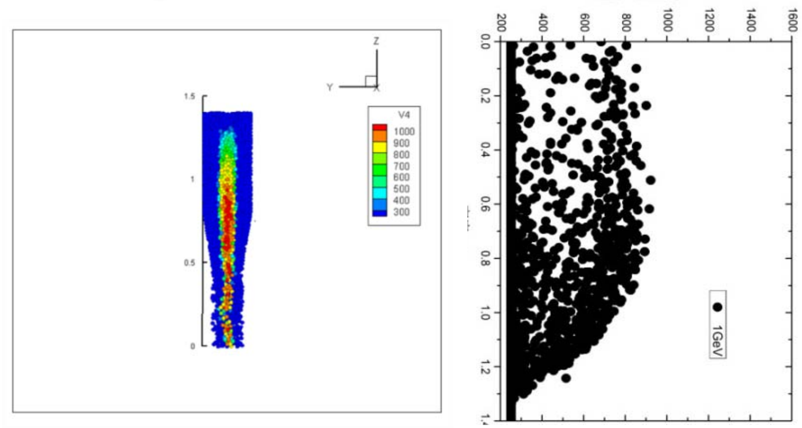


spectrum coupled reactor

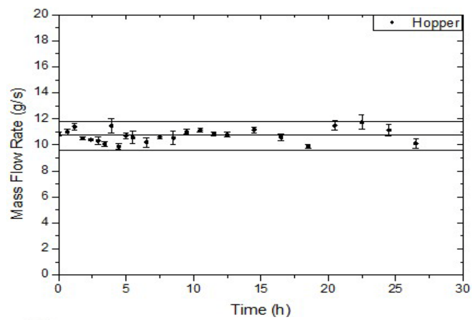
Granular target have chance to increase power and using for ADS.

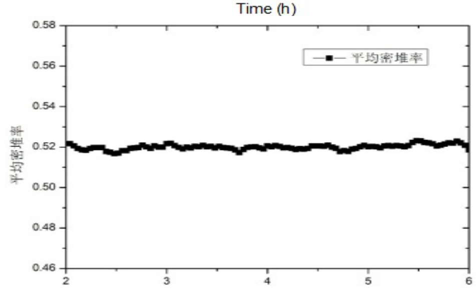
Granular target physical design & experiments



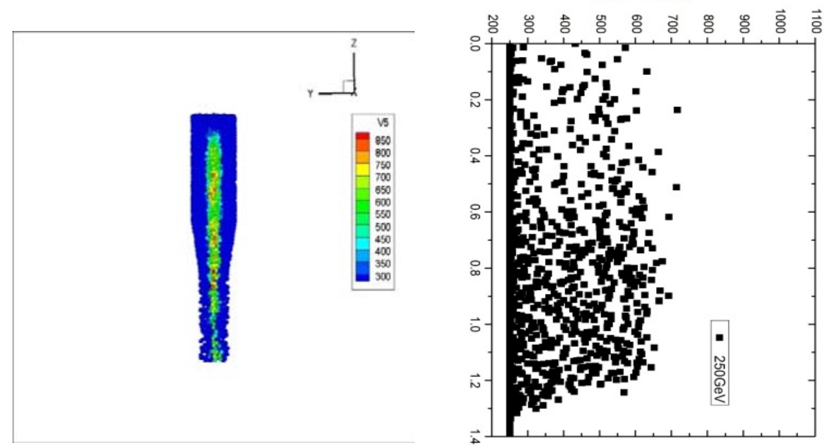


Temperature distribution (10MW=1GeV@10mA)





Fraction of volume vs. time



Temperature distribution (2.5MW=250MeV@10mA)

Preliminary calculations show: 2.5MW target, the average temperature is less than 550 degrees Celsius export particles, Fraction of volume is stable; 10MW target system, the average temperature is less than 650 degrees Celsius export particles.

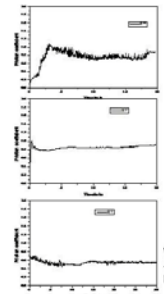
Tungsten grains erosion research

W

	RT	300℃	500℃	800℃	1000℃
min	30	30	20	20	20
Specific wear ratemm^3/Nm	-4.92E-5	-7.08E-5	-4.62E-6	-9.24E-6	+1.29E-4

SiC

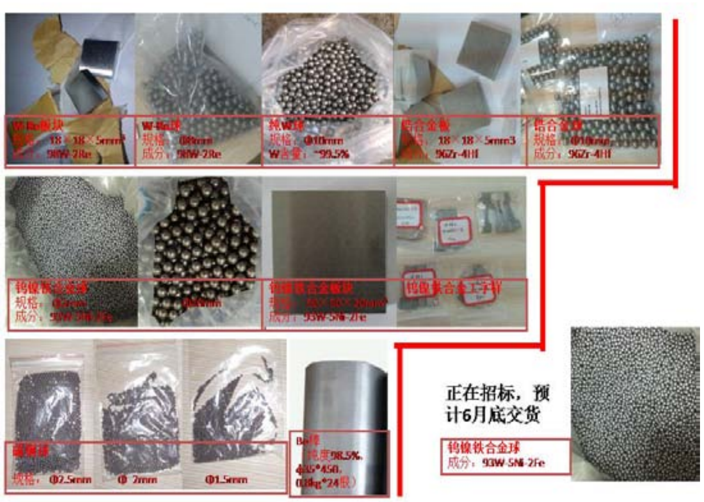
	RT	300℃	500℃	800℃	1000℃
min	30	20	20	20	20
Specific wear rate mm^3/Nm	-3.56E-7	-2.41E-6	-1.56E-6	-9.63E-7	

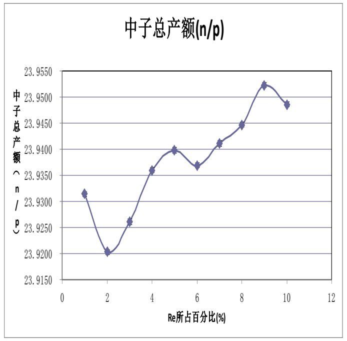


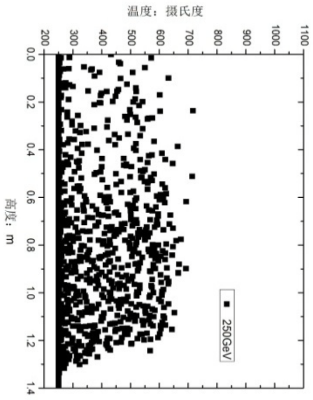
实验条件：速度 0.2m/s；载荷 5N；温度：RT，300-1000℃

	对磨材质	RT	300	500	800	1000
WNiFe合金球 比磨损率mm³/Nm	铜块	-4.62E-6	-4.62E-6	-4.62E-6	4.62E-6	6.47E-5
	SiC	-4.62E-6	-6.47E-5	-3.78E-5	-3.78E-5	
	Ti_3SiC_2	-4.92E-5	-7.08E-5	-4.62E-6	-9.24E-6	+1.29E-4
WRe合金球 比磨损率mm³/Nm	W-Re	-7.39919E-5	-1.8498E-4	-0.00252	-4.62449E-6	4.62449E-6
	铜块	-1.38735E-5	-9.24898E-6	-2.31225E-5	8.32408E-5	2.08102E-4
	SiC	-4.62449E-6	-9.24898E-5	-6.93674E-5	-9.24898E-6	-5.54939E-5
	Ti_3SiC_2	-4.16204E-5	-9.24898E-6	1.38735E-5	1.8498E-5	1.38735E-5

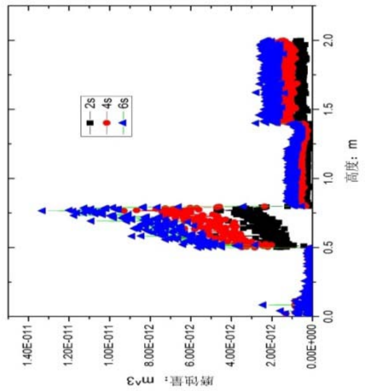
In the RT-1000 ℃ temperature range, W granular, polycrystalline sintered SiC is excellent in wear resistance, wear amount of <1mm.





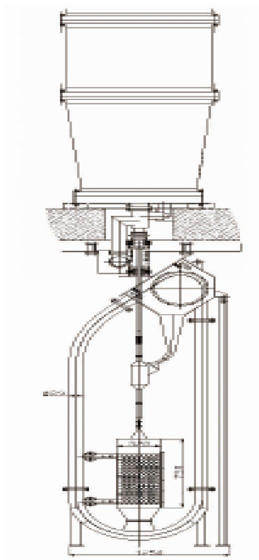


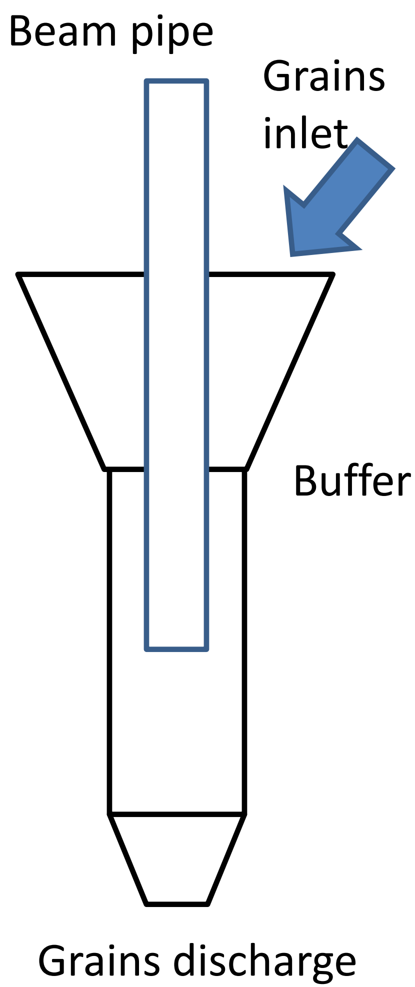
Temperature distribution (2.5MW=250MeV@10mA)

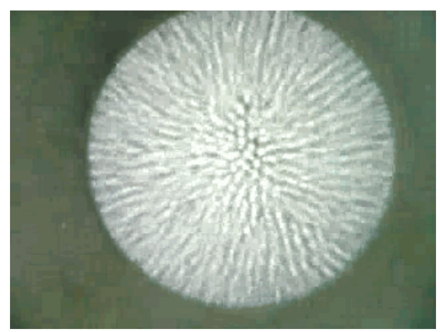


Maximum erosion estimation distribution

Granular electron beam coupled test



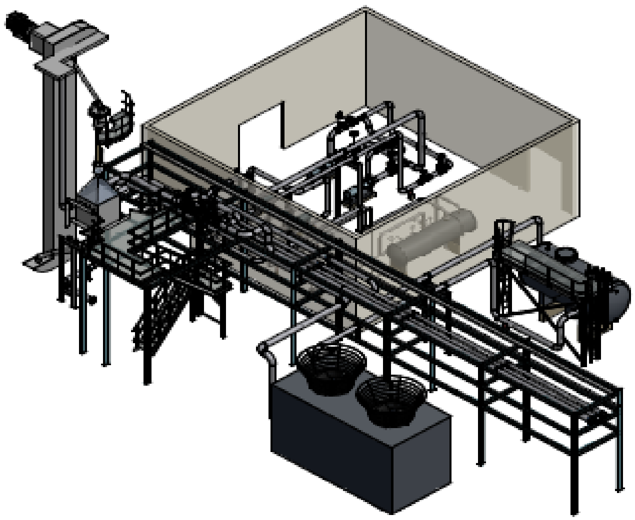




parameters
Electron beam ~2MeV@10mA
Heat exchanger ~25kW
Grains Left ~1.5kg/s
Helium pressure ~1ATM

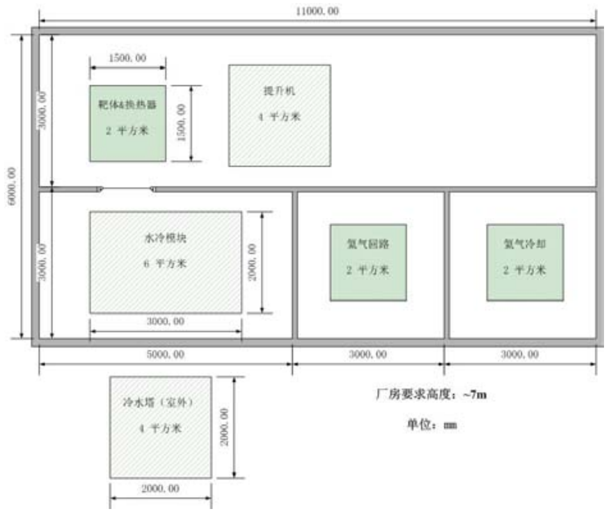
Power of deposition energy density will same as ADS target from 2.5MW to XX MW

Full scale Granular target test loop



Granular heat exchanger

Countercurrent water corrugated plate heat exchanger to be cooled beryllium 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.



Grains elevator

NE series hoist suitable for conveying the powder, granular and small block of non-abrasive and abrasive materials small,. because the traction hoist is a ring chain, thus allowing delivery of high temperature materials. General transport height up to 40 meters, TG type up to 80 meters。

Granular engineering has mature technology,

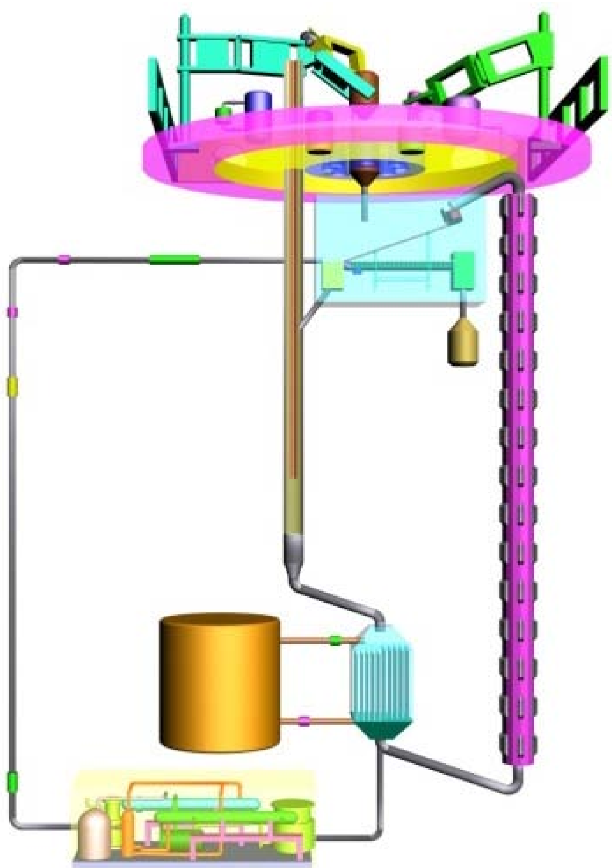
Annual production value > 100 billion $, including: Mining; chemical; food; Drug; etc.

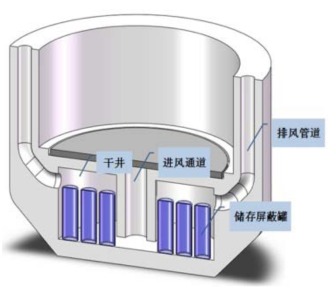
Potential advantages of the dense granular target by gravity driven	
Heat removal	off line disposal
Hydrodynamic stability	P=ro g h liquid; fluidized bed P=C dense granular flow
Hydrodynamic effect	No Splashing; No Cavitations
Shock waves	Stress waves no easy to spread
Lifetime	Average radiation damage could small; Replenishable
Volume fraction	2 times compare with fluidized bed Intermediate fluid pressure is low
Benefits by particles Selected	High neutron yield & low radio-toxicity
	Thermal properties: high capacity & conductivity for potential for higher temperature different
	Chemistry: low chemical toxicity & low corrosion
System Architecture & Engineering Fundamentals	Simple; Granular engineering has mature technology in the chemical, material and food processing industries. Such experience can be exploited with the design of various components in the development of a complete target system.
Interface with accelerator	Windowless; normal pressure environment

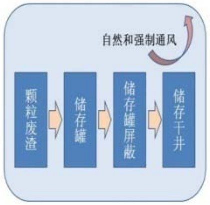
Research for the next step

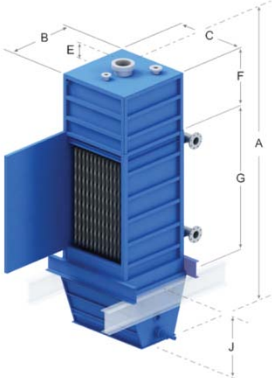
Principle feasibility	Blockage	Empirical regularity: more than 6 times the diameter can not plug, the current design is more than 20 times the diameter	ok
	Hydraynamical stability	Empirical regularity: P = C, macro-scale micro-simulations and testing.	ok
feasibility device	erosion	Wear test; design dust remove system	ok …
	Heat exchanger	Heat exchanger with jointly developed	ok
	Dust effect (grain lift)	Small lift test	ok …
	Protype loop	Next month	…
	Beam coupled test	Next month	…
Operational reliability	Lifetime	Irradiation data to estimate tungsten/SiC/WC	…
	Operation complexity	preparing at the venue, permits, etc., for proton beam coupling	?

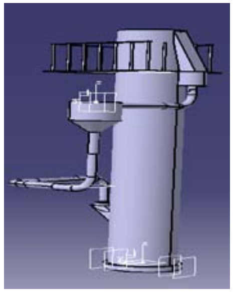
Granular target concept design for CIADS

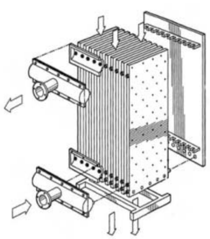


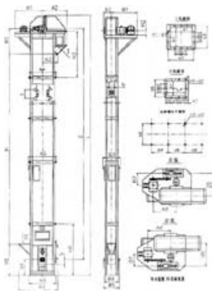


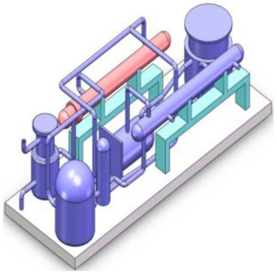


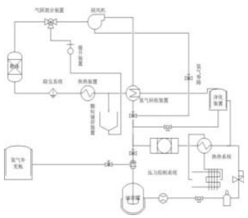












parameters	
Granular material	Tungsten/Tungsten alloy
Structure material	Tungsten alloy/SiC
Granular size	~5mm
Inlet temperature	~250 C
MAX Outlet temperature	~650 C
Proton beam	250eV@10mA=2.5MW
Intensity of beam	>100 μA/cm^2
Diameter of beam spot	~10cm
Average velocity of granular flow	~0.5m/s

*International patent

Thank you！