Current Status of CADS:

New kind of the coolant for subcritical core and the target research

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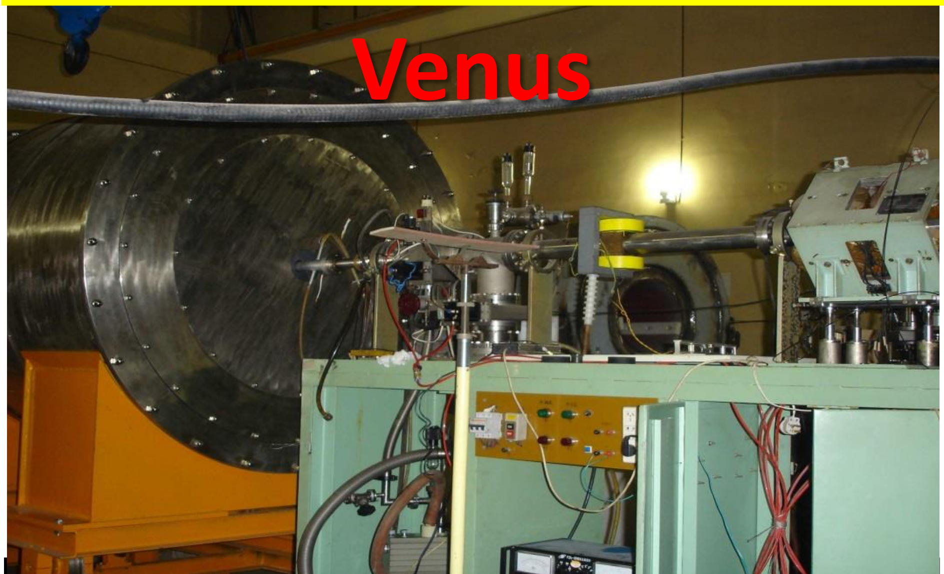
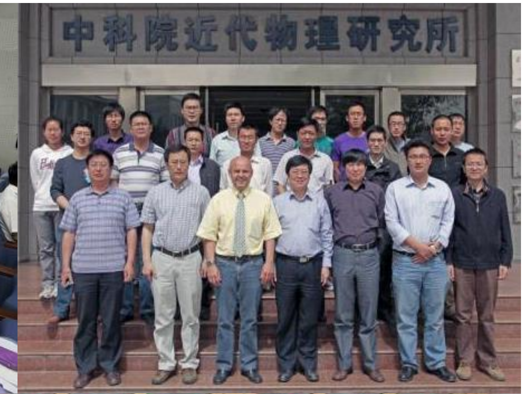
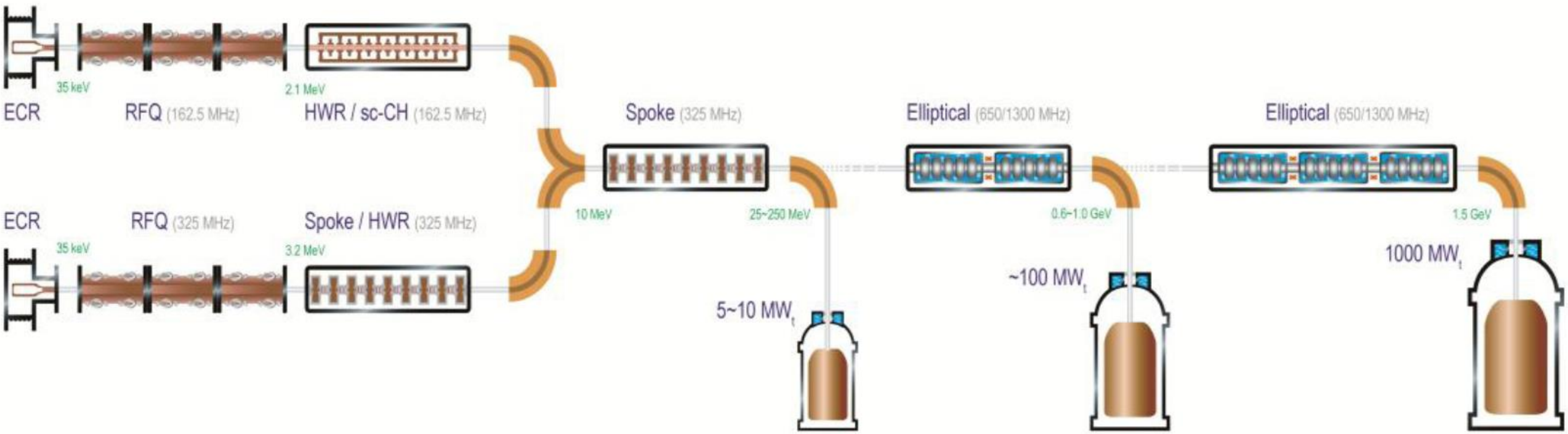


2 R&D projects of 973
2000—2010 CIAE,CAS



Chinese ADS roadmap

2010 **2016** **2022**



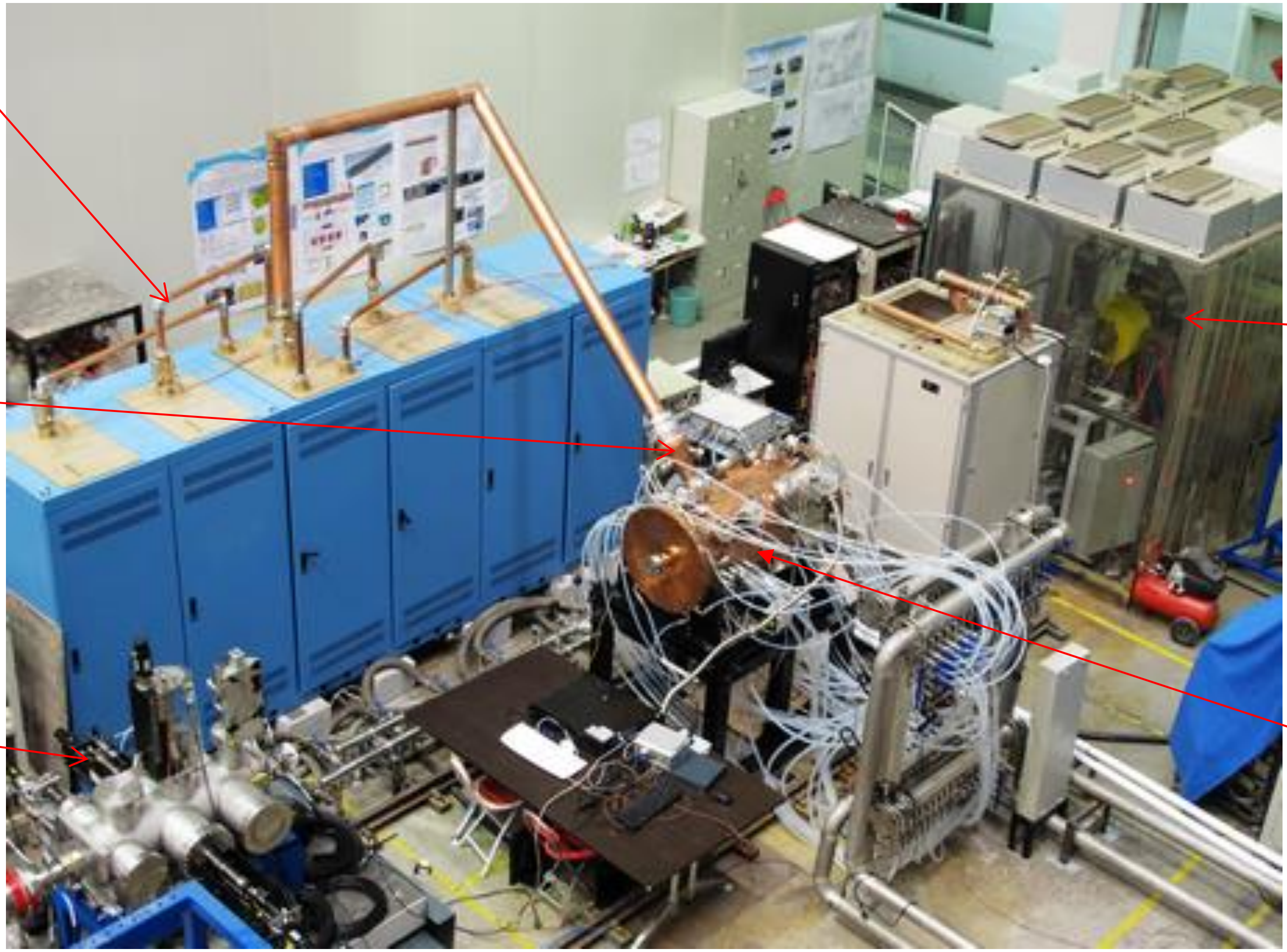
CIADS: INITIAL FACILITY

250MeV@10mA
5-10MW

RESEARCH FACILITY

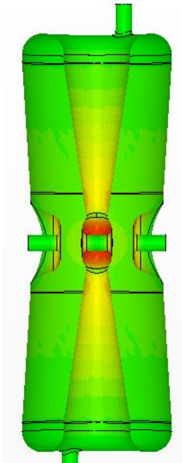
DEMO FACILITY

Example: Injector II



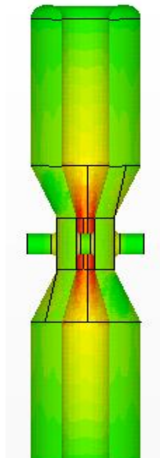
Prototype of proton accelerator test (ECR+LEBT+RFQ) for CADS

Example: HWR Superconducting cavity



S-HWR

Electromagnetic field contours



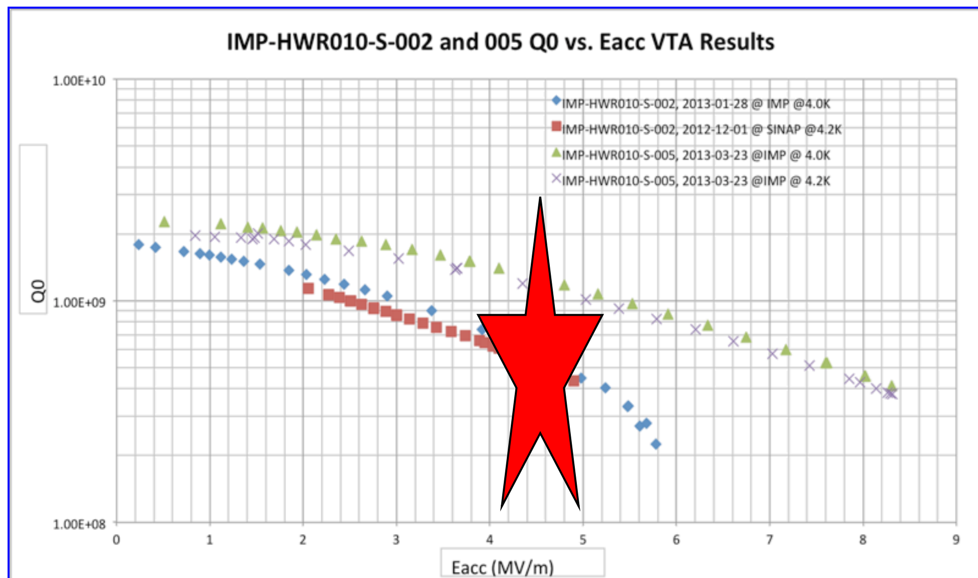
T-HWR

Electromagnetic field contours

Superconducting cavity parameters

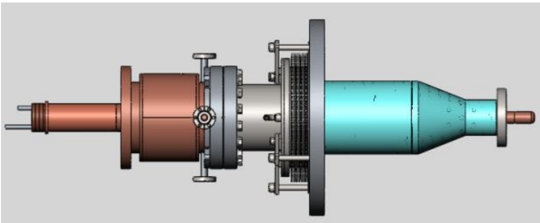
f(MHz)	162.5	162.5
β	0.09	0.15
Epk/Eacc	5.96	4.8
Bpk/Eacc	12.18	6.1
G=Rs×Q0(Ω)	32.31	51.7
R/Q0	134.99	286.67
Q0(4.4K, Rs=71.4nΩ)	4.52E8	7.25E8
Uacc(MV)	0.75	1.83
Epeak(MV/m)	**27**	**32**
Bpeak(mT)	**55**	**40.5**
Pdiss(W) (4.4K, Rs=71.4nΩ)	9.2	16.2

Freq./MHz	Uacc. Max /MV	Emax /MV/m	Bmax /mT	R/Q /Ω
162.5	0.78	25	50	148

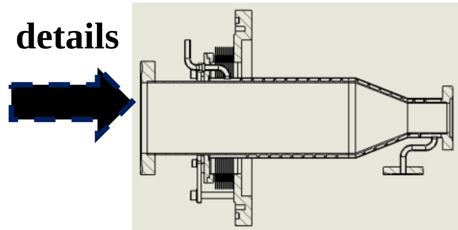


Vertical measurement results

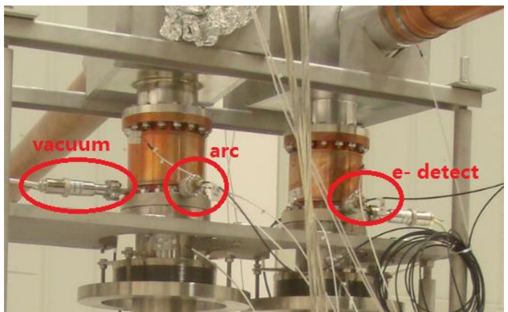
Exmaple: HWR Coupler and high power testing



details



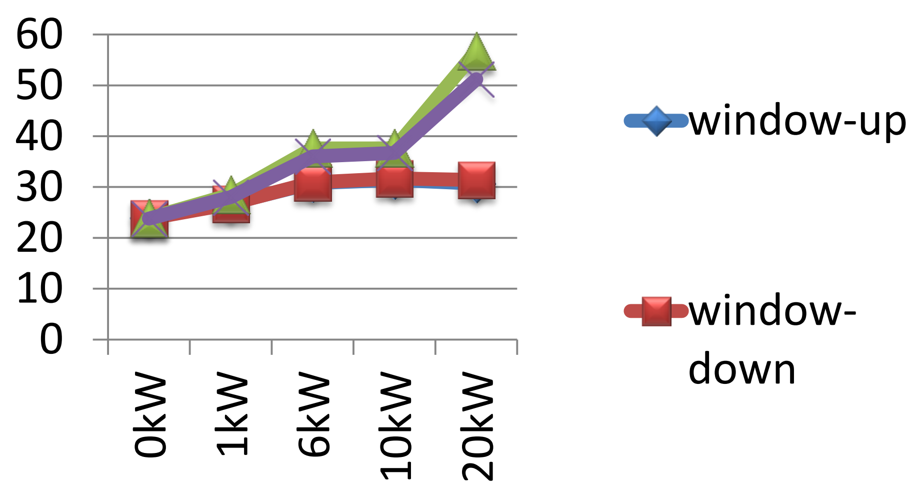
The outer conductor was designed to be cooled by helium gas through the spiral grooves around the outer surface while the inner conductor was cooled by water.



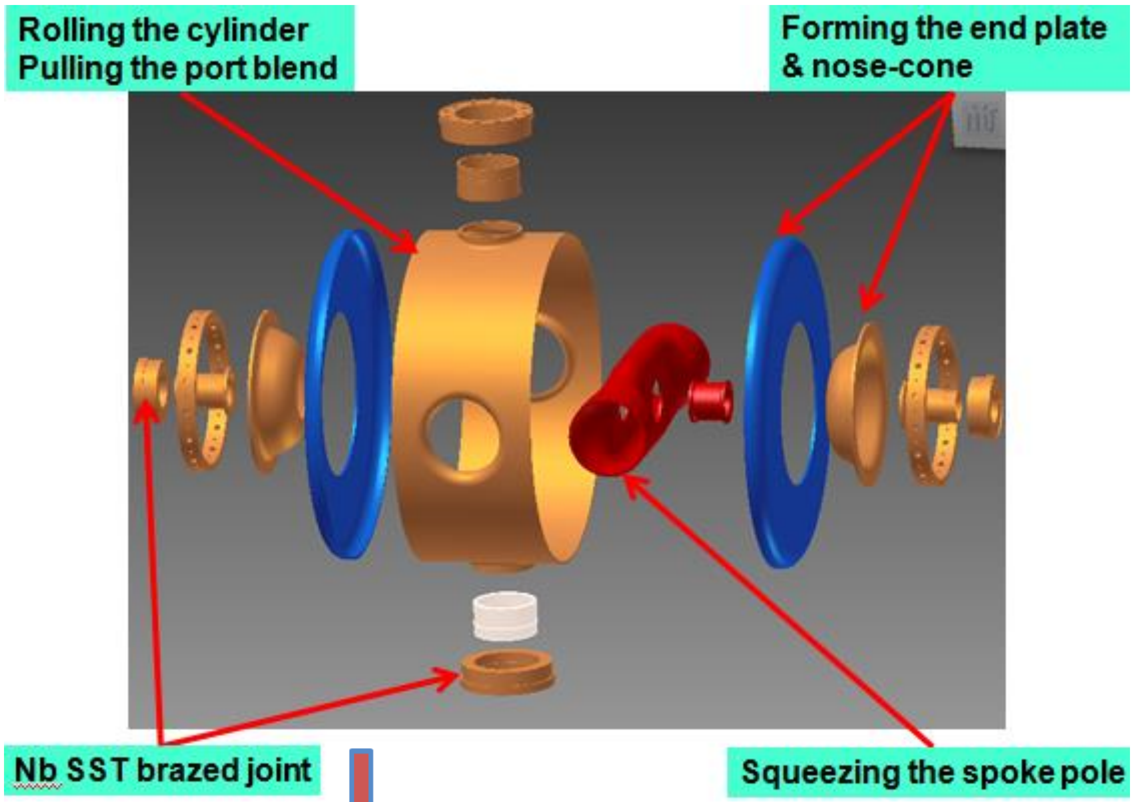
The coupler has passed a RF power of 20kW in continuous travelling wave mode limited by the RF source available.

Spiral grooves

Date	Start time	Stop time	Pf1 max	Elapsed time/hrs
2013-6-1	13:50	20:00	~212W	5.3 hrs
2013-6-2	9:25	16:30	~738W	7 hrs
2013-6-3	9:10	17:17	~Peak 1.3kW	6 hrs
2013-6-4	9:55	23:47	~2.90kW	12.3hrs
2013-6-5	9:10	22:32	~5kW	12 hrs
2013-6-6	9:13	21:56	~9.42kW	8 hrs
2013-6-7	9:07	20:50	~10.6kW	10hrs
2013-6-8	9:13	18:00	~20.0kW	8.6 hrs
Total conditioning time : 63~69 hrs				

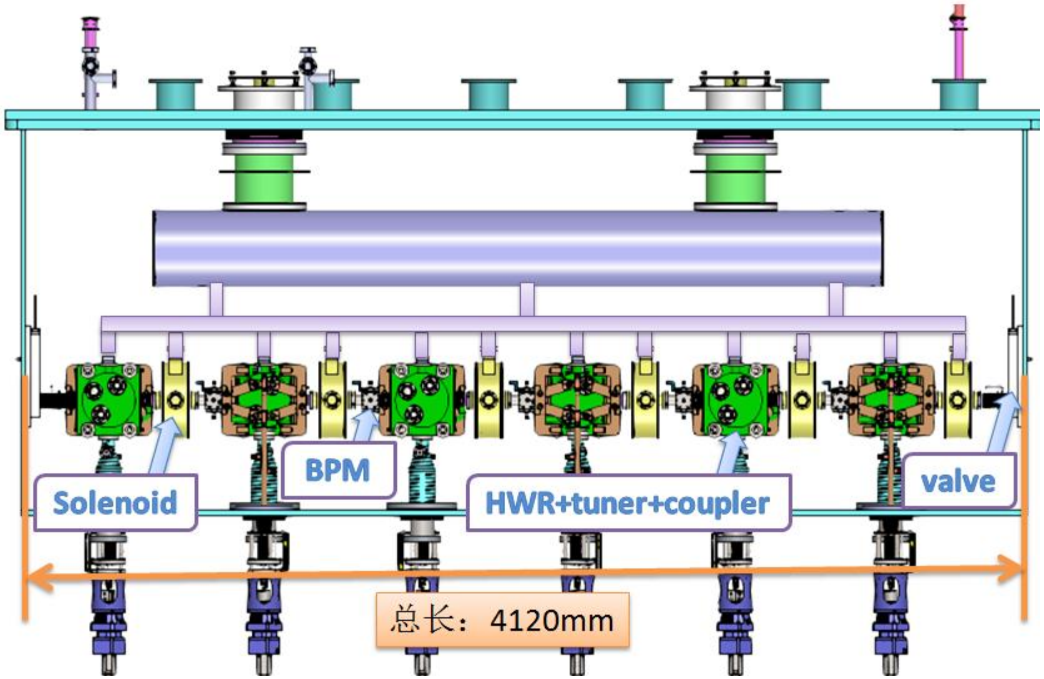


Example: Fabrication of Spoke Cavity

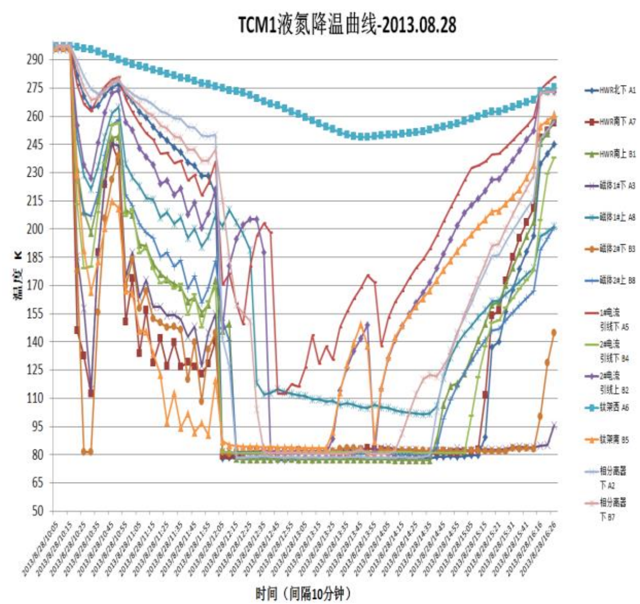


Ready for VT.

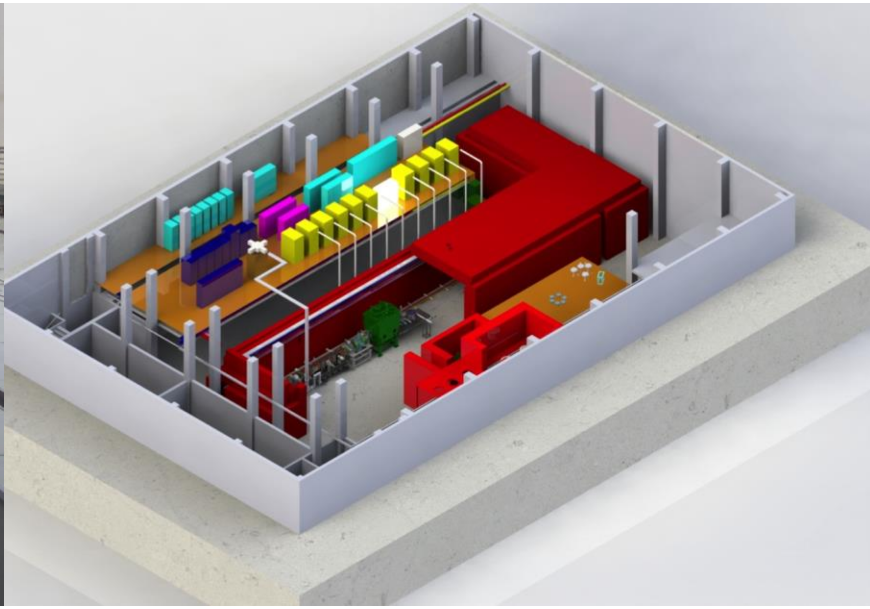
Example: Cryomodules design and test

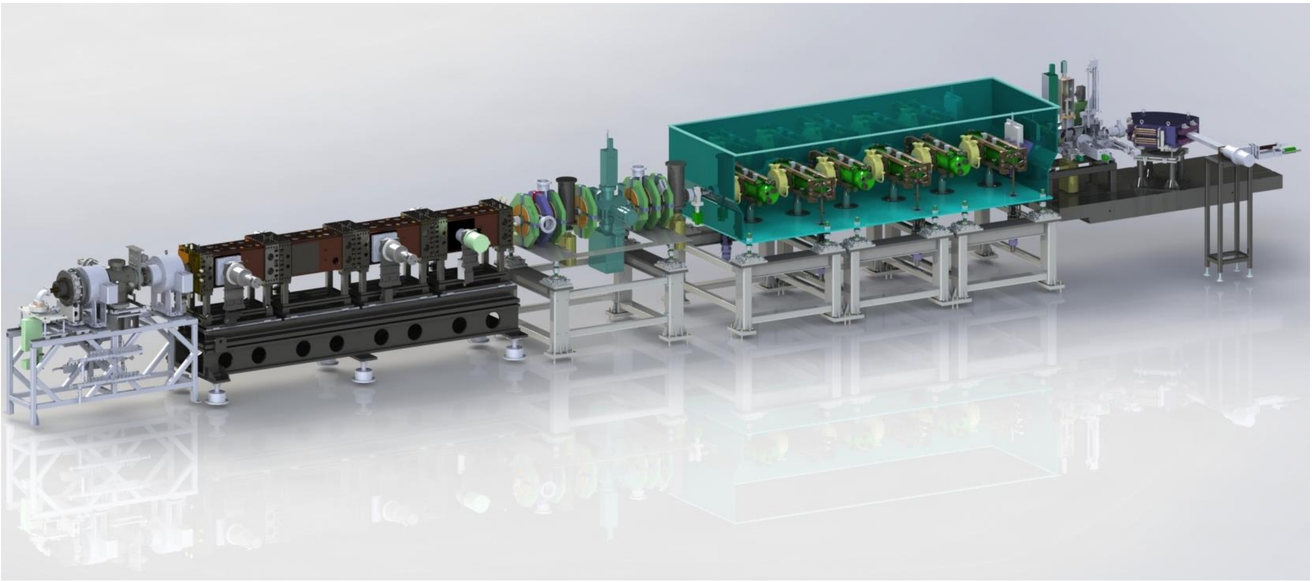


Design parameters	
frequency (MHz)	162.5
intensity (mA)	10
Input energy (MeV)	3
Output energy (MeV)	6
S-HWR number	6
HWR Heat Leakage (W)	10
Coupler cooled load (g/s)	0.024



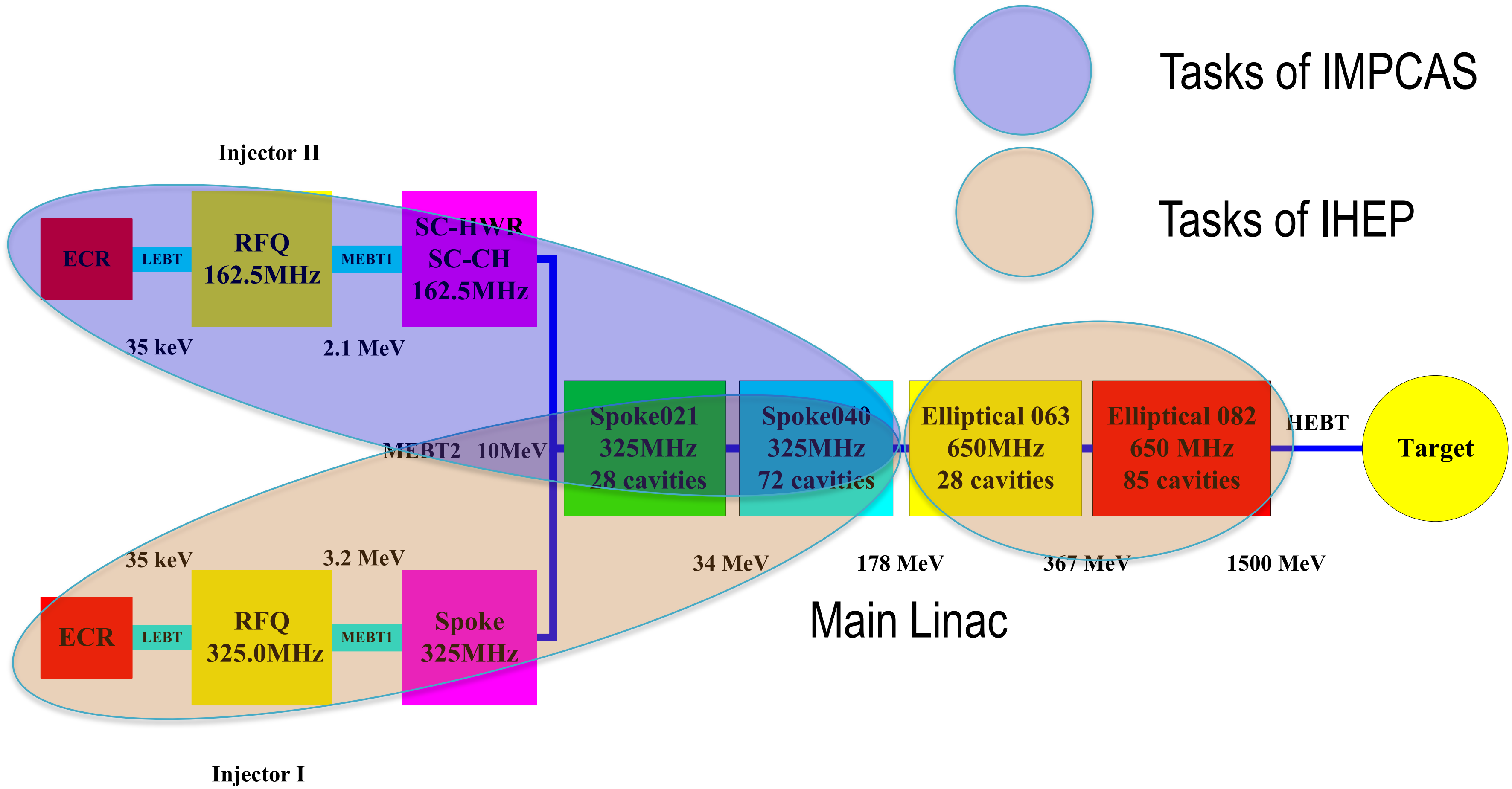
Example: Commissioning of injector II





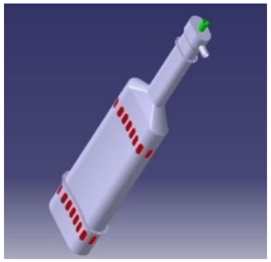
2014-2015： ECRIS+LEBT+RFQ+MEBT+CM6

Layout of Accelerator for CADS

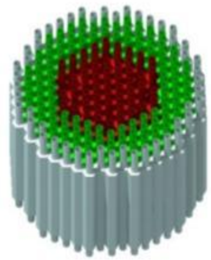


IHEP and IMPCAS co-work on the accelerator. Final project has two identical injectors. Two designs of injector is due to technical uncertainty at very low energy segment.

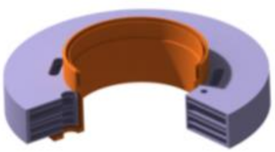
LBE reactor design



heat exchanger

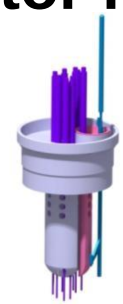


core arrangement



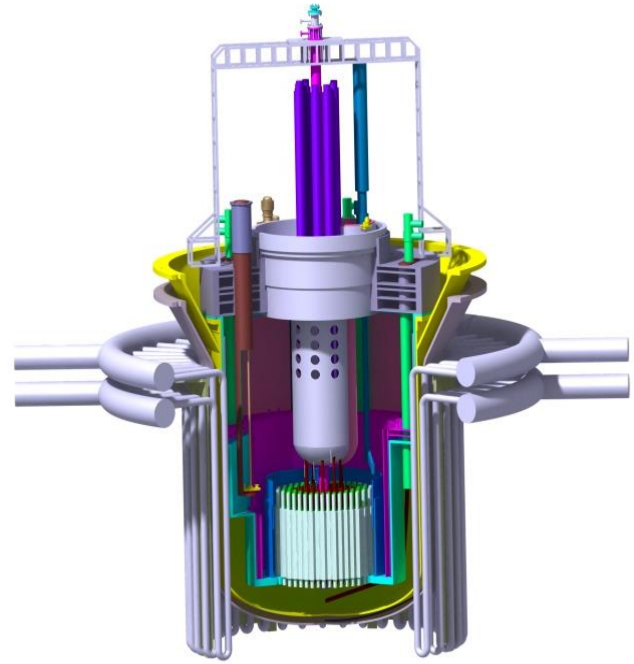
reactor roof

pressure vessel



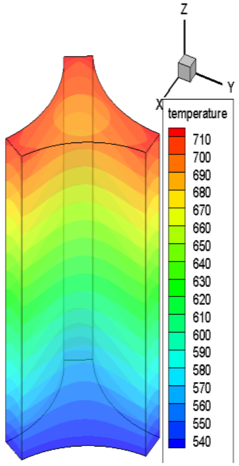
refueling system

reactor components

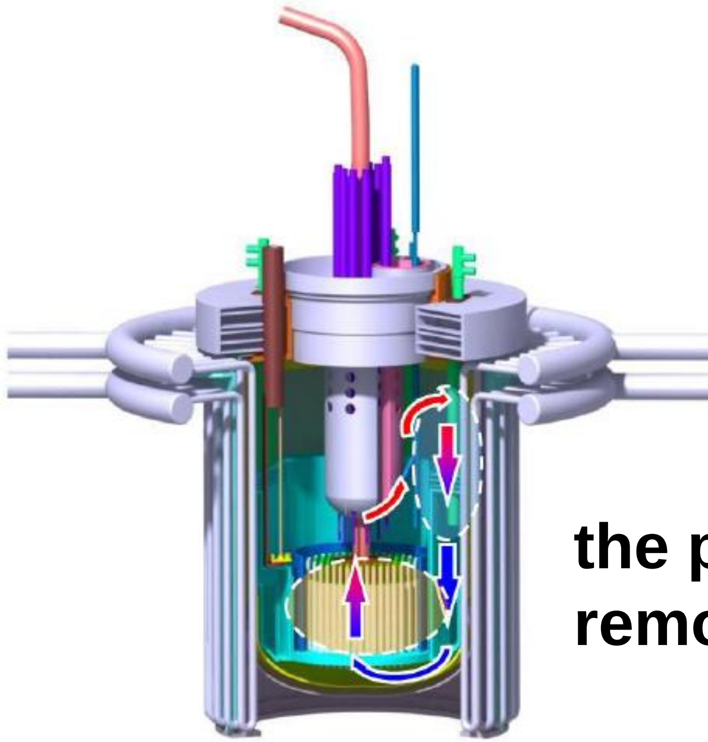


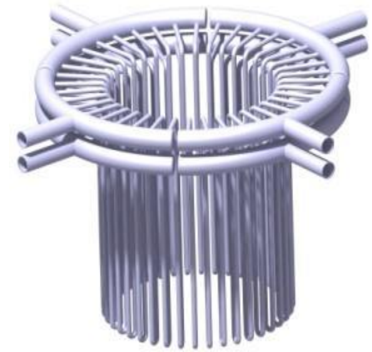
parameters		
core barrel		
diameter	m	4.38
height	m	6.4
reactor vessel		
diameter	m	4.72
height	m	7.22
reactor roof		
outer diameter	m	4.4
Inter diameter	m	2.88

Thermal-hydraulic: heat removal

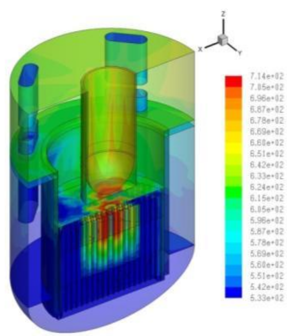


CFD simulation results coolant channel



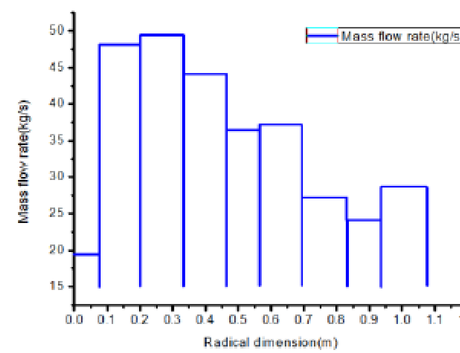


the passive residual heat removal (PRHR) system

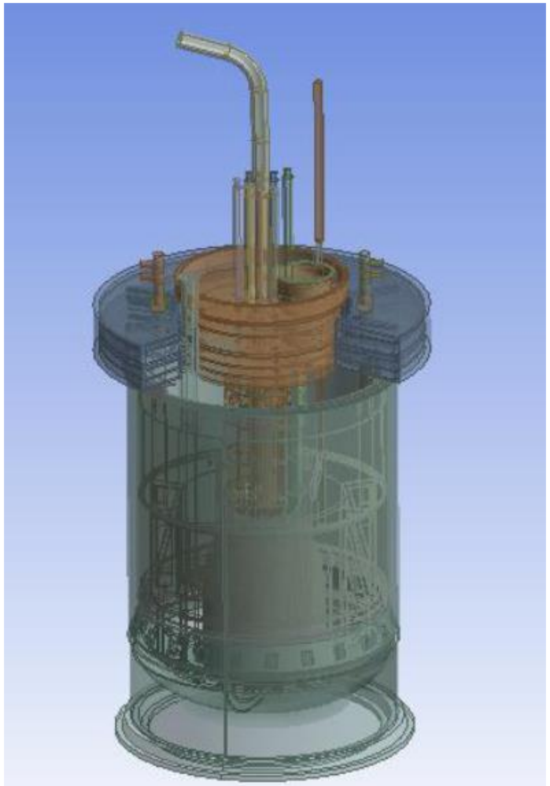


CFD Simulation of a natural circulation loop

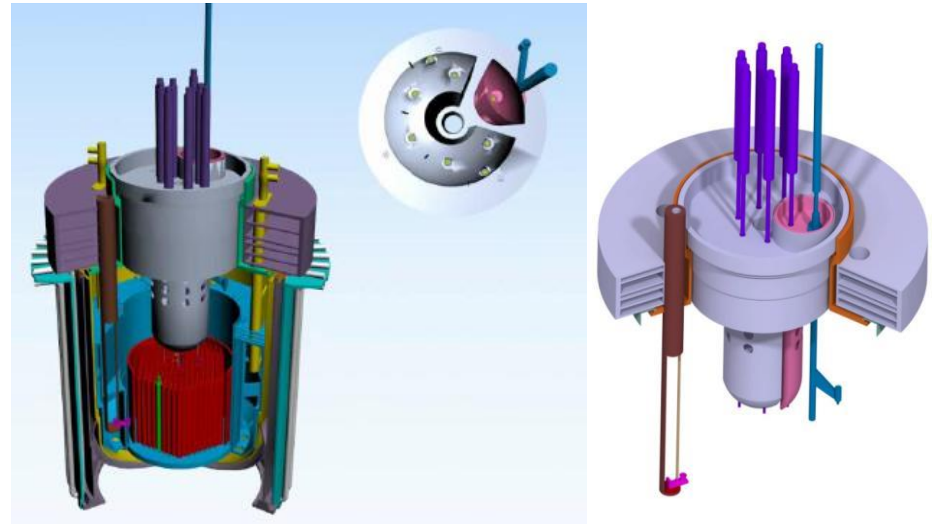
parameters	
Power (MW)	10
Average linear power density (kW/m)	3.9
Coolant inlet/outlet temperature (℃)	260/390
Height of cycle (m)	2
Average velocity of coolant (m/s)	0.17
Flow rate (kg/s)	529.5
fuel rod clad tube temperature(℃)	462
Fuel rod temperature (℃)	660



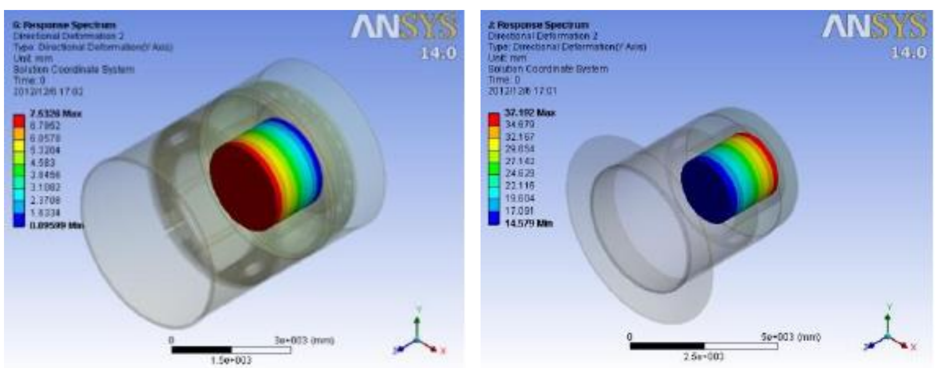
core flow distribution



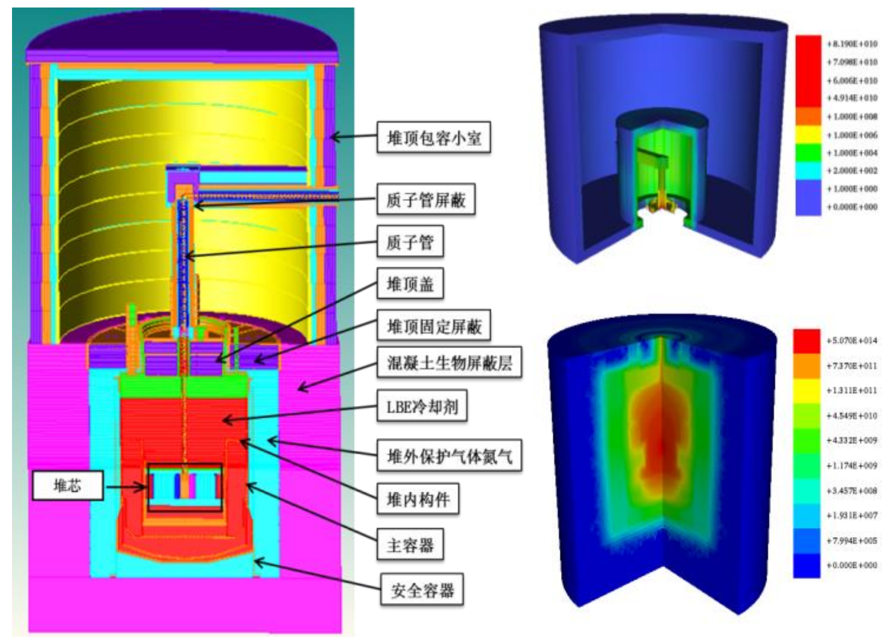
3D model



refueling system

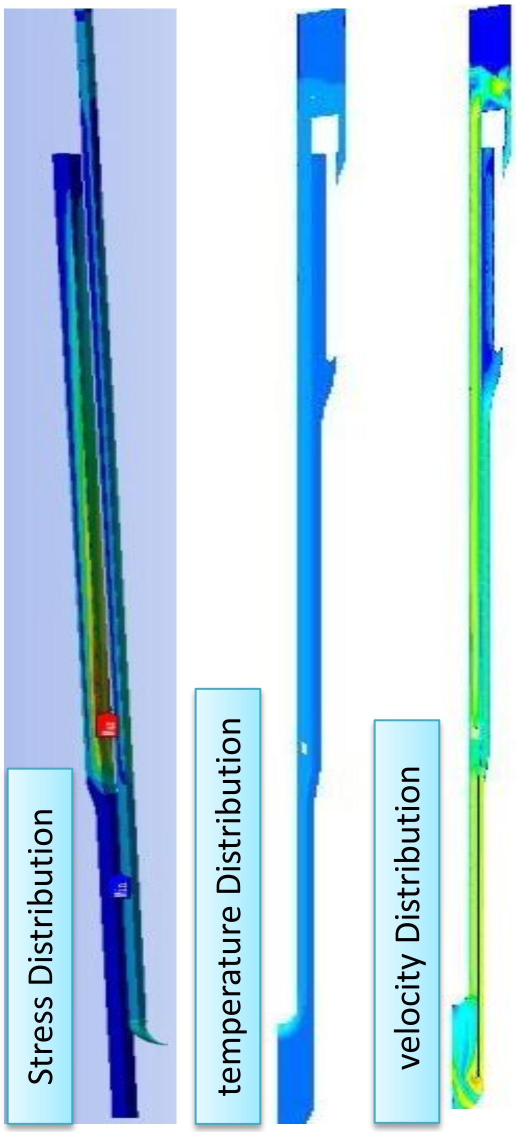


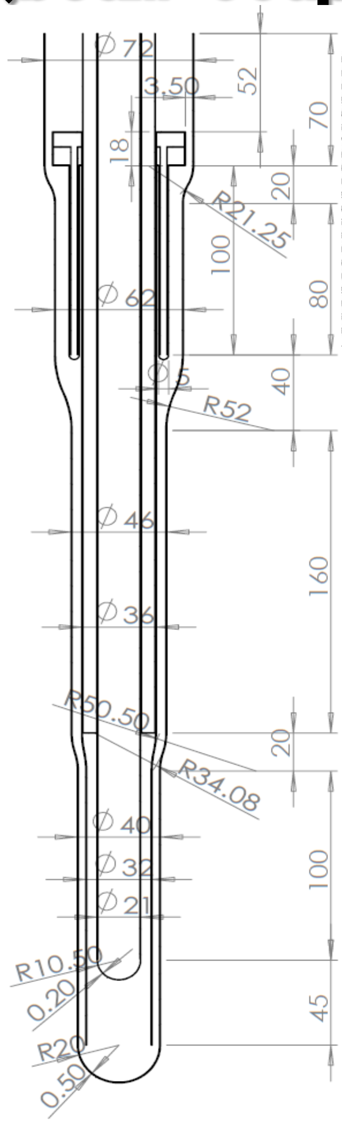
engineering structure analysis



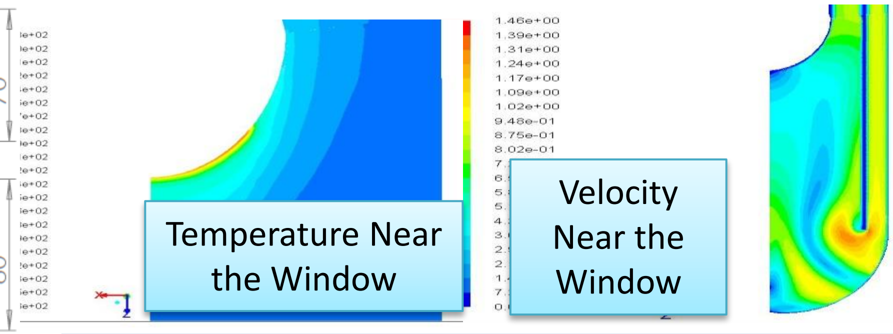
shielding design

3D coupled analysis: temperature, hydrodymics and structure (beam coupled)





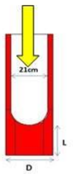
Grid:>6*10^7

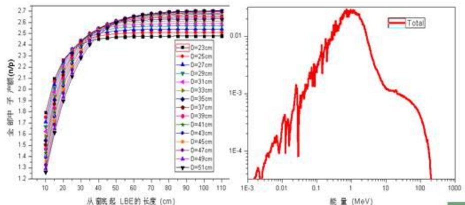


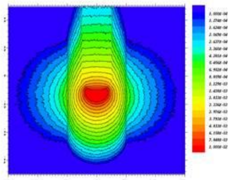
Physical Design Parameters	
Neutron Yield	3.2 n/p
Diameter of Beam	8cm
Beam Energy	**250MeV**
Beam Current	**2mA**
LBE average velocity	0.21~0.49m/s
LBE max velocity	1.29m/s
Window Thickness	2mm
Temp. Difference of Heat Exchanger	90K
Max velocity of cold fluid	1.52m/s
Wall Thickness of Heat Exchanger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

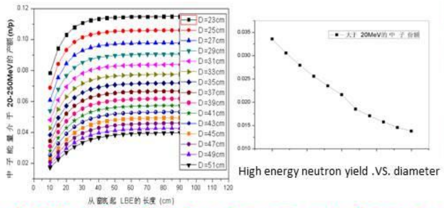
Neutronics

Incidence of beam









High energy neutron yield .VS. diameter

parameters	
Proton energy	250 MeV
Beam diameter	8± 2cm
Beam intensity	30±5 μA/cm²
Beam current	2±0. 7 mA

Neutron yield increase by size of target and diameter of Beam.
High energy Neutron yield decrease by size of target and diameter of Beam.
For ATW high energy neutron is important.

Beam Windows and Beam-target interaction component

T91 parameters

Temperature ℃	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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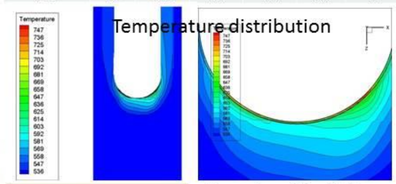
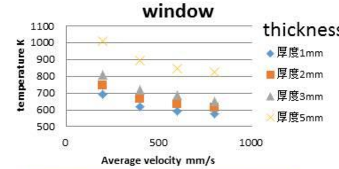
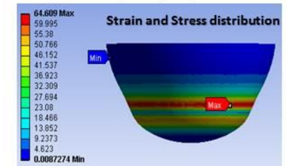
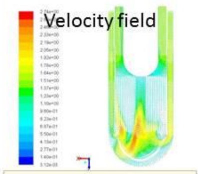


Average velocity : 0.25m/s

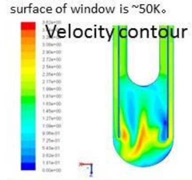
Temperature different between the inner surface and out surface of window is ~50K。







Average velocity: 0.76m/s

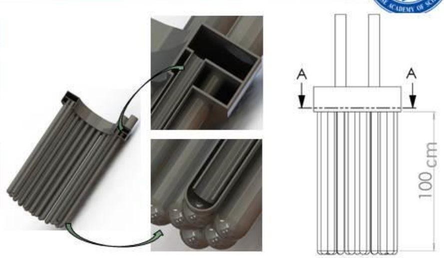


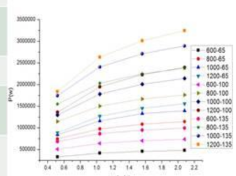
Average velocity:0.76m/s

Hydrodynamic-Structural-Heat Analysis: parameters	
structural safety factor	~3
Thickness of widow	2.0±0.5mm
Inlet temperature	525±25 K
Average velocity	0.3±0.05m/s

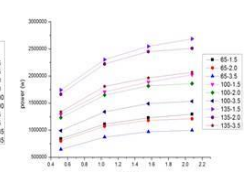
Heat exchanger

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



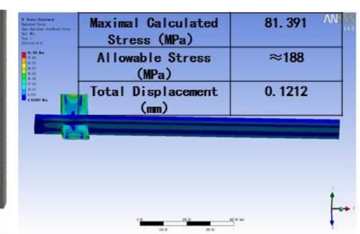


Different cooling fluid flow rate, tube length, hot and cold heat transfer fluid temperature difference power change.



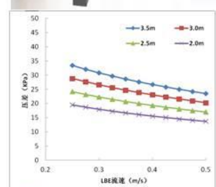
Different wall thickness, the temperature difference between the hot and cold fluid heat exchanger power change.

Bubble Pump

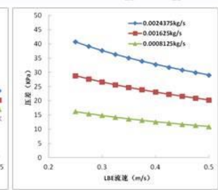


Maximal Calculated Stress (MPa)	81.391
Allowable Stress (MPa)	≈188
Total Displacement (mm)	0.1212

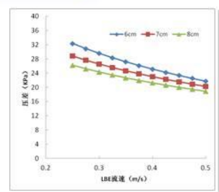
Bubble Pump Parameters	
Gas	He
Pressure	400±50kPa
Gas Temperature	500K±50K
Height of Pump	3±0.5m
Gas Inject Velocity	0.001±0.0008kg/s
Width of Lacuna	7CM
Consistency of Holes	30±10%
Diameter of Holes	4±2mm



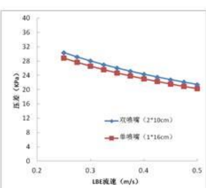
Performance Curve — different height



Performance Curve—different gas inject velocity

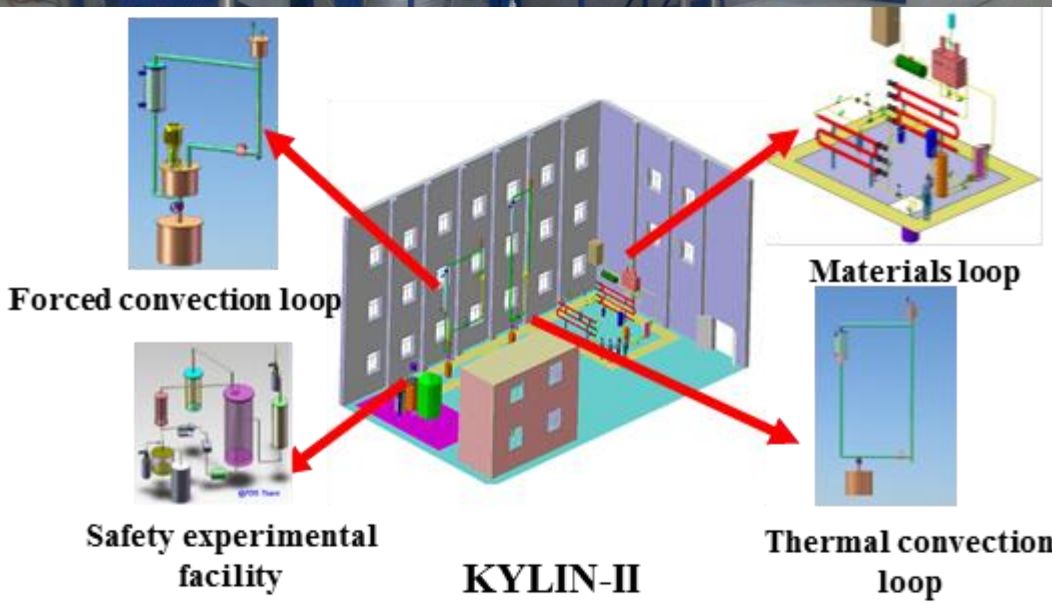


Performance Curve—different width of holes



Performance Curve—different number of holes

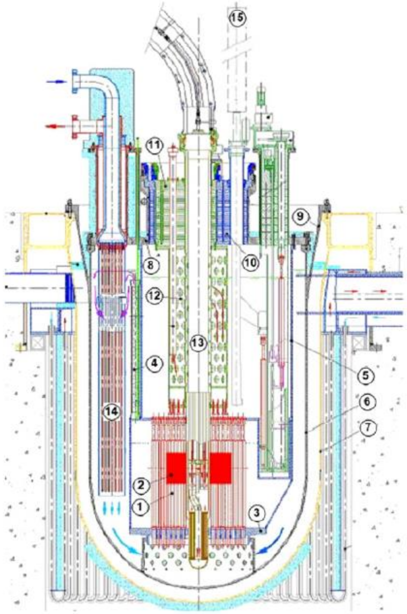
Test Loops for LBE



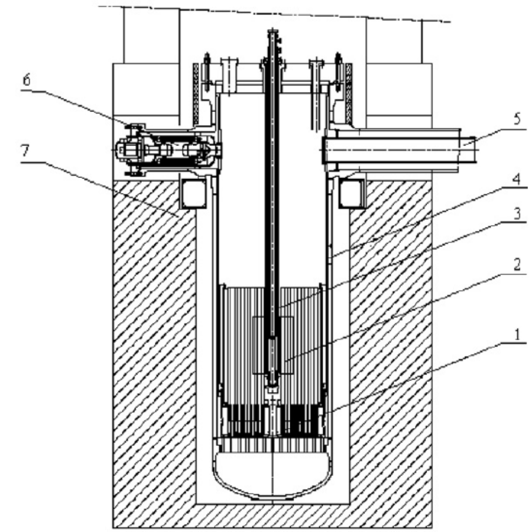
MAX Temperature: 800 °C
MAX Velocity: 10m/s

	Advantages of accelerator-driven systems	Disadvantages of accelerator-driven systems
Design and operation	♦ The possibility to operate a reactor core at a *neutron multiplication factor below 1* opens opportunities for new reactor concepts, including concepts which are otherwise ruled out by an insufficient neutron economy ♦ In particular, this allows transmuters to be designed as pure TRU or MA burners and hence the fraction of specialised transmuters in the reactor park to be minimised ♦ The proportionality of the reactor power to the accelerator current simplifies the reactor control	♦ *Accelerator:* Very high reliability required to protect structures from thermal shocks ♦ *Beam window and target* subjected to unusual stress, corrosion and irradiation conditions ♦ *Sub-critical core:* Increased power peaking effects due to external neutron source ♦ Compromises between neutron multiplication factor and accelerator power required ♦ Increased overall complexity of the plant ♦ Reduction in net plant electrical efficiency due to power consumption of accelerator
Safety	♦ The reactivity margin to prompt criticality can be increased by an extra margin which does *not depend on the delayed neutrons* ♦ This enables the safe operation of cores with degraded characteristics as they are typical e.g. for pure MA burners ♦ *Excess reactivity can be eliminated*, allowing the design of cores with a reduced potential for reactivity-induced accidents	♦ New types of reactivity and source transients have to be dealt with (external neutron source can vary rapidly and reactivity feedbacks in TRU- and MA-dominated cores are weak)

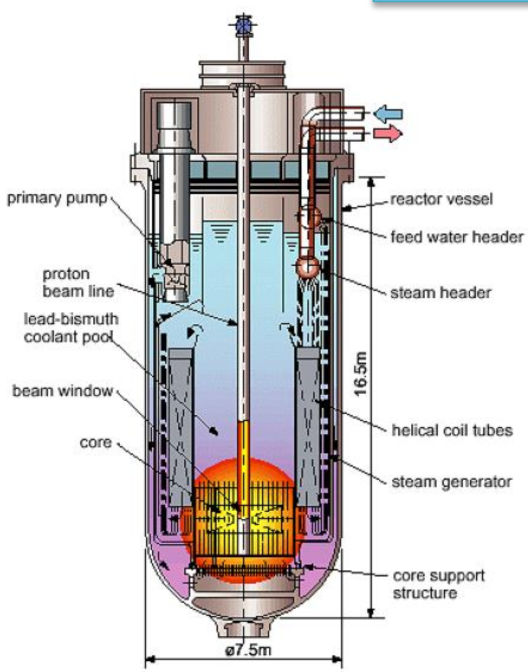
Note: Issues of particular relevance for the transmutation of TRU and minor actinides (MA) are underlined.



Parameter	LBE	He
Nominal thermal power, MWt	80	80
Multiplication factor k_{eff} at BOC	0.973	0.969
Number of fuel sub-assemblies (FSAs)	120	90
Number of pins per FSA	90	37
FSA flat-to-flat distance (mm)	138	120
Fuel type/fuel mass (t)	MOX/3.24	MOX/4.37
Plutonium content (%)	23	35
Core inner/outer diameter (m)	0.58/1.7	0.48/1.4
Fuel height (mm)	900	1500
Fuel pellet inner diameter (mm)	1.8	3.2
Fuel pellet outer diameter (mm)	7.14	11.5
Clad outer diameter (mm)	8.5	13
Pitch to diameter ratio	1.58	1.29
Average power rating (W/cm)	82	160
Peak power rating (W/cm)	130	256
Primary coolant/pressure (MPa)	PbBi/1	He/6
Inlet coolant temperature (°C)	300	200
Outlet coolant temperature (°C)	400	450
Peak fuel temperature (°C)*	1047	1648
Peak clad temperature (°C)*	494	541
Core mass flowrate (kg/s)	5460	61.6
Core pressure drop (kPa)	25	100



Coolant: Liquid Heavy Metal and Gas



Main design parameter:

Parameter	Material / Value
Coolant	He/ CO_2
Max. thermal power	100 MW
Power of the accelerator	3 MW
Energy of the Protons	600 MeV
Current	5 mA
Accelerator Mode	Constant wave (CW)
Spallation target form	Conical resp. segmented plates
Spallation material	Tungsten
Nuclear fuel	MOX
Plutonium content	=< 20 %
Multiplication factor - k_{eff}	0.95 – 0.97
Cladding	T91, HT-9, SiC
Gas pressure	6 MPa
Fuel assembly length	1200 mm
Pitch	10 mm

Thermal Properties, Chemical Properties and etc.

	Lead / LBE	He
Density ($kg \cdot m^{-3}$)	11340 / 11096	0.1786
Volume Specific heat ($J \cdot ml^{-1} \cdot K^{-1}$)	1.41 / 1.65	0.03 (4MPa)
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	35.3 / 6.9	0.1513
Corrosion	Large / Large	Small
Erosion	Large / Large	Middle (high velocity)
Radioactivity & toxicity	Large / Huge	Small

Lead/LBE Cooling Fast Reactor

Strong points

- Unpressurized reactor vessel
- High boiling temperature
- High thermal inertia
- Good passive safety (convection)
- Transmutation
- Compatible with wate
- Some experience (Ru

Weak points

- High melting temperature (lead)
- Corrosive and toxic

- Corrosive and toxic
- Problematic cleaning and decontamination
- Activation of Pb and Bi → ^{210}Po

Gas Cooling Fast Reactor

Strong points

- Resistant fuel barrier (ceramic fuel)
- Thermal negative feedb
- Inert coolant (He)
- Transmutation capabilit

Weak points

•High power density (100 MW/m^3)

•High power density (100 MW/m^3)

•Low thermal inertia (gas)

•No operating experience

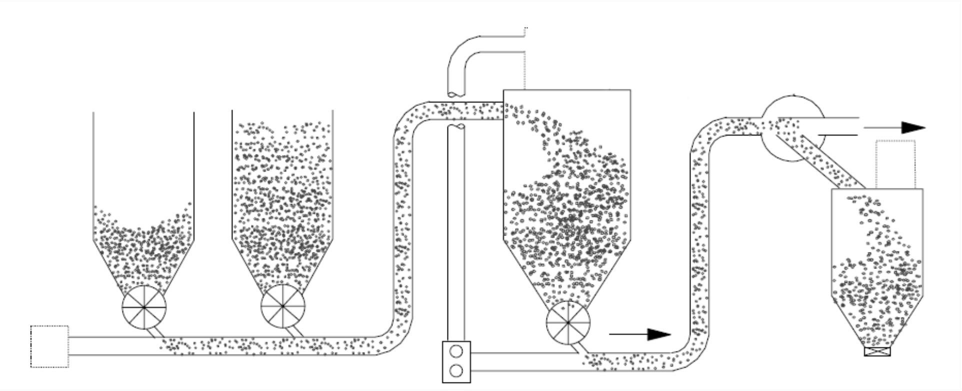
•High coolant flow → vibrations

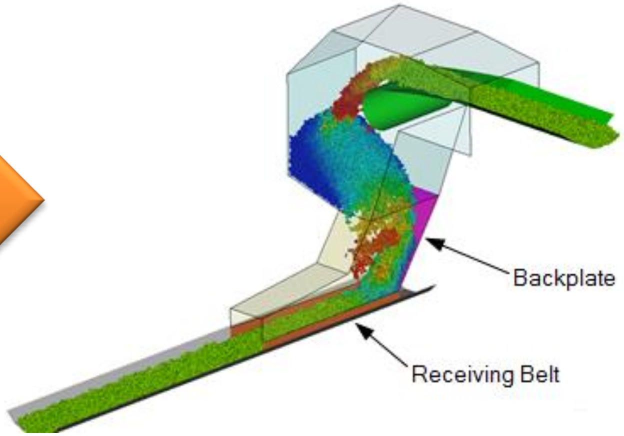
•Decay heat removal and depressurisation → high pump power

IAEA Nuclear Power (NENP) Technical Meeting, 2012.

Q: How to avoid the weak points of Gas Cooling Fast Reactor and keep the strong points.

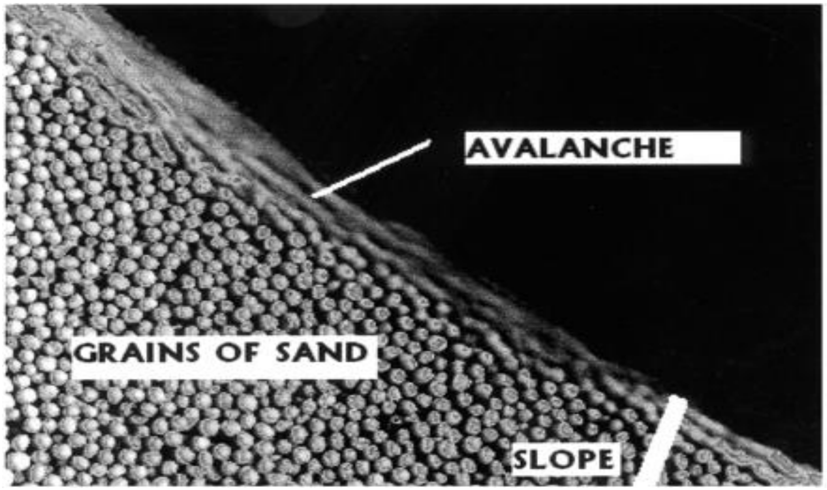
A: Granular + Helium (Low pressure) for the coolant?

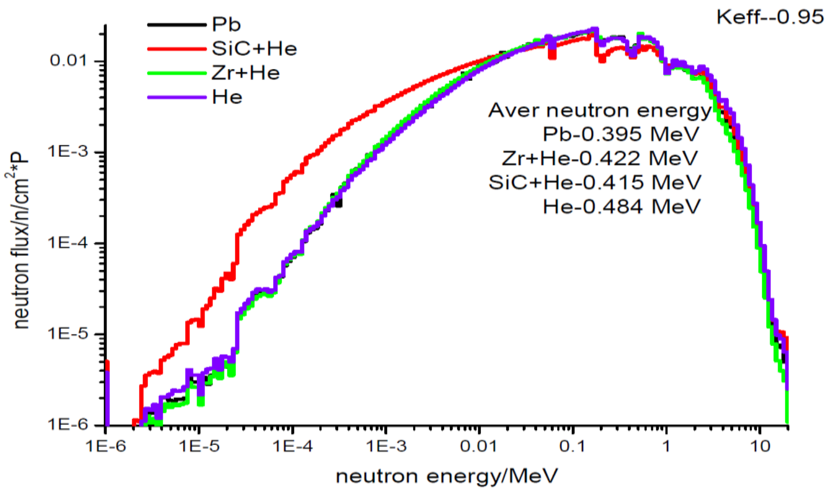




can increase the specific heat; High pressure

From the fluidized bed to the dense granular flow





The kinds of the solid grains can be considered

Granular coolant

Coolant	Volume specific heat (J/ml·K)
Water	~4
Na	~1
LBE	~1.6
Molten Salt	~4
Helium	~0.03(4Mpa)
SiC Granular	~1.4

Coolant	K (W/m·K)	d (mm)	K_{eff}(20℃) (W/m·K)
SiC granular	~120	~0.16	~1
$LiZrO_3$ granular	3.2	1	0.9
Steel granular	60	20	2
Helium	0.15		

Solid	K(W/m·K)	Gas	d(mm)	Time(s)	h(W/m²·K)
SiO2	1.7	Air	1	10	~100-~200
Ceramic	0.5	H2(1000℃,10bar)	0.1	1	659
Al	217	He	0.043	short	1500
Glass	0.93	Air	1	60& 1	60 & 290
		Helium			~100

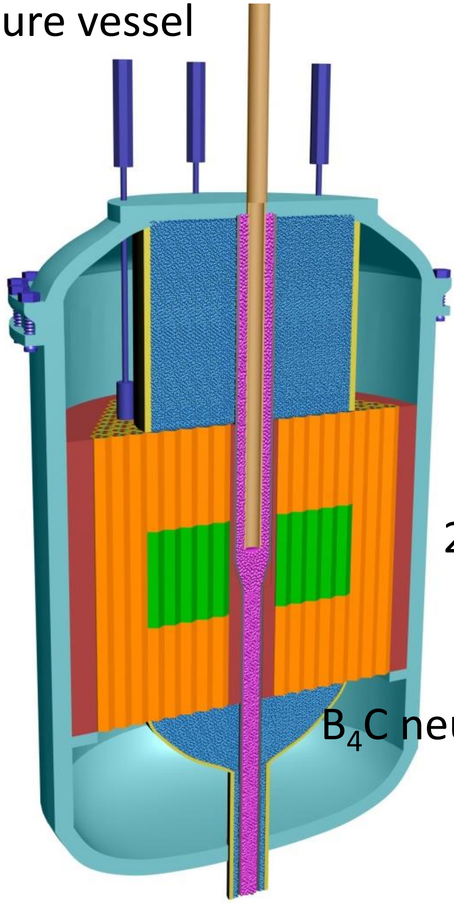
Convective heat transfer coefficient

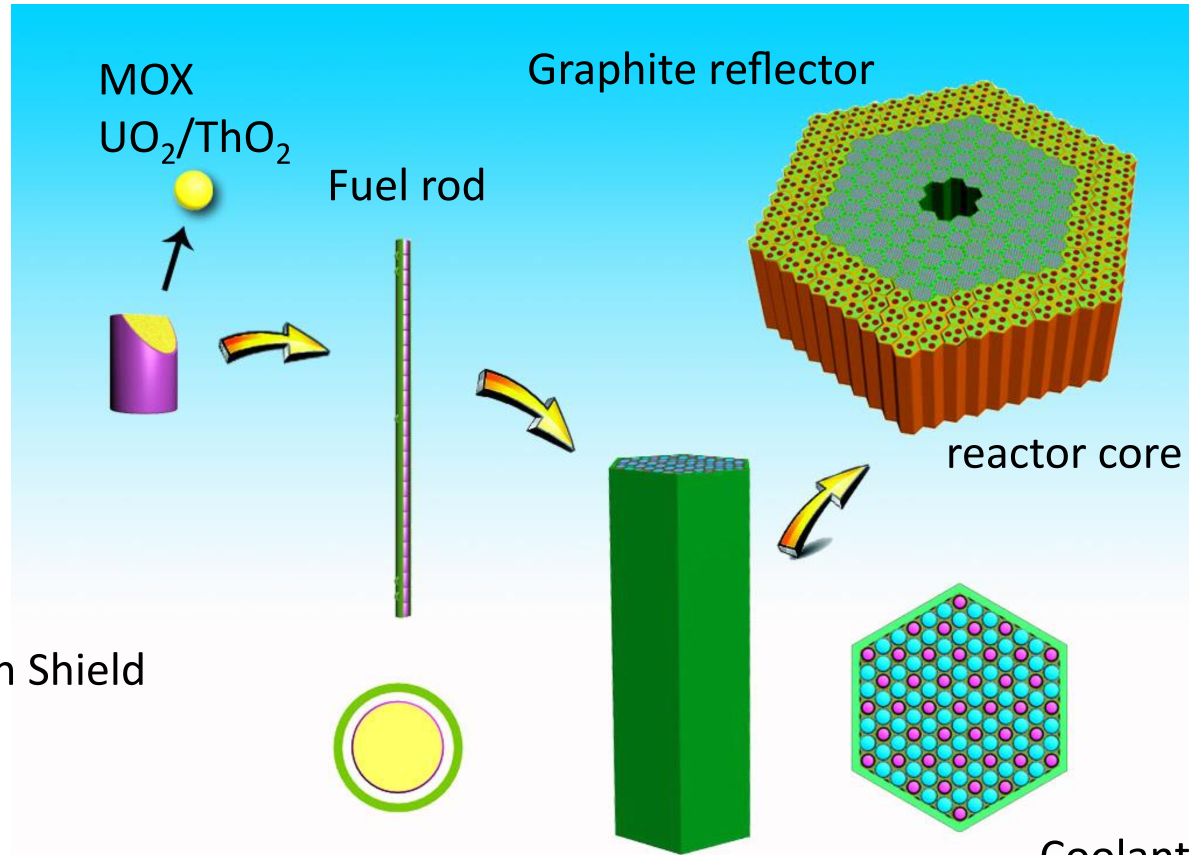
Granular coolant

- Low pressure inter-fluid (He)
- High thermal inertia
- The grains can be optimized for
  - Fast spectrum
  - Low radio-toxicity
  - Small erosion and chemical toxicity…

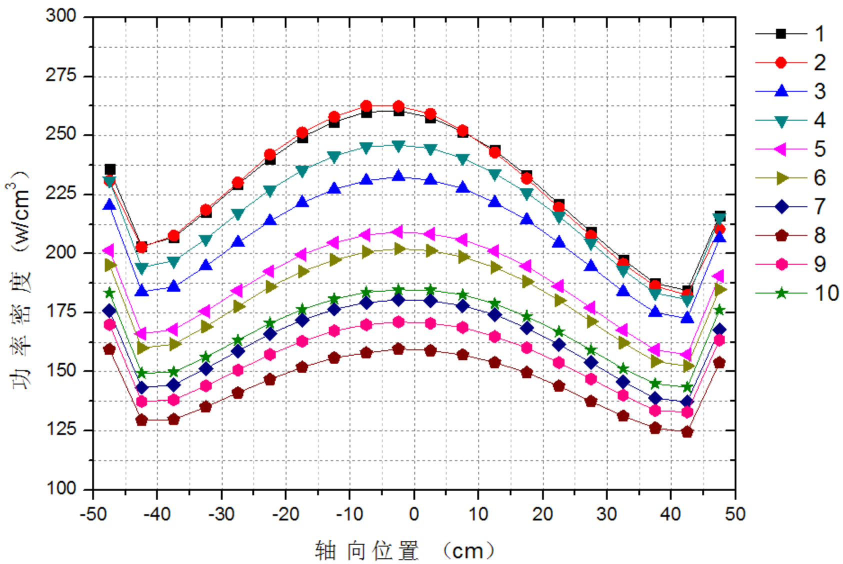
For example: SiC grains and SiC Hexagonal prism

Concept of the granular coolant reactor

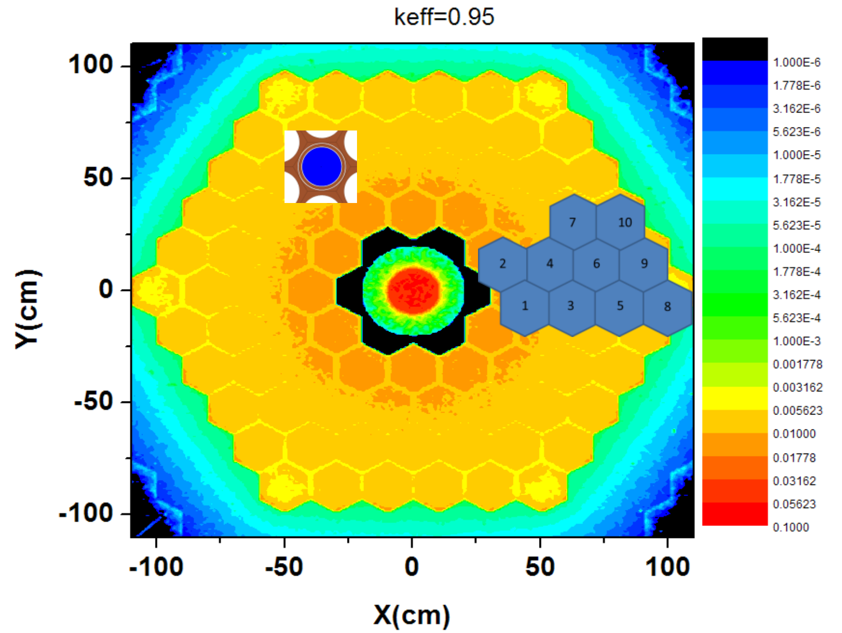




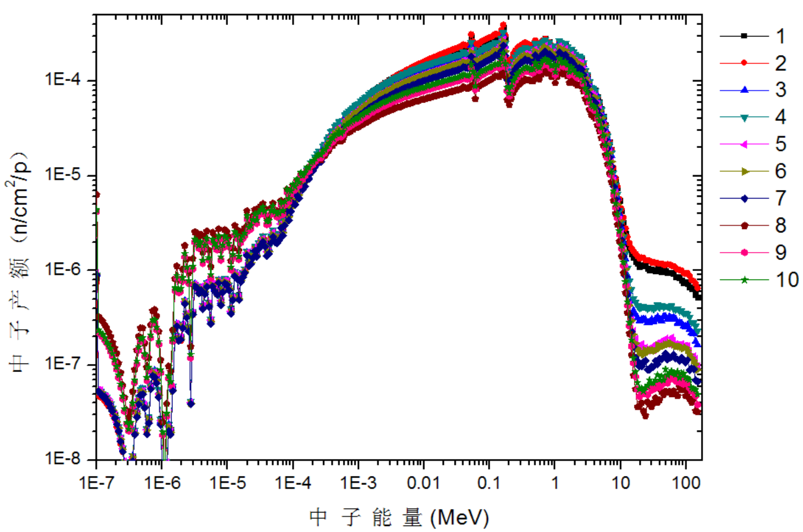
Diameter of SiC granular: ~0.5 mm
Helium pressure: 0.1 MPa



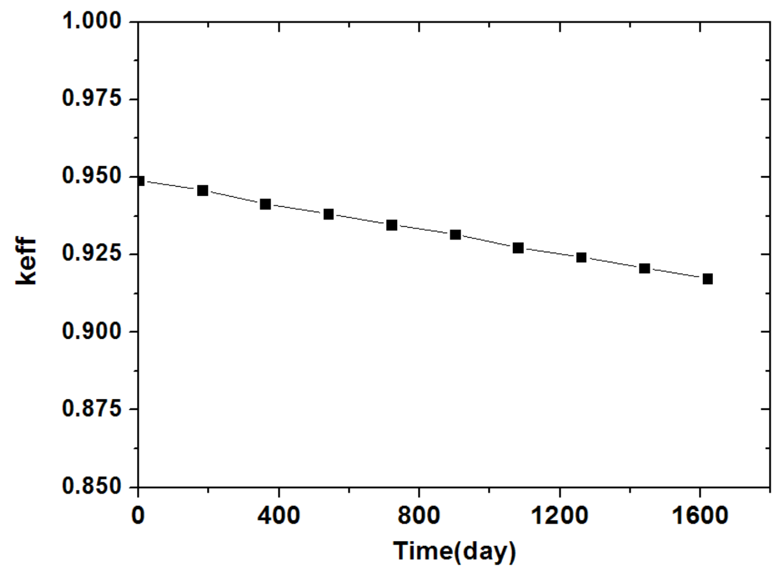
Density of Power in vertical distribution



Density of Power distribution

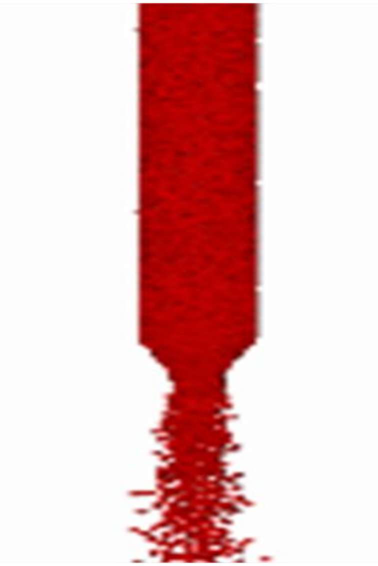


The neutron spectrum

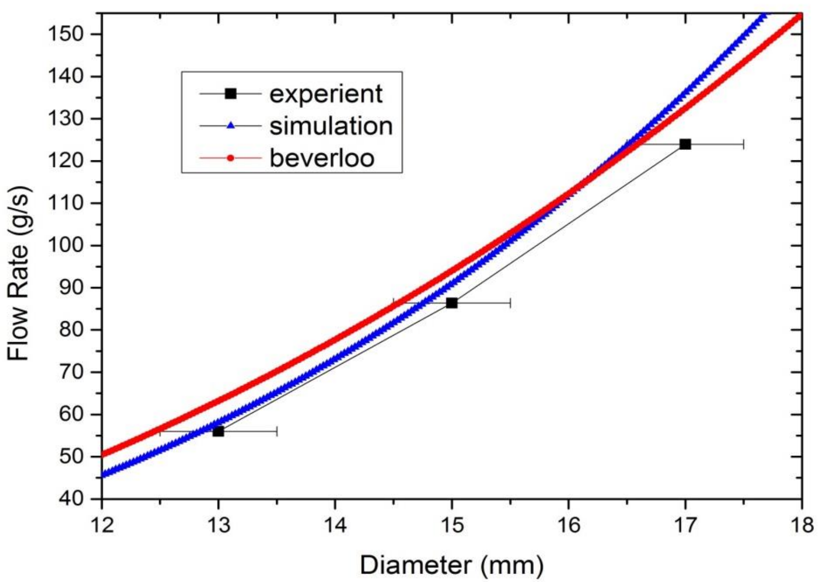


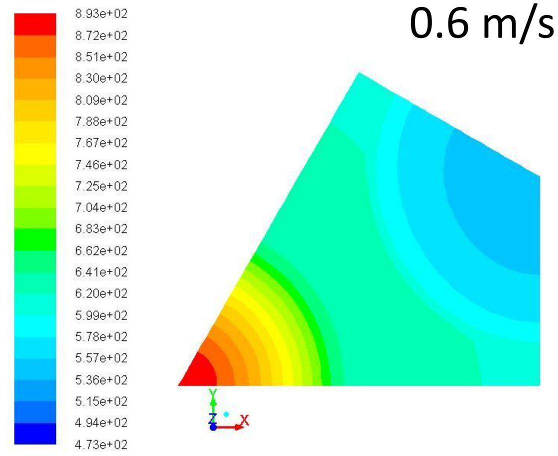
Burning calculation

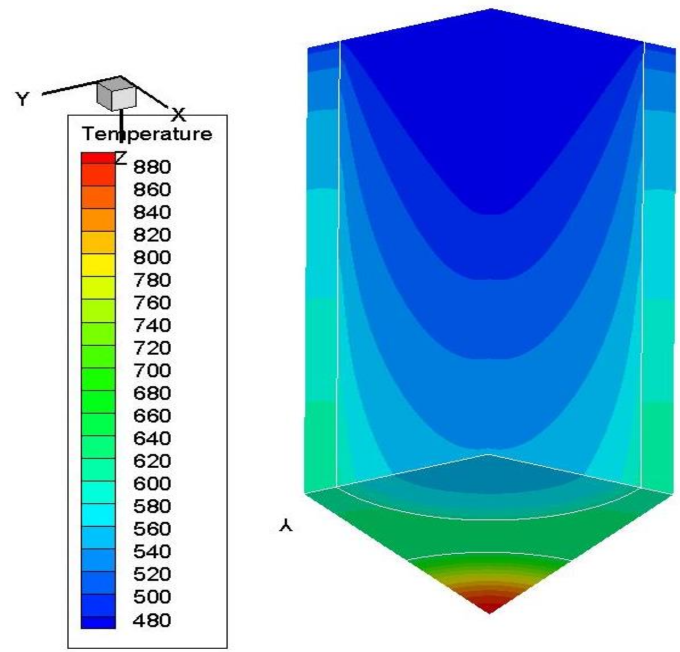
Granular flow in the coolant channel



Dense granular flow by gravity driven





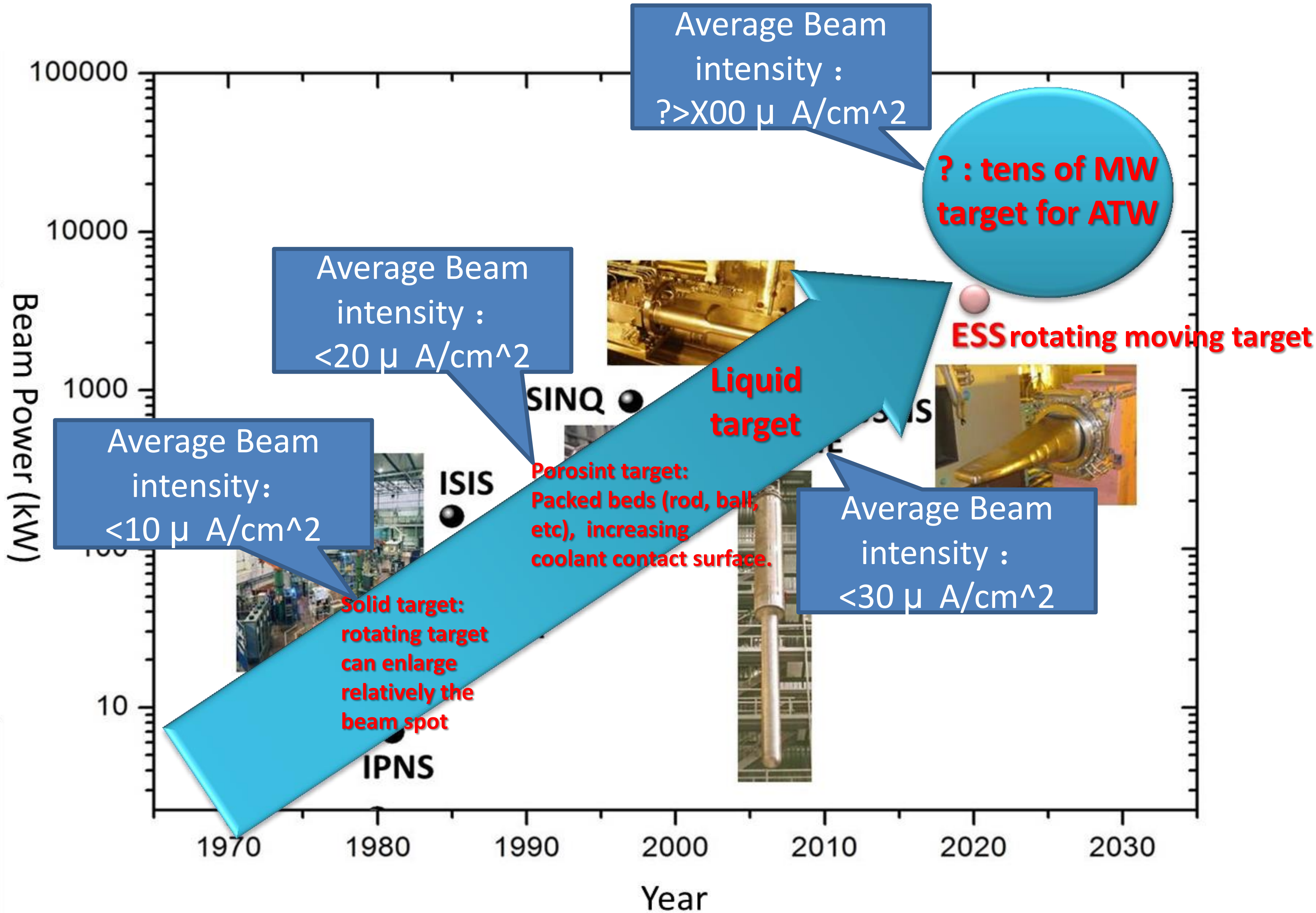


Heat transfer by granular flow

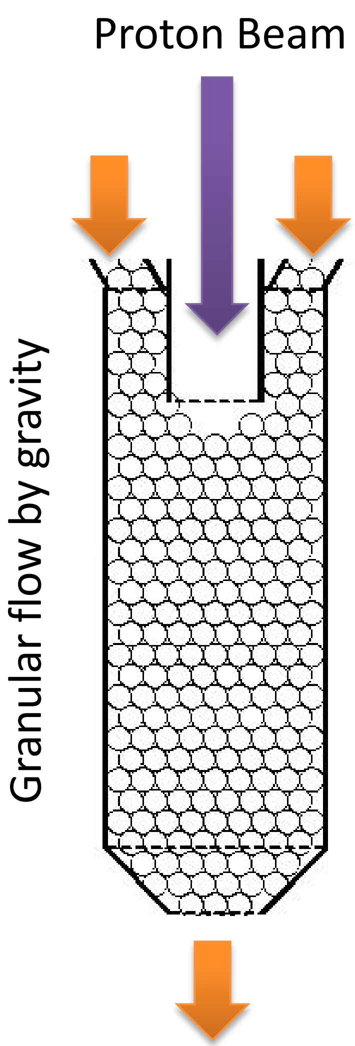
parameters

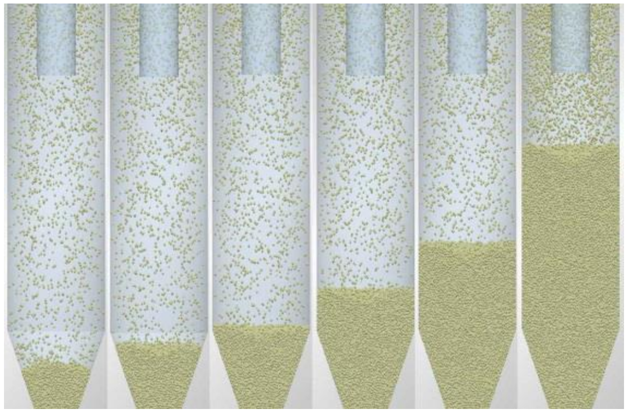
- High of the fuel rod：100 cm
- High of the ：70 cm
- Thermal Power：100 MW
- Fuel:（Pu_xAm_{1-x}）$O_{1.88}$
- Theoretical density of fuel：10.346 g/cm^3
- Density of power：34W/cm^3
- K_{eff}=0.95（BOL）
- Proton beam: 1GeV@4.3mA（BOL）
- Diameter of SiC granular: ~0.5 mm
- Helium pressure: 0.1 MPa

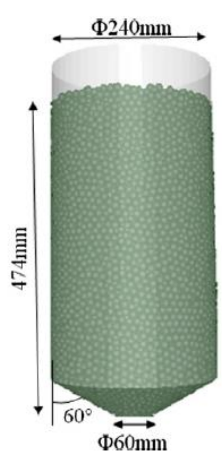
High Power Spallation target

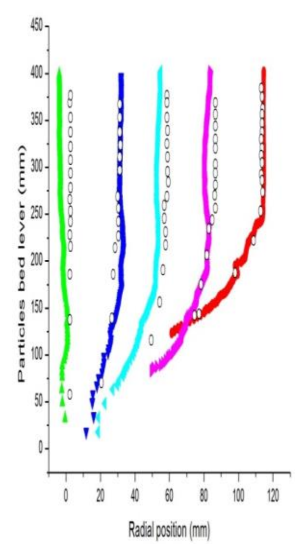


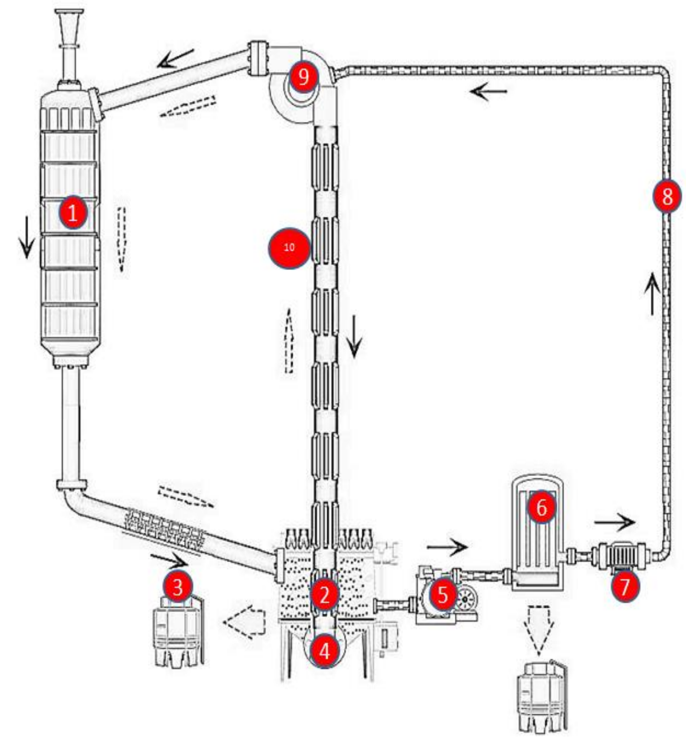
Granular target system concept





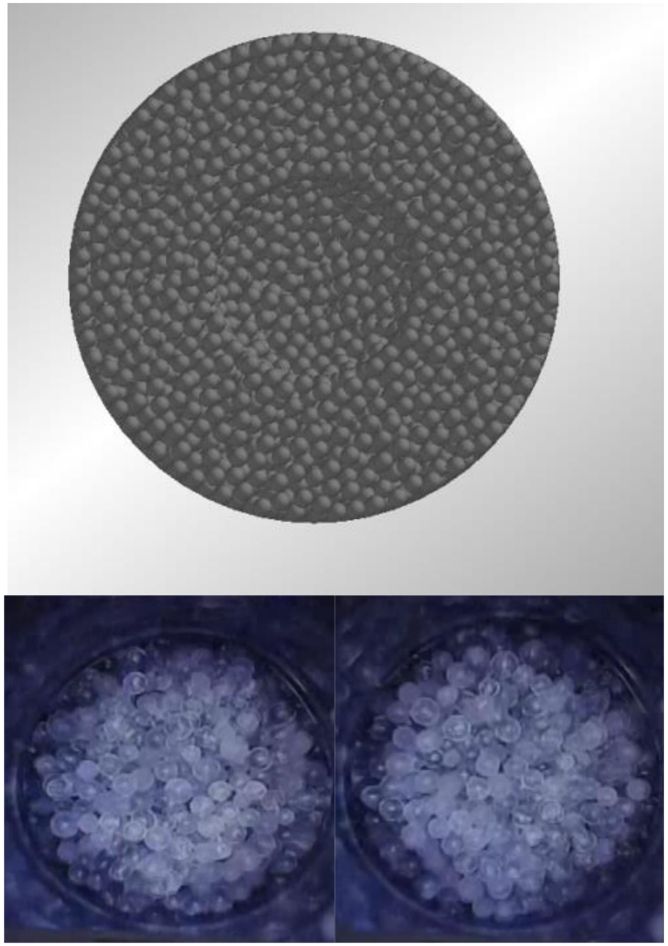


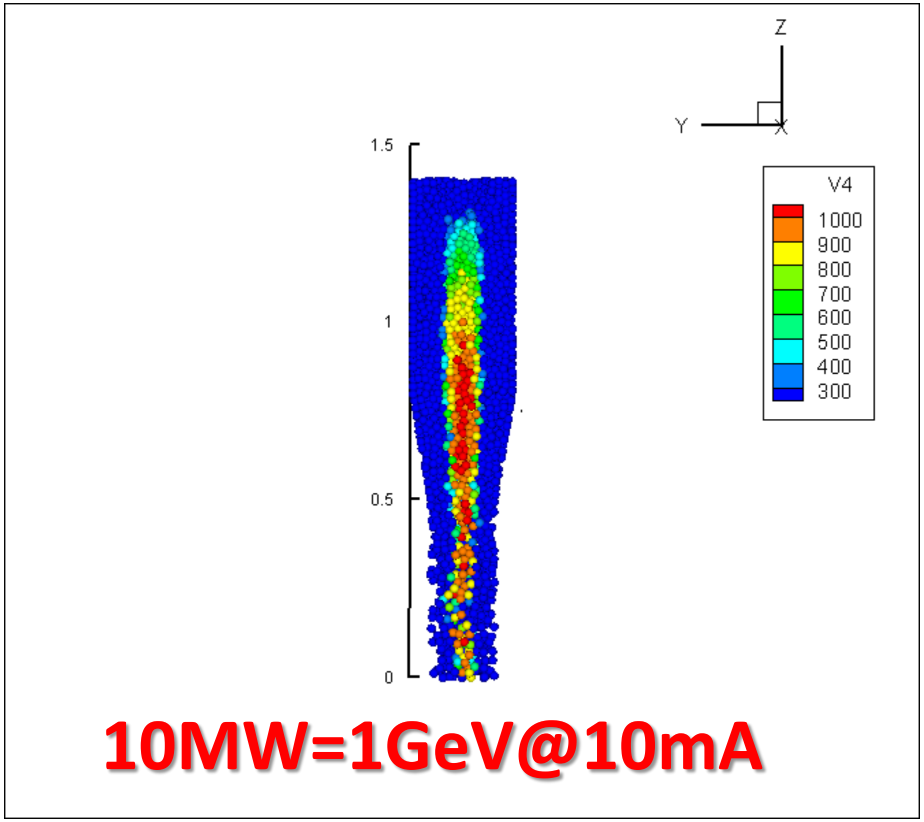




1. Target Body 2.Heat Exchanger 3. Solid horizontal Transport & Dreg Filter 4. Gas-Solid Separator 5. Gas Dust Filter 6. Gas Heat Exchanger 7.Gas Blower 8.Gas Pipes 9.Gas-Solid Mixer 10. Solid Lifter

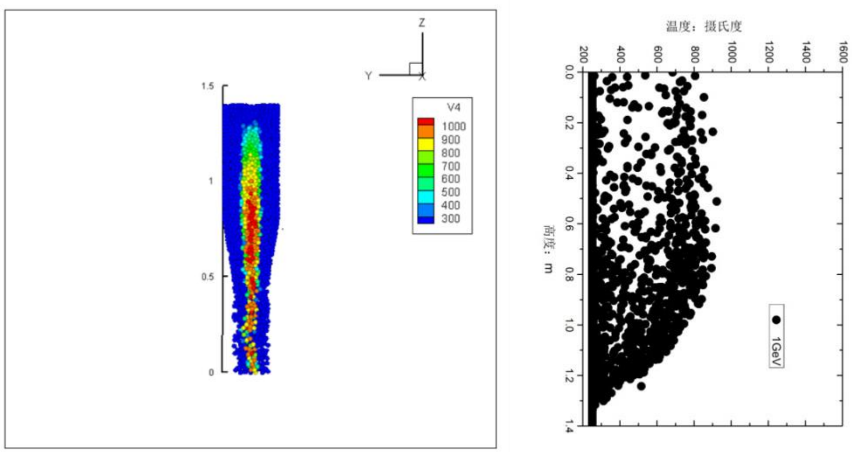
Beam target coupled segment



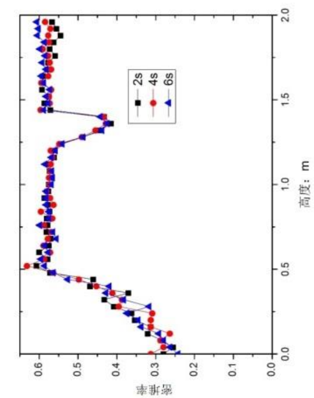


Mass parallel Simulation:
Contact mechanism + MD + MC transport
K20GPU 2500ALU
Number of particles: 0.5 M

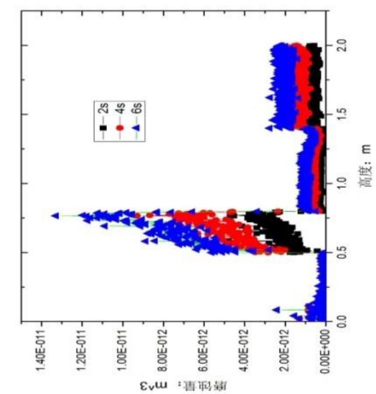
Beam target coupled



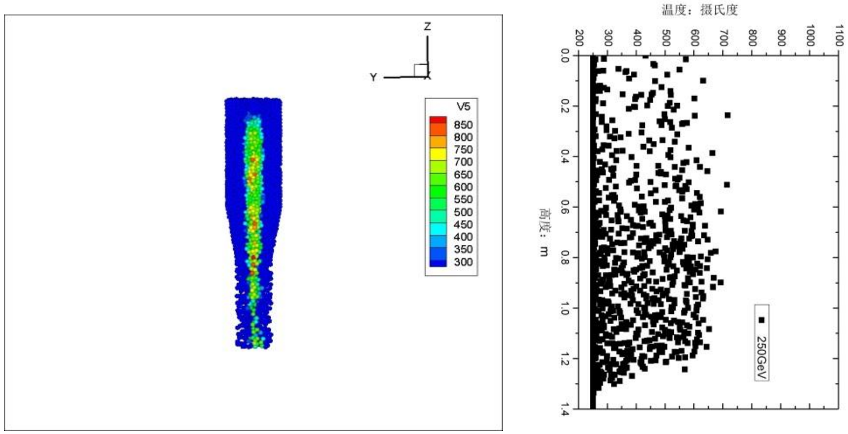
Temperature distribution (10MW=1GeV@10mA)



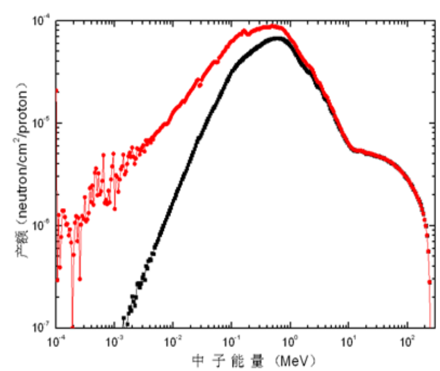
Fraction of volume distribution



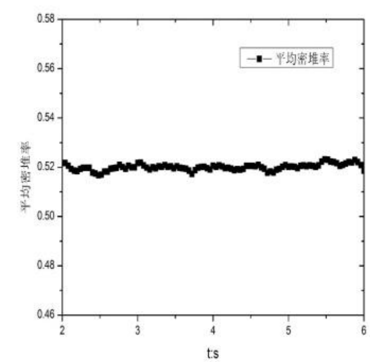
Maximum erosion estimation distribution



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



neutronics



Fraction of volume vs. time

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.

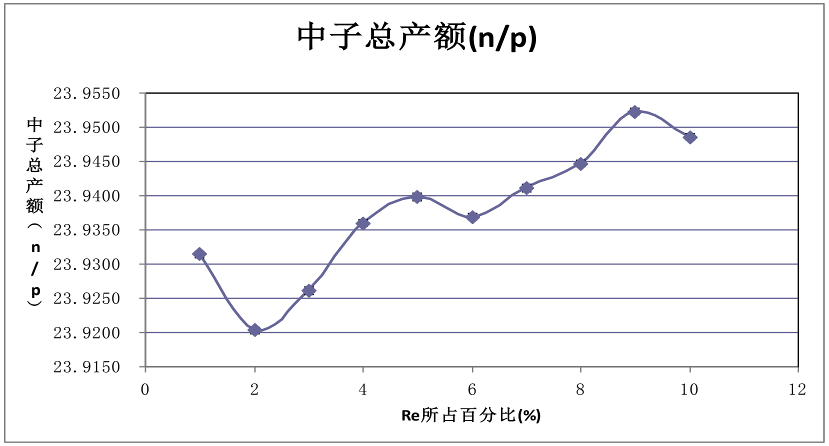
Heat exchanger principle and main structure

parameters		
Heat exchanger	2.5	kW
Flow rate	200	kg/s
Granular outlet temperature	~200	℃
Granular	<1000	℃
The cooling water inlet temperature	20	℃
Cooling water outlet temperature	80	℃

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 (material temperature does not exceed 250 ℃). General transport height up to 40 meters, TG type up to 80 meters。

The erosion test of Tungsten/SiC grains



W

	RT	300℃	500℃	800℃	1000℃
min	30	30	20	20	20
Specific wear ratemm³/Nm	-4.92E-5	-7.08E-5	-4.62E-6	-9.24E-6	+1.29E-4

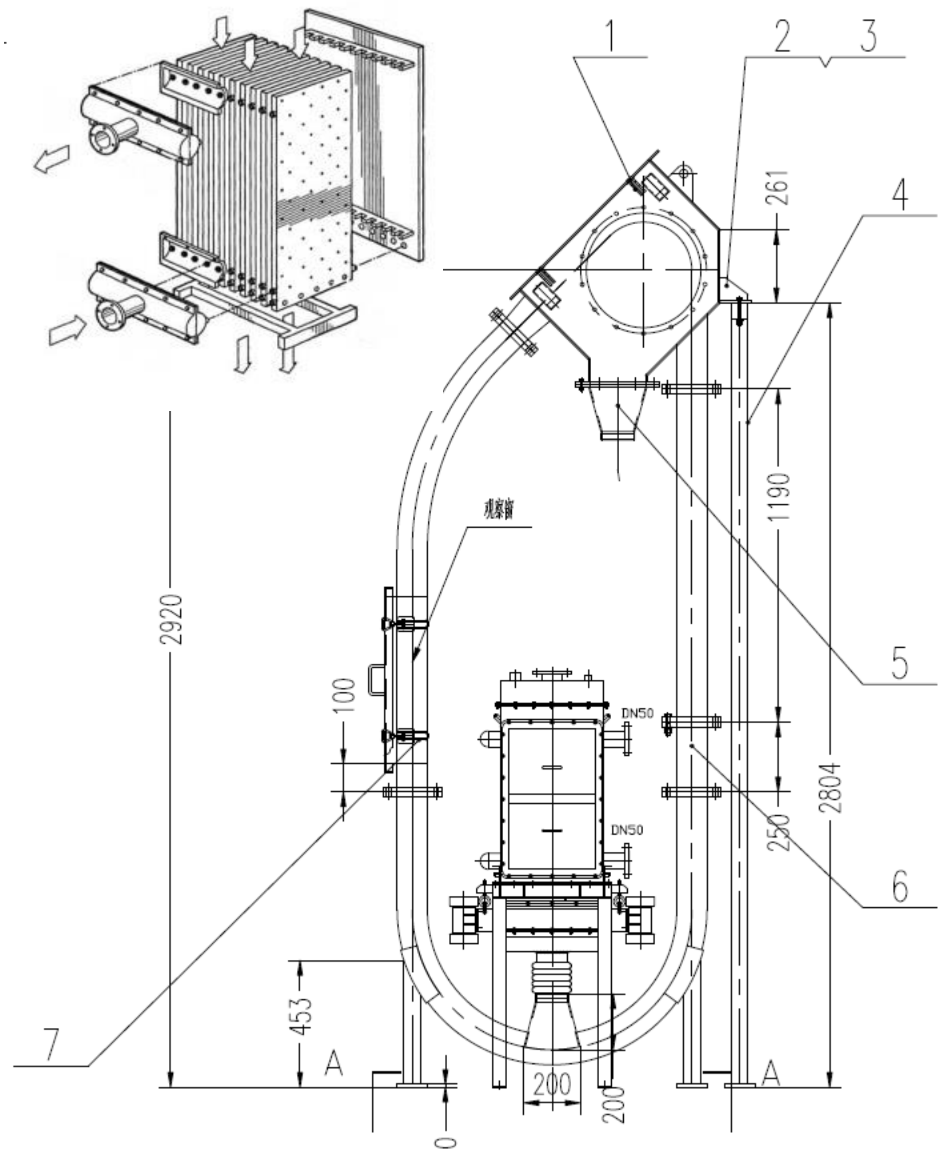
SiC

	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	

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

Granular target design and test loop

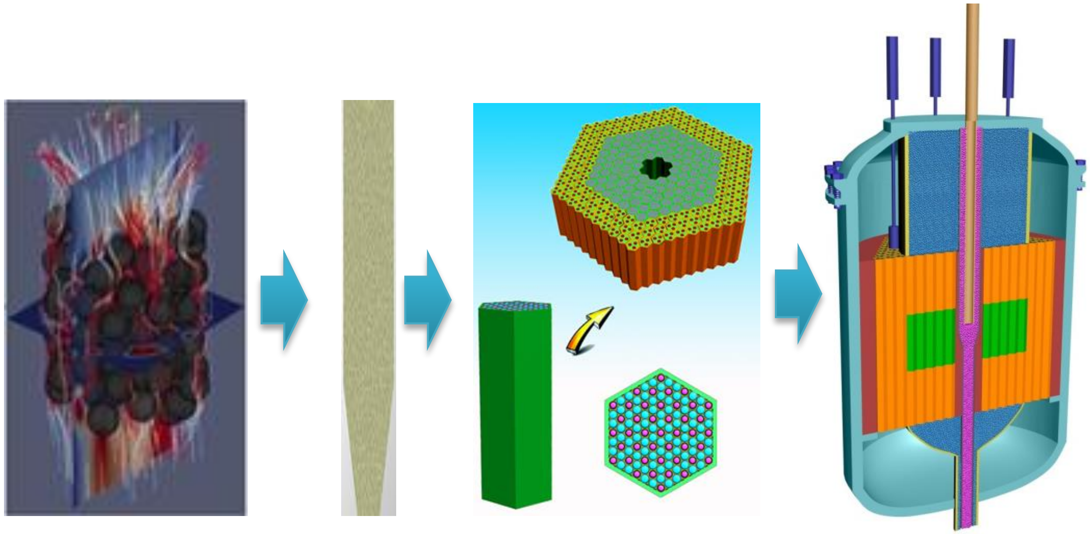
Solid target:	Liquid target:
Thermal stress	Corrosion
Radiation damage	Cavitation
Shock waves	Shock waves
Cooling	splashing
Lubrication	Radiochemistry



parameters	
Granular material	Tungsten/Tungsten alloy
Structure material	TZM/SiC
Granular size	10±5mm
Inlet temperature of granular	250 C
Outlet temperature of granular	550 C
Proton beam	1GeV@10mA=10MW
Intensity of beam	>100 μ A/cm^2
Diameter of beam spot	10cm
Average velocity of granular flow	~0.9m/s

Dense granular flow target have chance to increase power and using for ATW

Mass parallel simulation method (GPU) for granular



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

Large scale test (GPU)

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

Thank you！