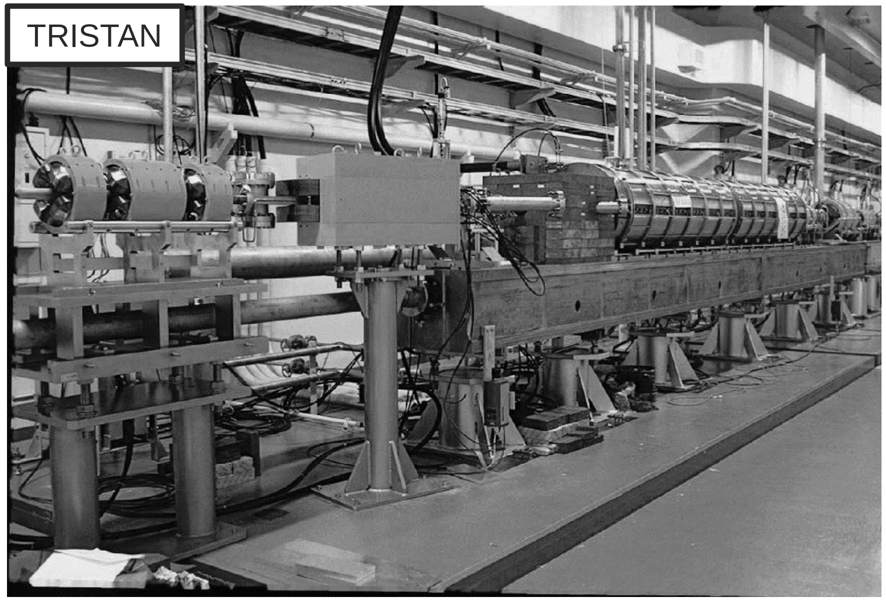
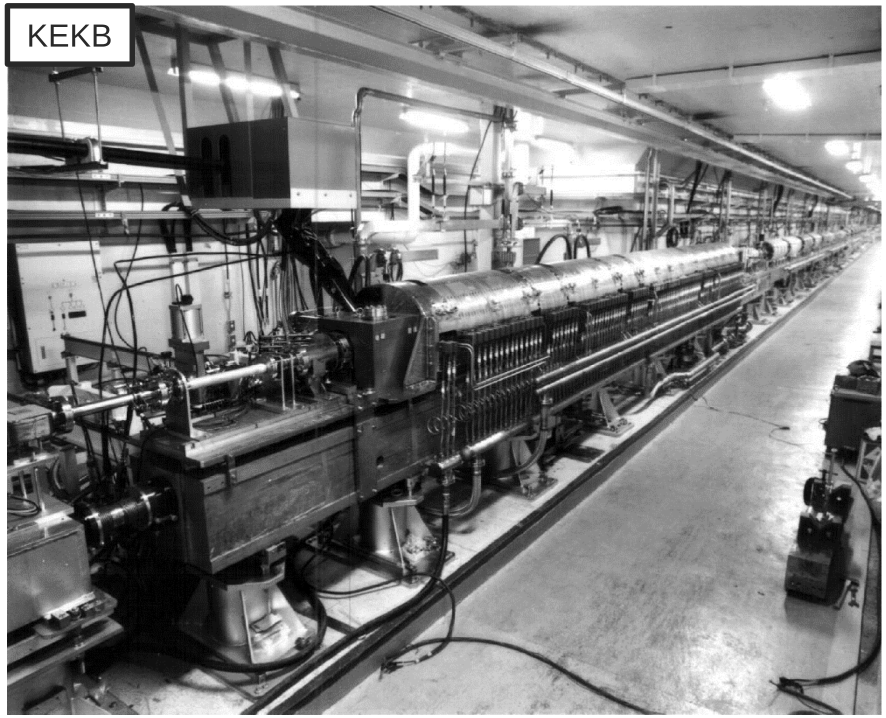
Present status of e-driven positron source for ILC

Yoshinori Enomoto (KEK)
On behalf of iCASA positron group
2023/8/23

KEK and positron

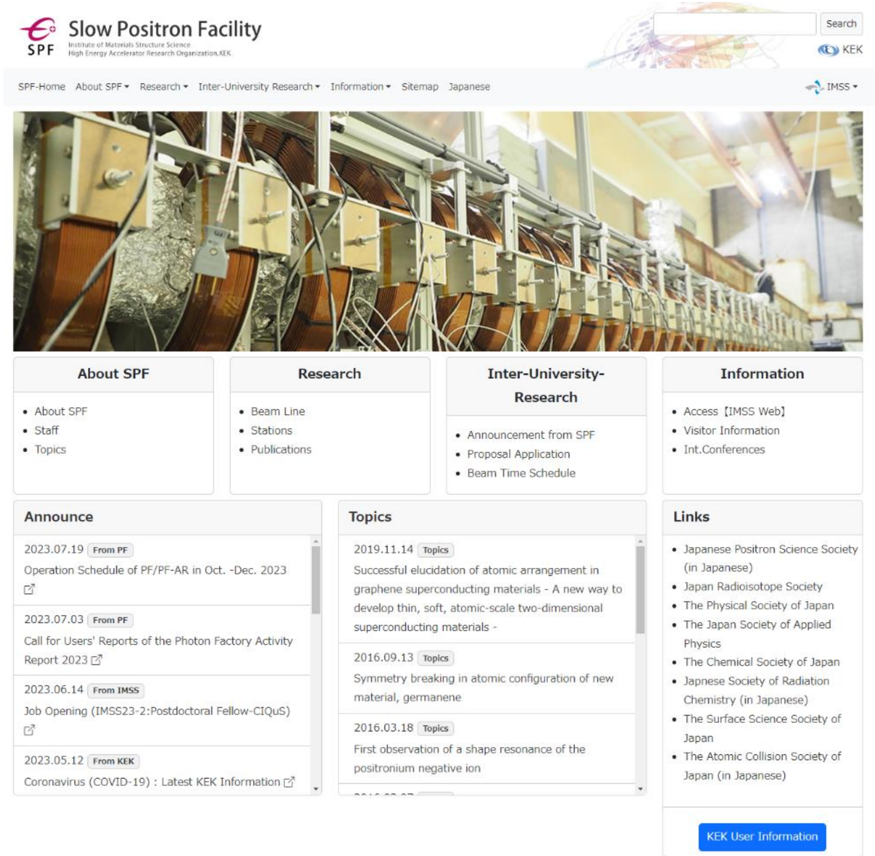
- From TRISTAN to ILC
  - KEK LINAC has keep providing positron beam to e^+e^- collider experiment since 1980s.
  - Positron source for SuperKEKB is world's most intense positron source in operation.
  - We play an important role to develop future positron source for ILC.

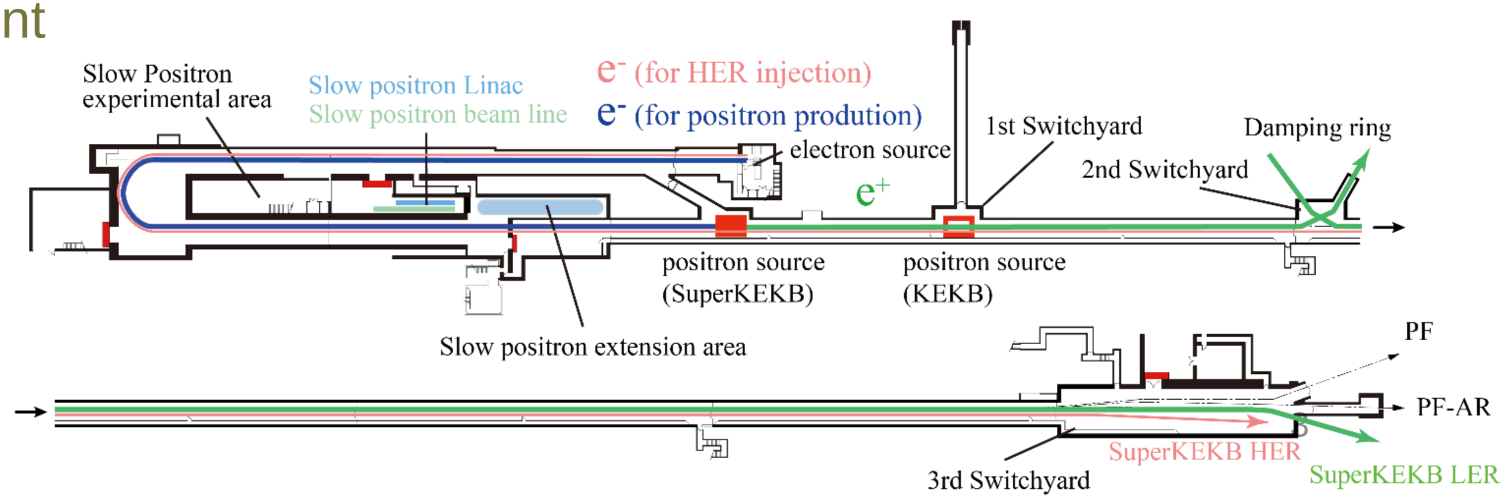




KEK and positron

- Slow positron facility
  - Slow positron is one of four probes, which KEK provides for material scientists, photon (PF), neutron, (J-PARC), Muon (J-PARC)
  - The SPF exists between two lines of LINAC
  - Upgrade plan to 50 kW (from 0.5 kW) proposed
  - It’s possible to be a good test bench for future high power positron source
  - High gradient acc. Structure is another important component





Recent situation

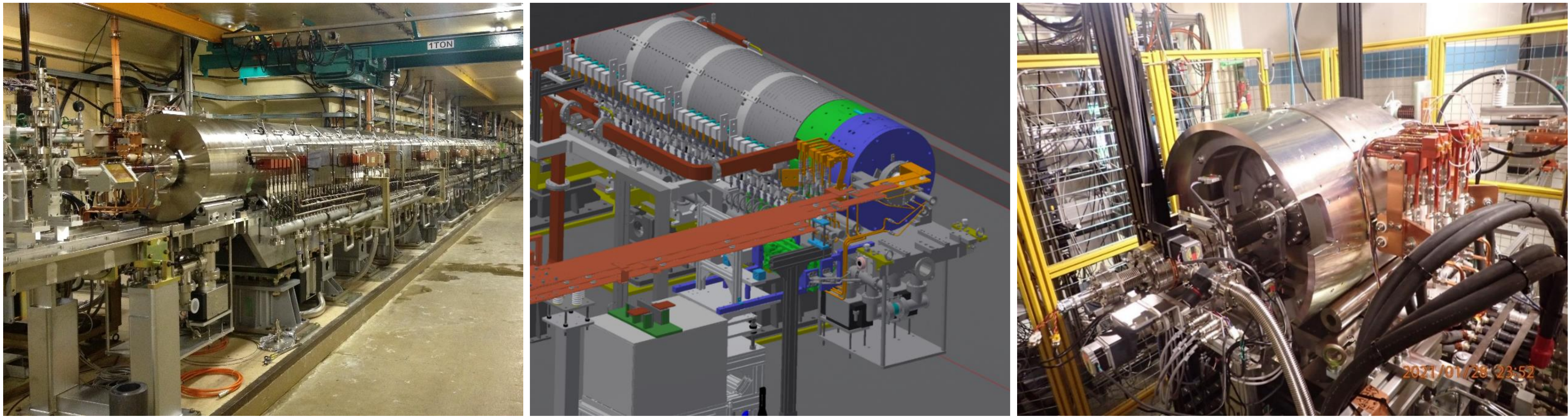
- 2022/9 New group to develop positron source for ILC launched in KEK iCASA (Innovation Center for Applied Superconducting Accelerators)
- 2023/4 5 years grant for selected time-critical work packages* was approved

  *Source, SRF, nano-beam

- I (YE) was working on SuperKEKB positron source since 2015
- In 2022, performance of the positron source almost reached its design value
- I moved from injector group to iCASA to launch a group for positron source for ILC.

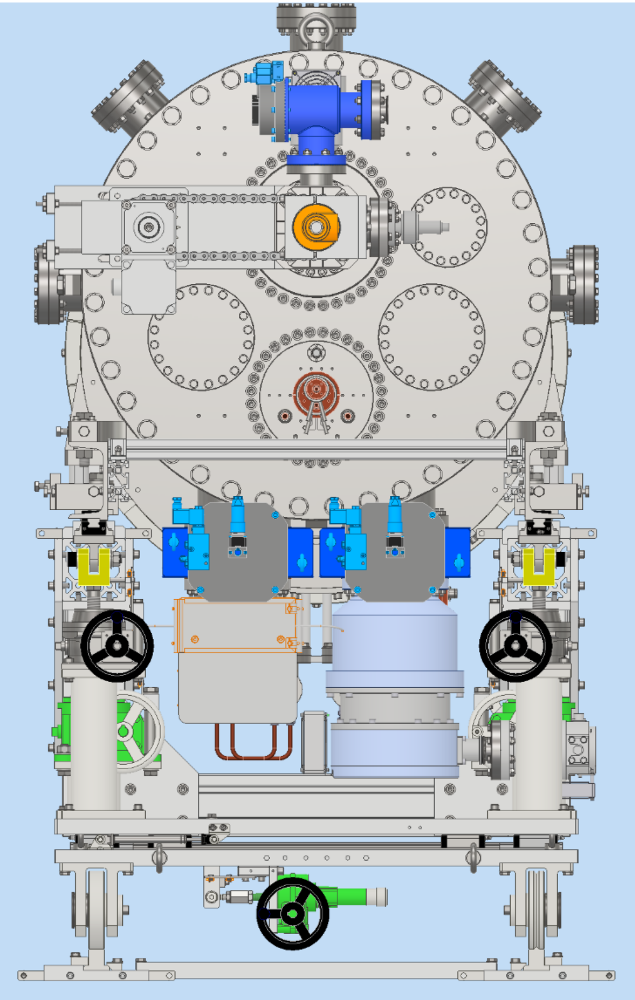
Main mission of positron source group

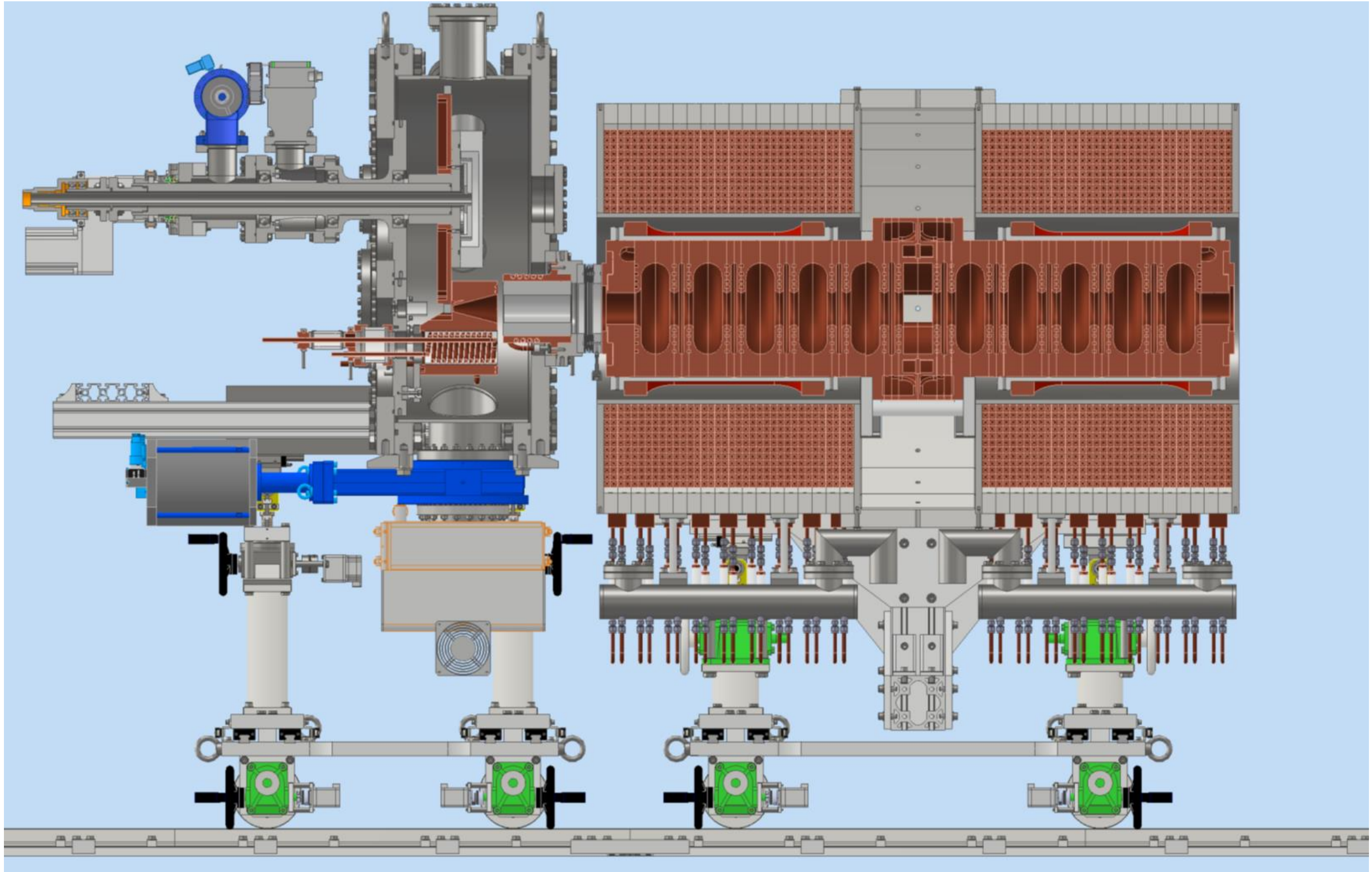
- Goals of ILC positron group in KEK is demonstrate our design
  - Prepare
    - engineering design report (EDR)
    - 3D CAD model
    - Drawings for manufacturing
  - Arrange test environment
  - Construct prototype and test it



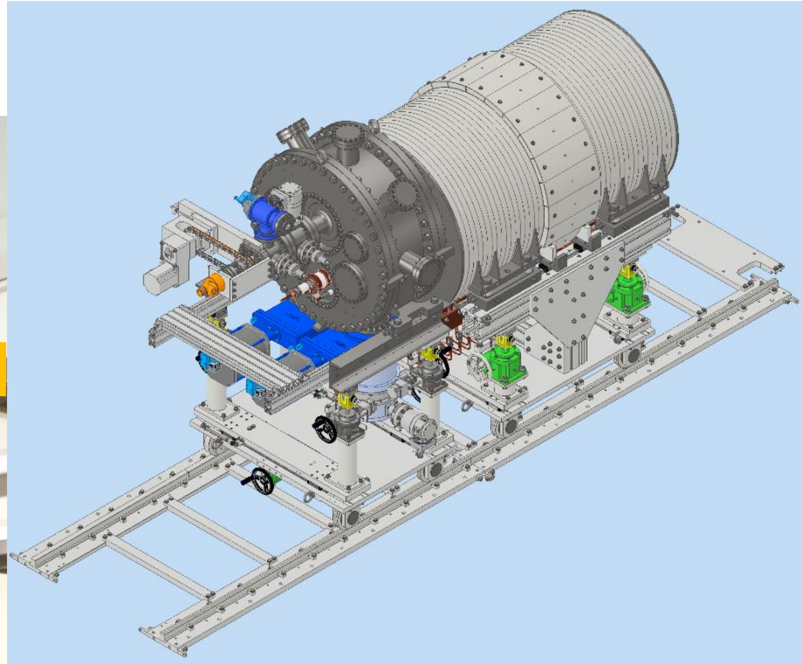
Real positron source, its 3D model and test bench for SuperKEKB
We are going to prepare the similar ones for ILC

Latest 3D model for ILC positron source



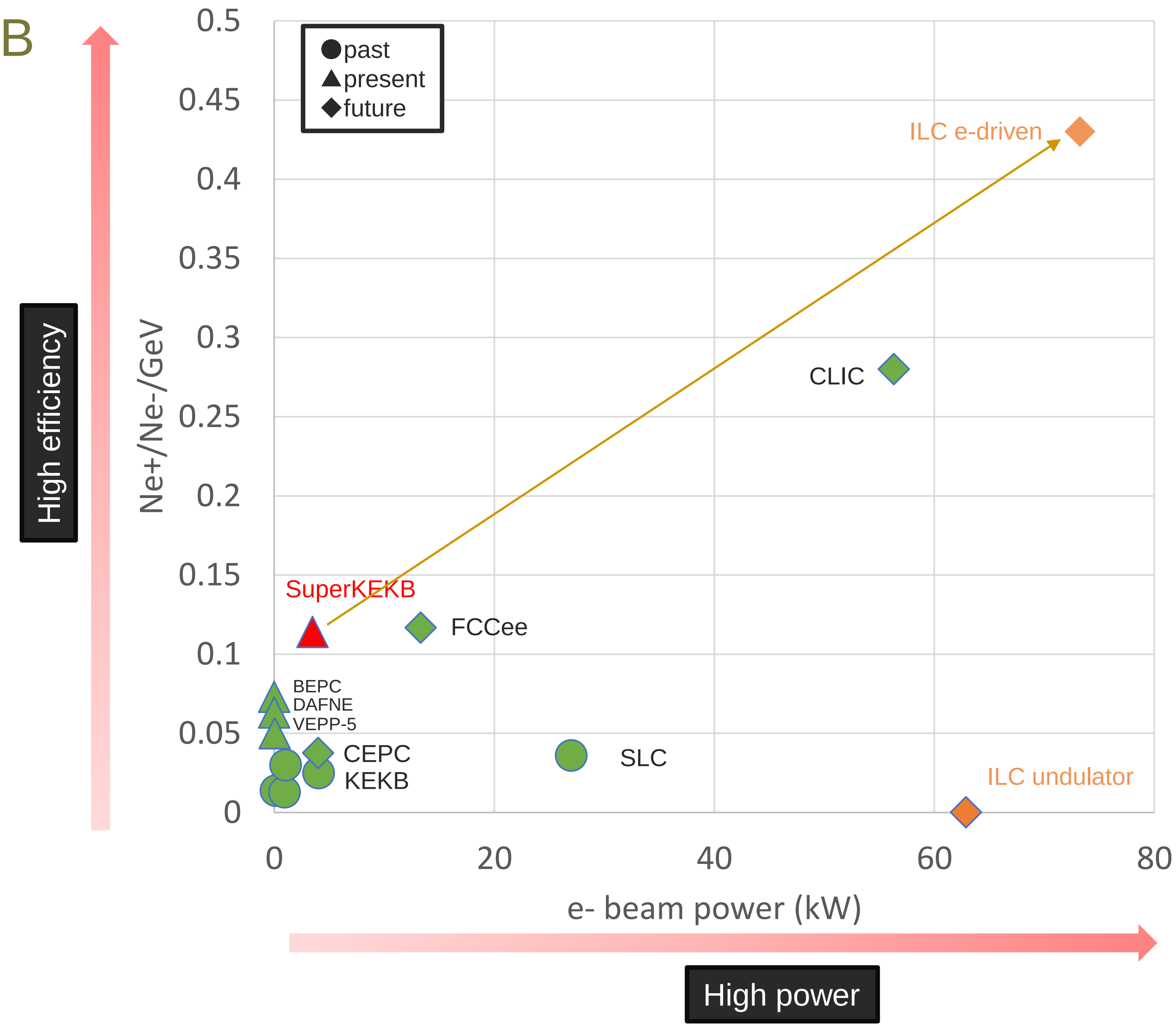


Test bench for ILC positron source

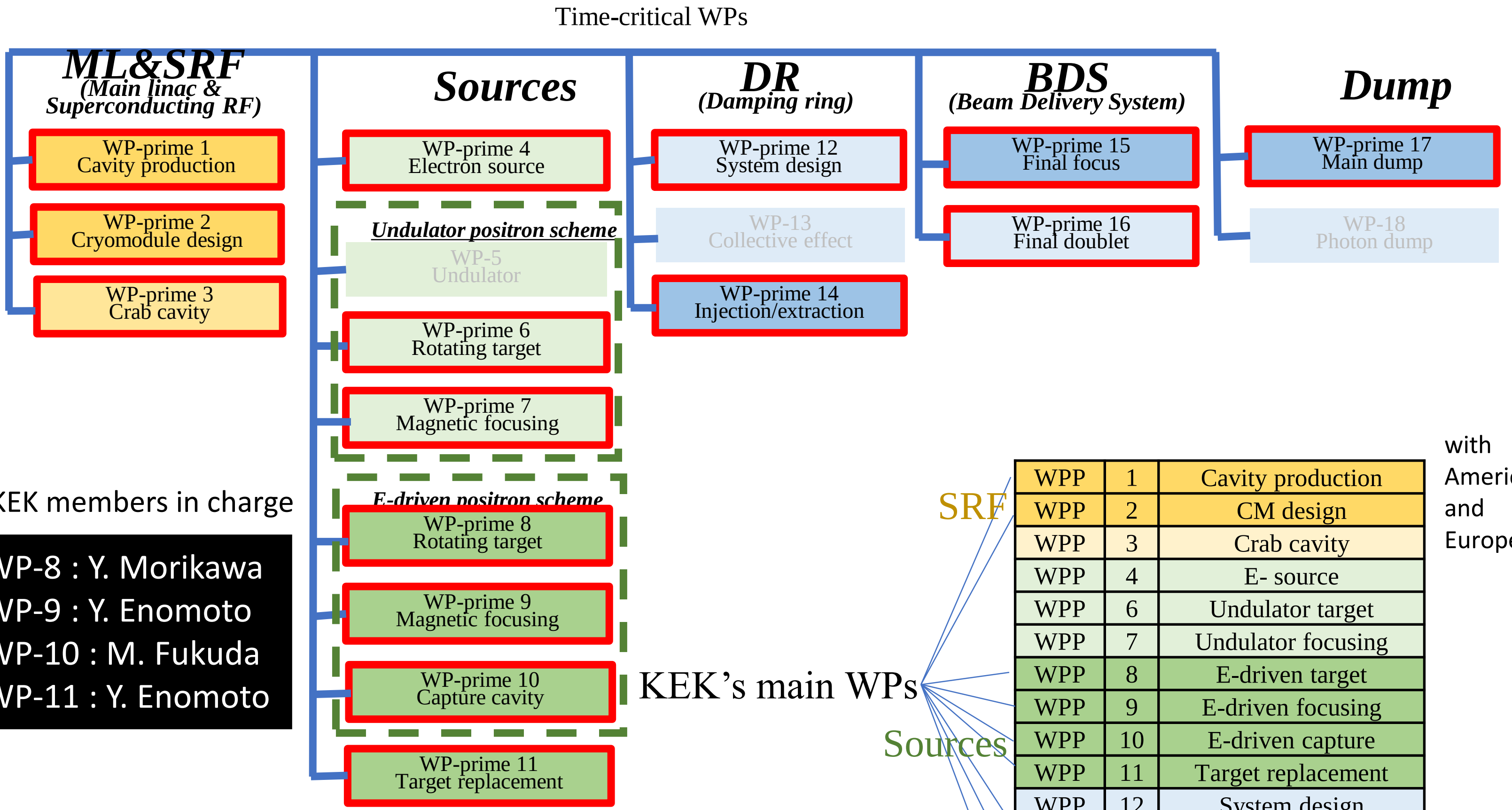


Comparison of positron sources

- Based on SuperKEKB
- Big jump from SuperKEKB
- 3 x SLC in beam power (74 kW)
- 4 x SuperKEKB in capture efficiency



ILC Technology Network



KEK members in charge

WP-8 : Y. Morikawa
WP-9 : Y. Enomoto
WP-10 : M. Fukuda
WP-11 : Y. Enomoto

H. Hayano support us mainly on capture cavity design

KEK's main WPs

SRF / Sources / Nanobeam

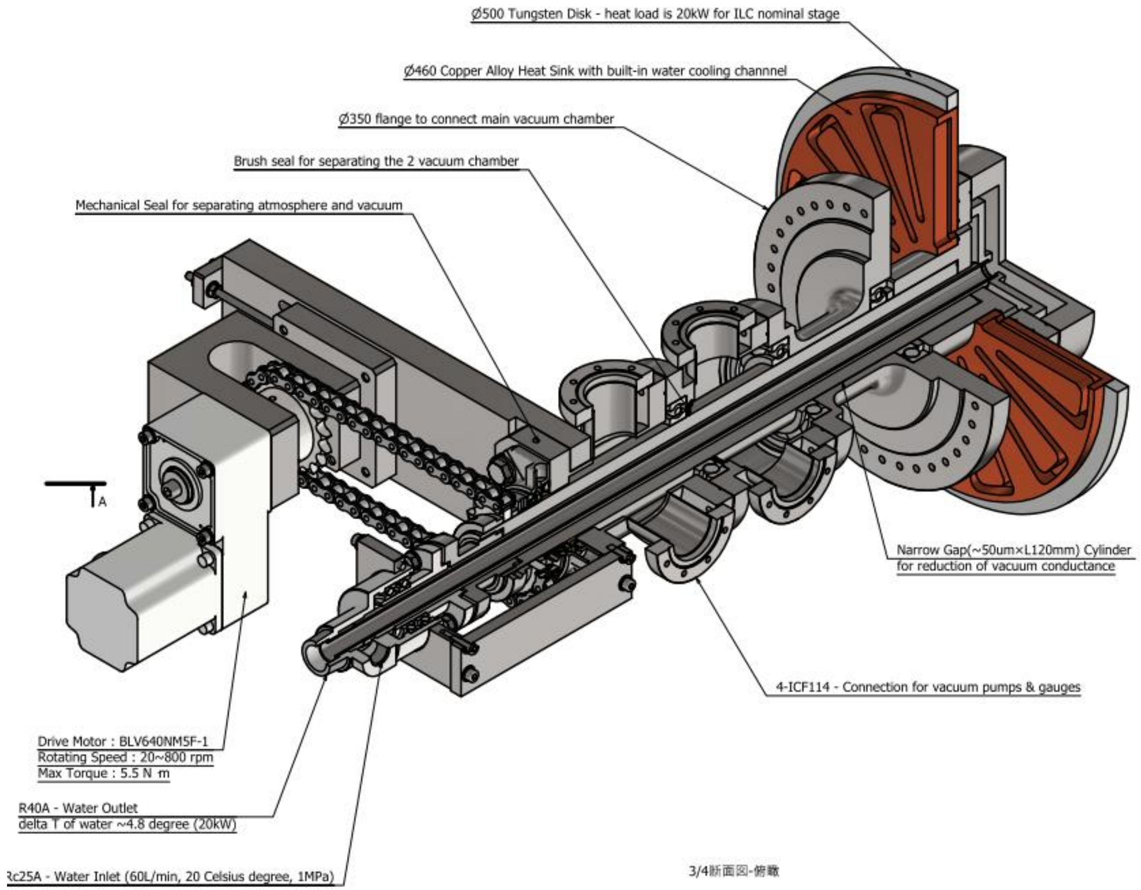
WPP	1	Cavity production
WPP	2	CM design
WPP	3	Crab cavity
WPP	4	E- source
WPP	6	Undulator target
WPP	7	Undulator focusing
WPP	8	E-driven target
WPP	9	E-driven focusing
WPP	10	E-driven capture
WPP	11	Target replacement
WPP	12	System design
WPP	14	Injection/extraction
WPP	15	Final focus
WPP	16	Final doublet
WPP	17	Main dump

with Americas and Europe

ATF collaboration

WP-prime 8 Rotating Target for e-Driven Scheme

- 74 kW (3 x SLC) beam power
- **Rotating mechanism**
  - **Water-cooled**
  - **UHV compatible**
  - **225 rpm**
- Target disk
  - W-Cu connection
    - Mechanical and thermal evaluation
    - CFD simulation using experimental data
    - HIP, SPS, Brazing
  - Target material selection and evaluation
    - Mechanical property at operating temperature
    - Cost, lead time, available size, uniformity



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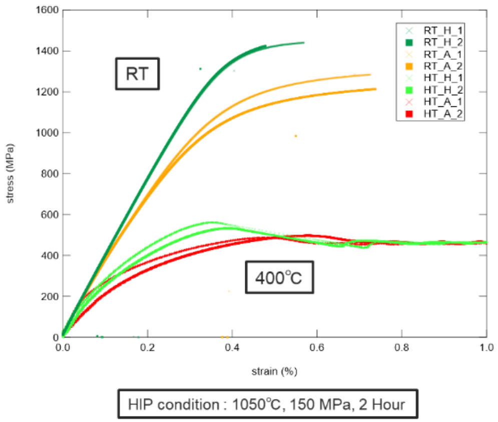
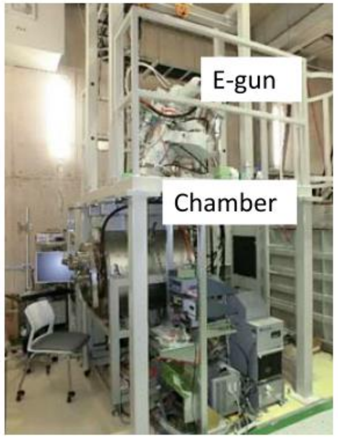
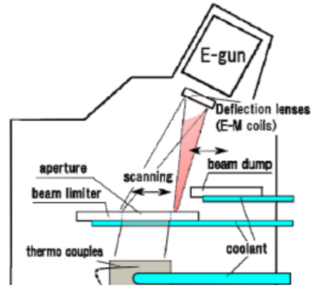
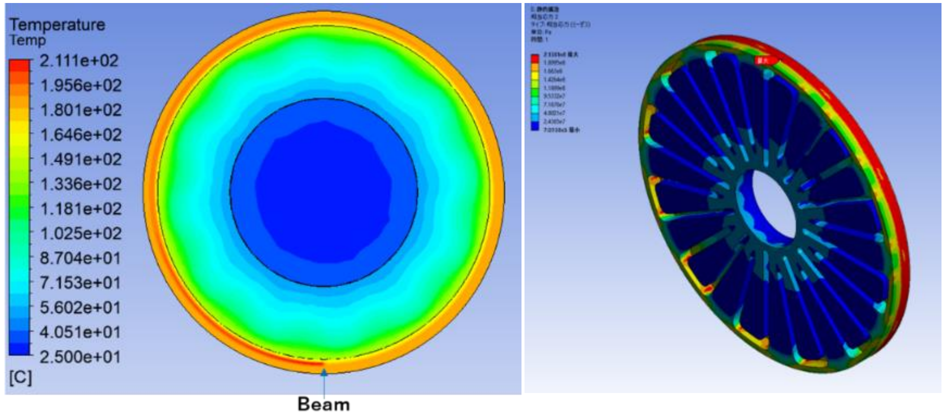


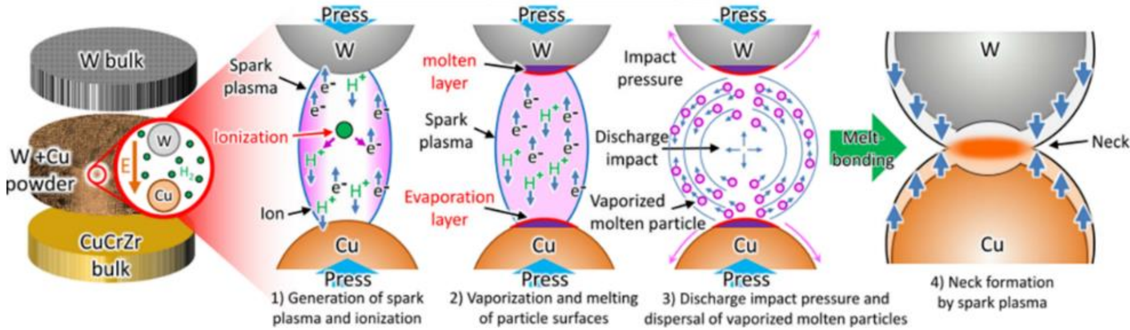


Electron gun: JEBG-3000UB manufactured by JEOL Ltd.



specifications		
parameters	value	unit
max. output power	300 (100)	kW
acceleration voltage	40	kV DC
max. current	7.5	A
max. scanning area	300 x 300	mm
spot size of e-beam	~10	mm





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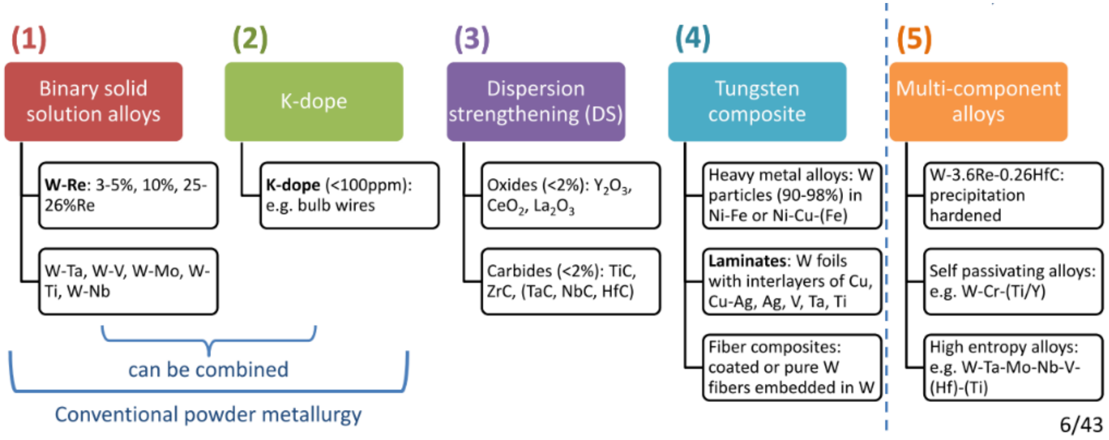
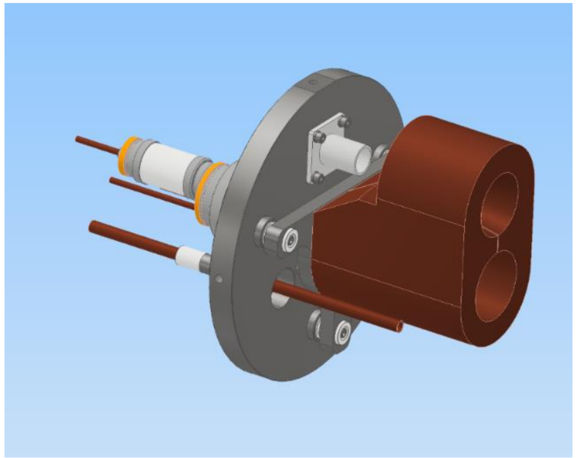


- To improve strength, ductility, recrystallization resistance, radiation tolerance, many alloying and composite technologies have been developed.
- We should keep in mind their availability, cost, lead time and availability.
- Especially, W is made by sintering, making large plate keeping uniformity is difficult.
- In the case of alloy, uniformity is much more important than that for pure W.
- There are no high-power positron target which use large size (50 cm diamater) W-alloy as far as I know.

WP-prime 9 Magnetic focusing

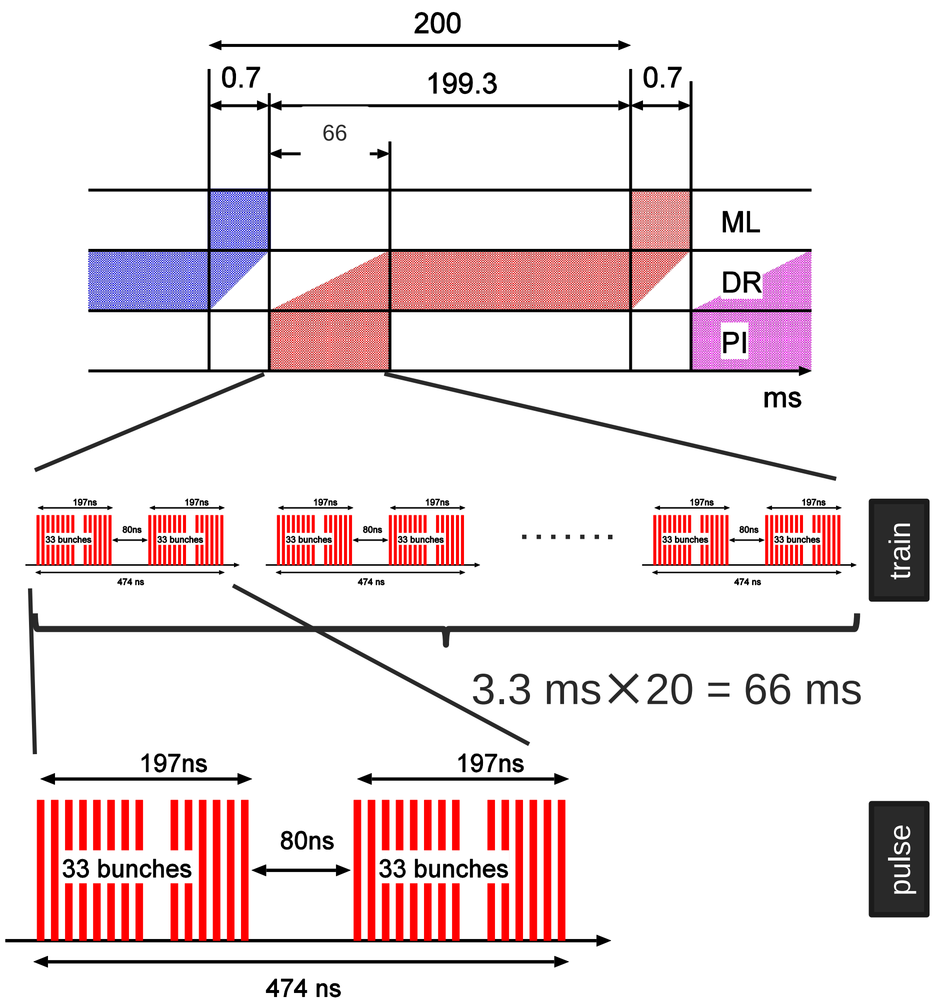
- Flux concentrator
  - 20 times higher ohmic loss compared with that of SKEKB
  - Additional beam loss from target
  - Fully 3D simulation established in the SKEKB project.
  - Two prototype and high-power test
- Pulsed power supply
  - 300 Hz compatible
  - 50 times higher power compared with that of SKEKB
  - Energy recovery mechanism is necessary
- Need parameter optimization
  - Present parameters are not realistic especially power supply
  - Shorter pulse length
    - Need higher voltage
    - Counter measure to discharge
    - Flat top control

	ILC	SKEKB
Primary current	33 kA	12 kA
Secondary current	25 kA	12 kA
Pulse width	25 us	5 us
Repetition	100 Hz	50 Hz
Ohmic loss	14 kW	0.7～0.8 kW (measured)
Beam loss	4 kW	Small
Total loss@ Load	18 kW	0.7～0.8 kW (measured)
P.S. power	(630 kW) 210 kW	12 kW



Bunch structure

M. Kuriki, OHO seminar 2021

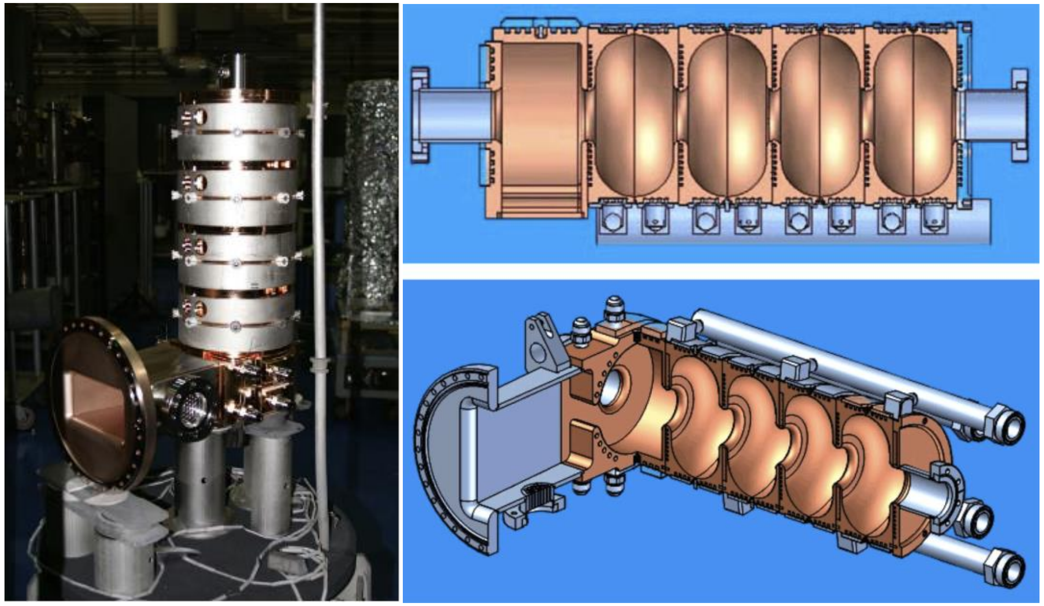


- Create positron for 66 ms
- Store them in the DR for 199.3 ms
- Extract them to main linac for 0.7 ms
- 20 pulse / train
- 66 bunch / pulse
- 1320 bunch / train
- Repetition 5 Hz

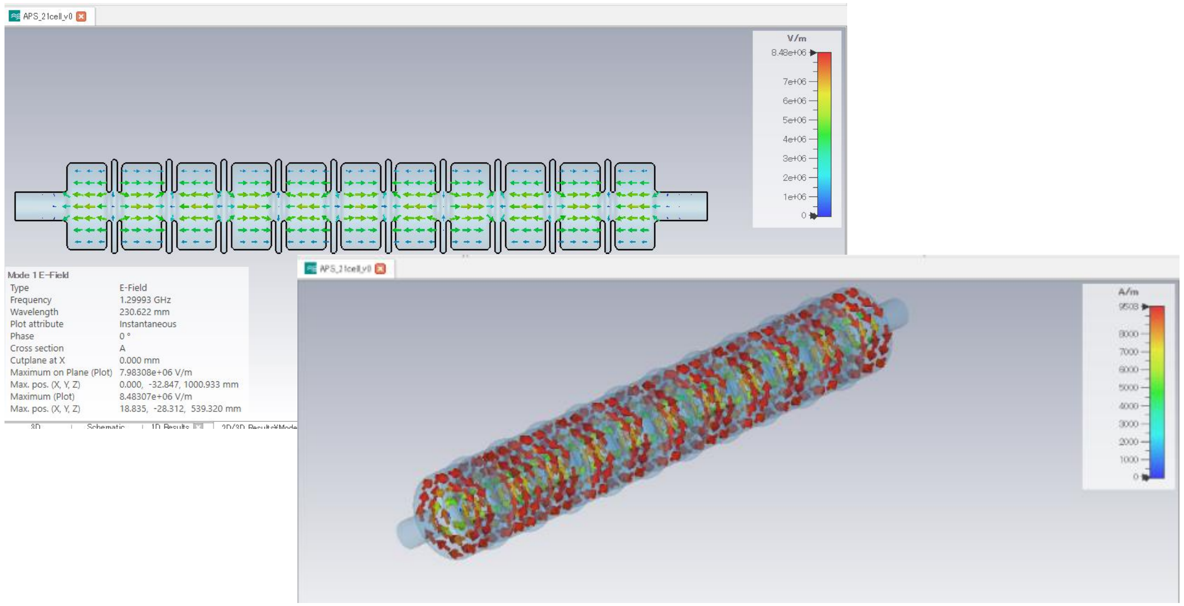
- FC must keep field variation below the requirement to keep bunch-by-bunch charge variation
- Minimum current pulse width is about 500 ns

WP-prime 10 Capture cavity

- Design challenges of Large aperture L-band cavity
  - Beam loading compensation for multi bunch operation
    - Full model RF and beam simulation
    - Simulation method using CST is almost established
  - Very high heat load of shower from the target
    - novel cooling design
  - Remote beam flange connection
    - Connection point is surrounded by solenoid
- Two prototype and high-power test



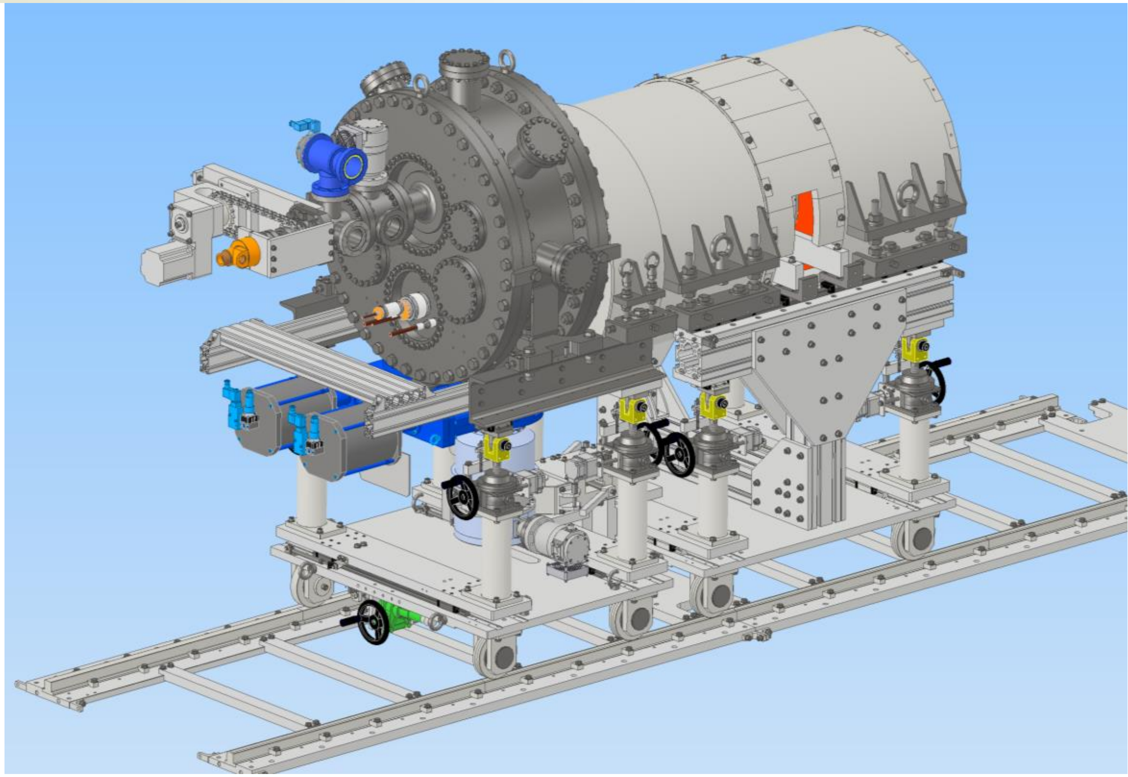
Previous design and prototype at SLAC
Phys. Rev. AB 12, 042001 (2009)



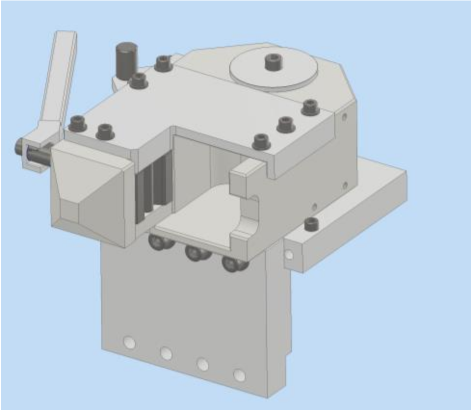
3D RF simulation of APS cavity at KEK

WP-prime 11 Target replacement

- Total model preparation
  - Construct as early as possible
    - Use dummy for FC, Acc. Structure at first
  - Prepare and manage full 3D CAD model
  - Improve continuously
- 3 times exchange experiences through SKEKB operation
- Collaboration with other high power target facilities, J-PARC, RIKEN, FRIB…
- Automatic connection disconnection mechanism
  - Flange connection
  - Movable base connection



Girder structure on rail



Automatic connection coupler

Pillow seal

Summary of WPs

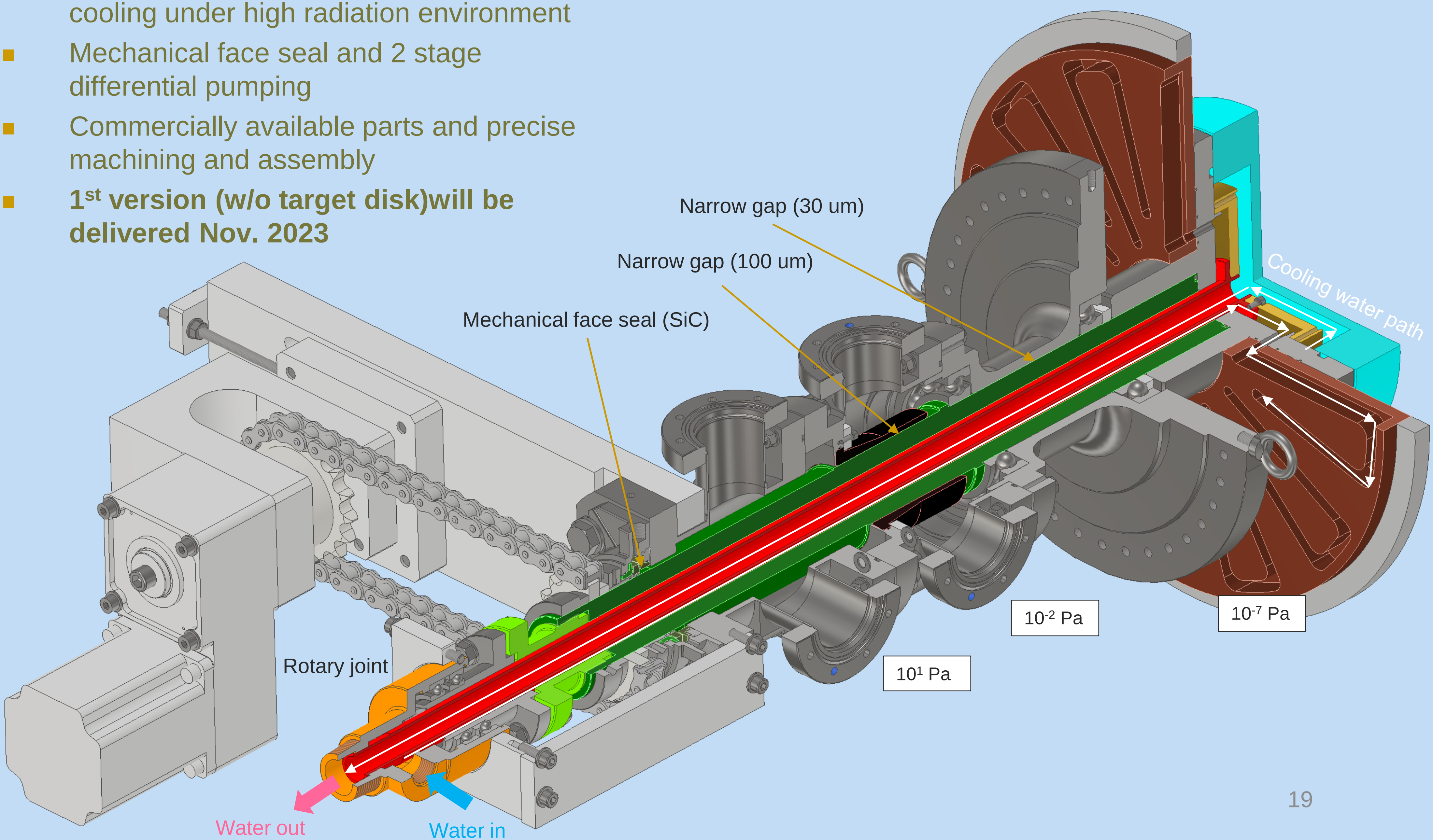
- Each development topic is challenging
- Development based on experiences through SuperKEKB
- Integration into one package is more important and difficult task
- Prototyping and continuous improvement are necessary

Present status

- Target rotation mechanism
- Target heatsink connection
- FC design
- Acc. Structure design
- Collimator and pillow seal
- Tracking simulation

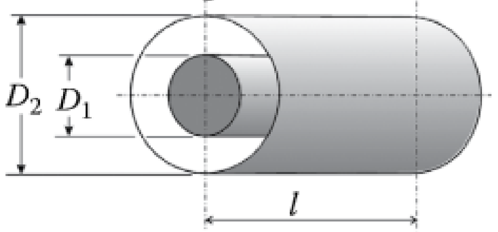
Target rotation mechanism

- UHV compatible rotating target with water cooling under high radiation environment
- Mechanical face seal and 2 stage differential pumping
- Commercially available parts and precise machining and assembly
- **1st version (w/o target disk)will be delivered Nov. 2023**



Differential pumping

3. Duct with annular cross section; for K_5 see Figure 3.6.



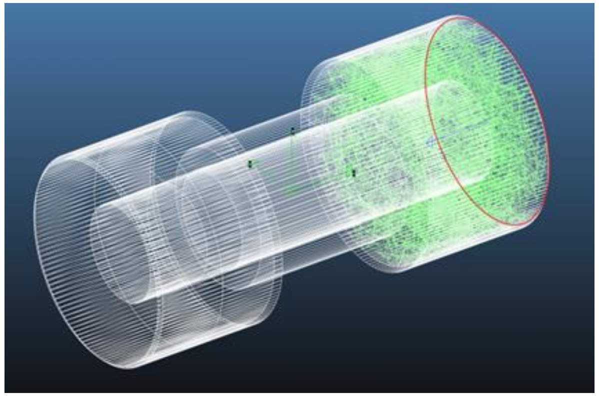
$$F_m = K_5 \frac{\pi v_a}{12} \frac{(D_2 - D_1)^2 (D_2 + D_1)}{l} \quad \left[m^3/s\right]$$

or

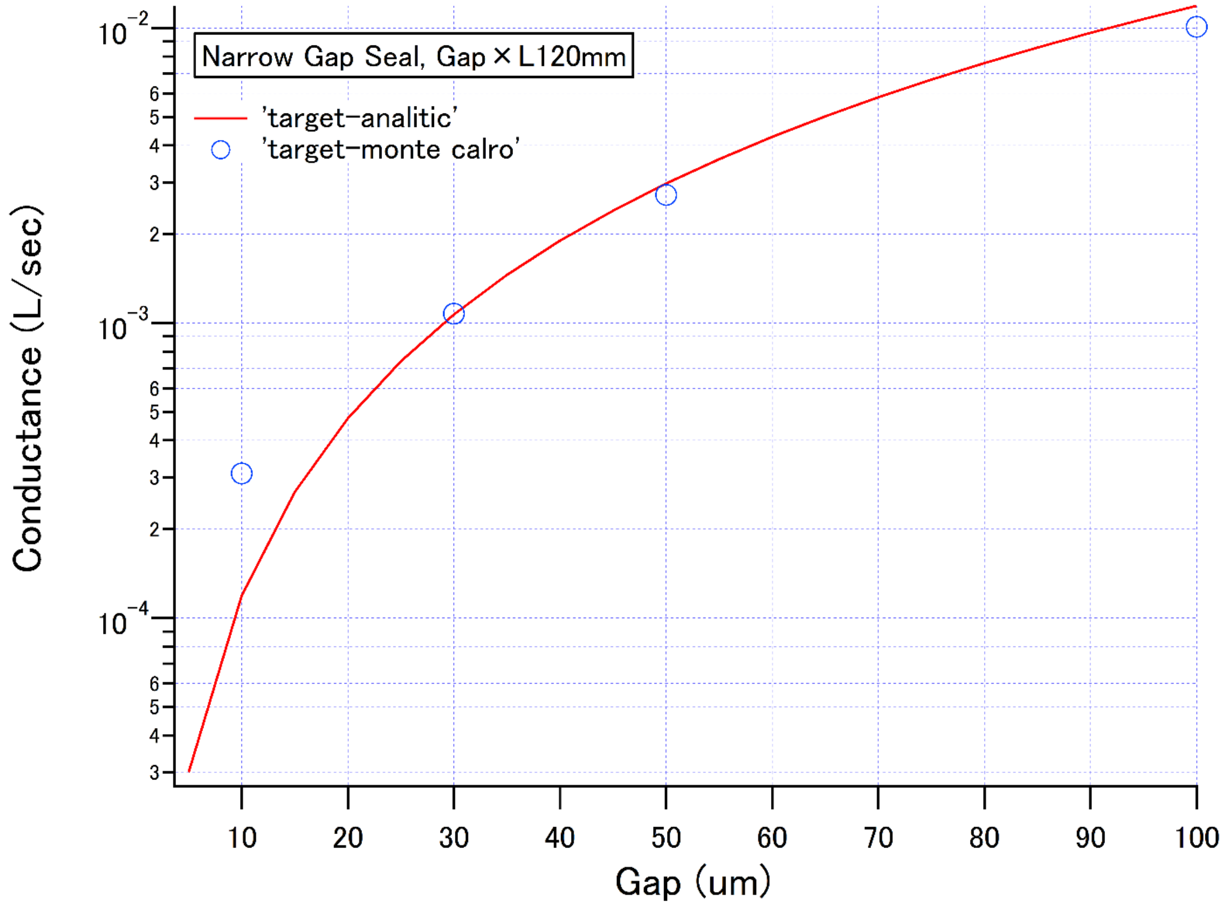
$$F_m = K_5 \left(\frac{T}{M_a}\right)^{1/2} \frac{(D_2 - D_1)^2 (D_2 + D_1)}{l} \quad \left[m^3/s\right]$$

For air 20 ^{0}C

$$F_m = 121.12 K_5 \frac{(D_2 - D_1)^2 (D_2 + D_1)}{l} \quad \left[m^3/s\right]$$



- Analytical formula and simulation
- Assume 100 L/sec effective pumping speed, 10^{-5} pressure difference will be achieved 30 um gap
- Filling gap by radiation resistant vacuum grease is possible option for further reducing conductance

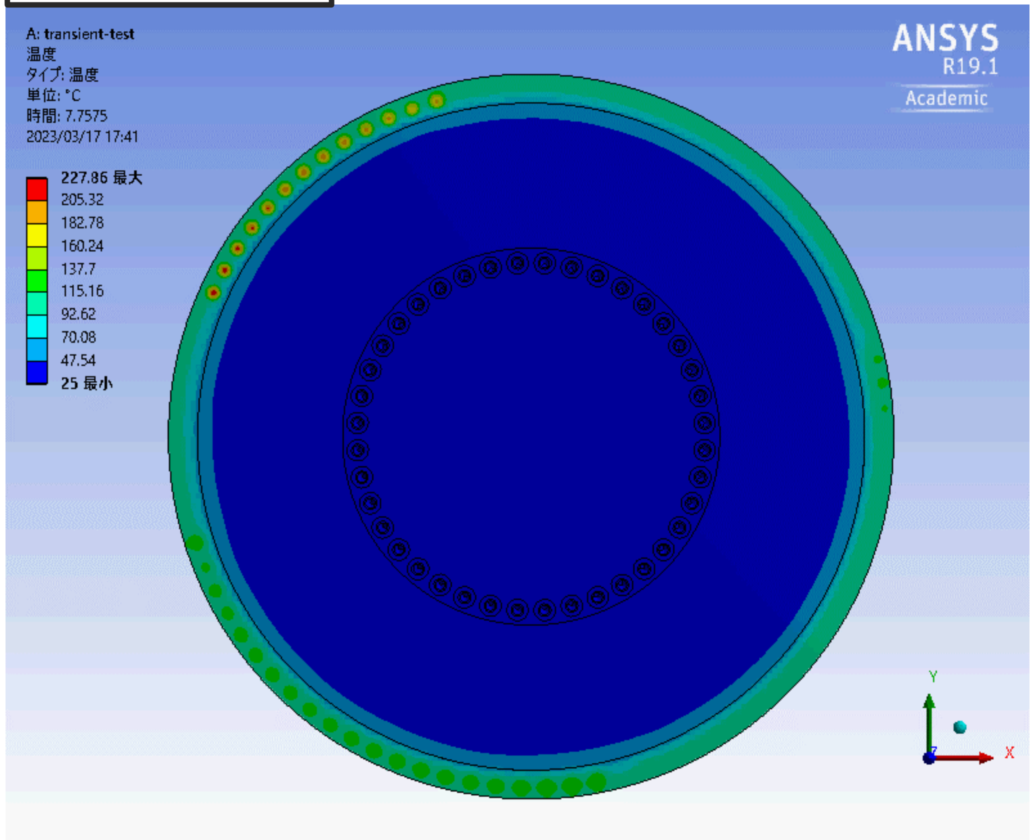


Target - heatsink connection

- HIP (Hot isotropic pressing)
  - ☑ Prepare sample
  - ☑ Strain-stress test
- SPS (spark plasma sintering)
  - ☑ Prepare sample
  - ☐ Strain-stress test
  - ☐ Thermal resistance measurment

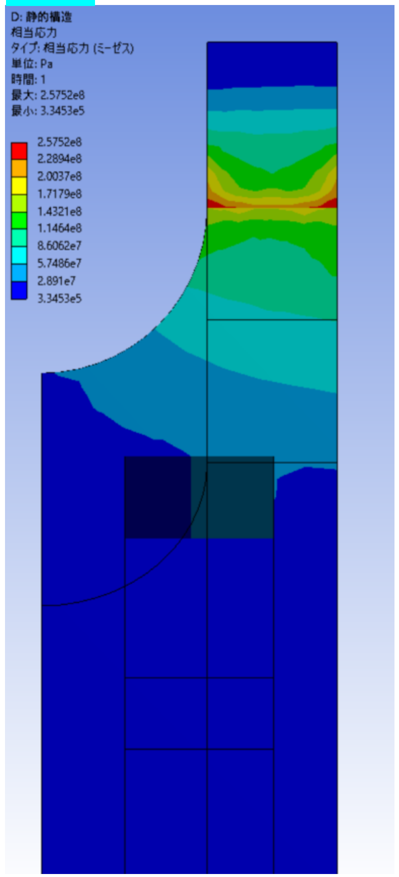
Thermo-mechanical simulation

Temperature

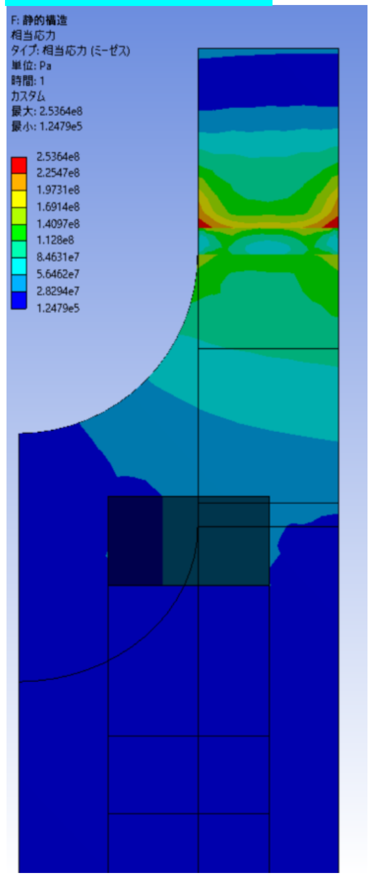


stress

W/Cu



W/Cu50-W50/Cu



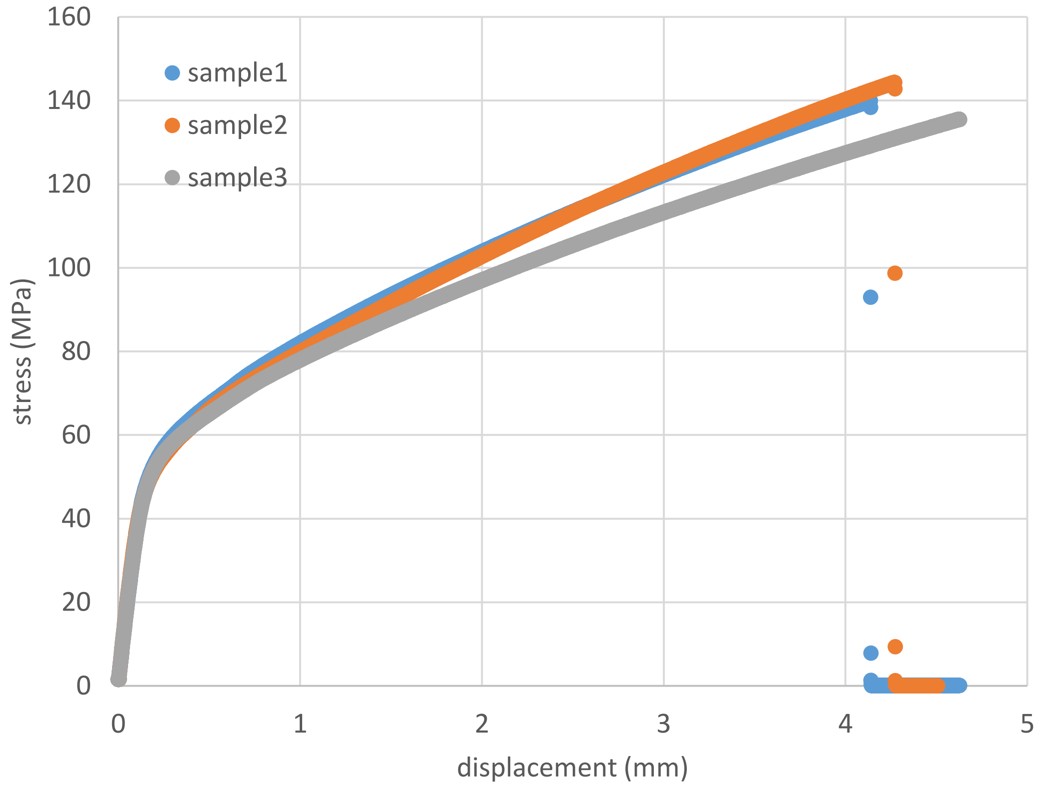
Preliminary Results

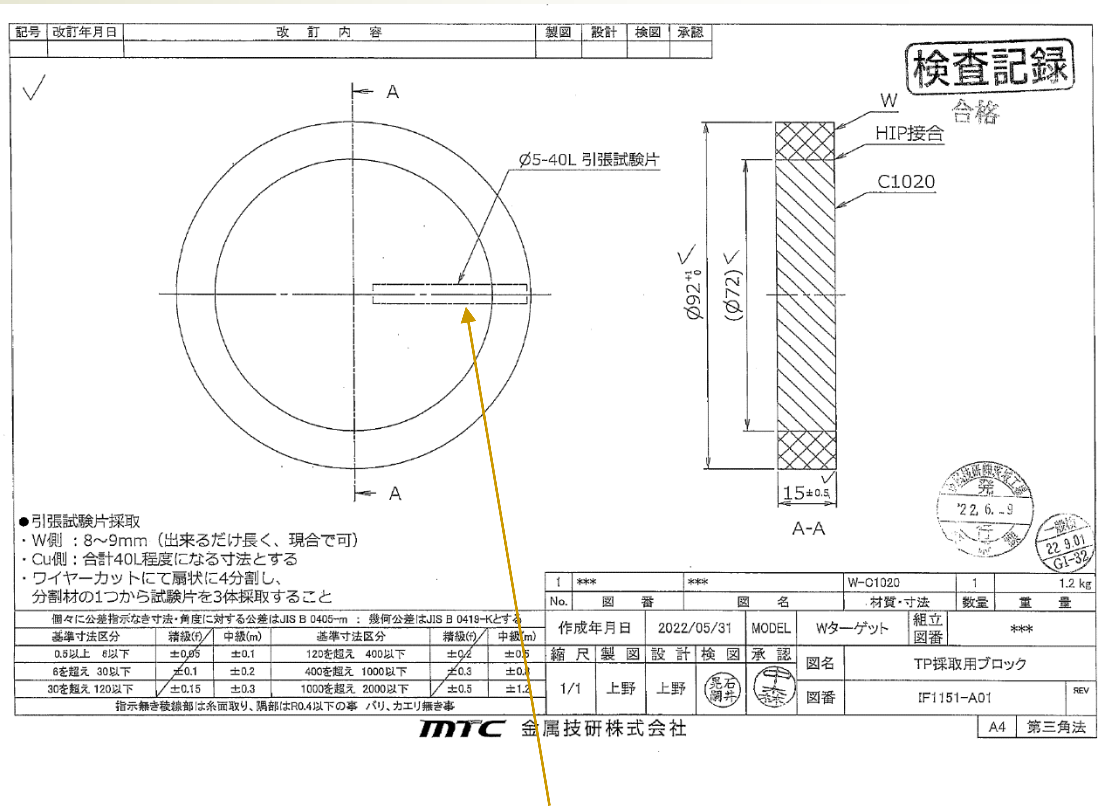
	ILC e-driven
Primary electron energy(e^-) [GeV]	3
e^- Beam power [kW]	74
e^- Beam size on target [σ - mm]	2
Target material	W (or W alloy)
Target thickness	$4.5X_0$-(15.7mm)
Power deposition on target [kW]	18.8
PEDD*** [J/g]	33.6
Max temperature of Cu alloy [°C]	~160
Max temperature of W [°C]	~420
Max equivalent stress at W/Cu junction [MPa]	~200
Max equivalent stress at W junction [MPa]	~250

	Temp. at W-Cu contact surface	Max stress in W	Max stress in Cu (direct)	Max stress in Cu (transition layer)
Original design	115℃	255 MPa	197 MPa	153 Mpa
Cooling water path optimization	68℃	150 MPa*	116 MPa*	90 MPa*

*expected value, simulation is ongoing

HIP





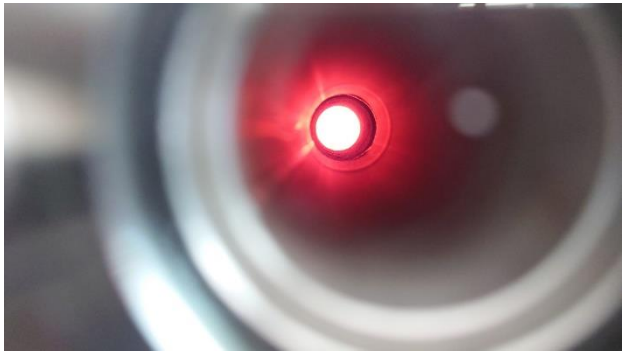
Sample(Φ5-40L) for strain-stress test

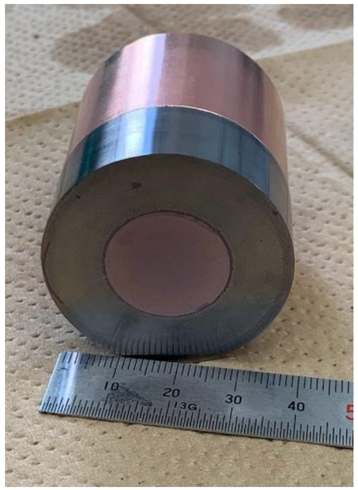
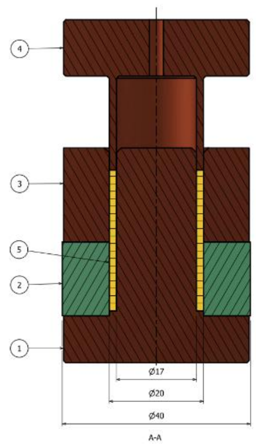
Separated at contact surface (∼150 MPa)
Strength of the connection is less than Cu yield strength (∼200 MPa)
HIP is used for SuperKEKB target

SPS(Sparc plasma sintering)

- Collaboration with NIFS (National Institute for Fusion Science)
- Fill Cu and W powder between W ring and Cu disk
  - Press, heat up, current flow
- Searching condition for sample production
  - First step Φ40
  - Second step Φ100 with water cooling port
- Strain-stress test
  - done for 1st sample
- Thermal resistance measurement
  - At NIFS high power electron beam facility (300 kW) in this winter

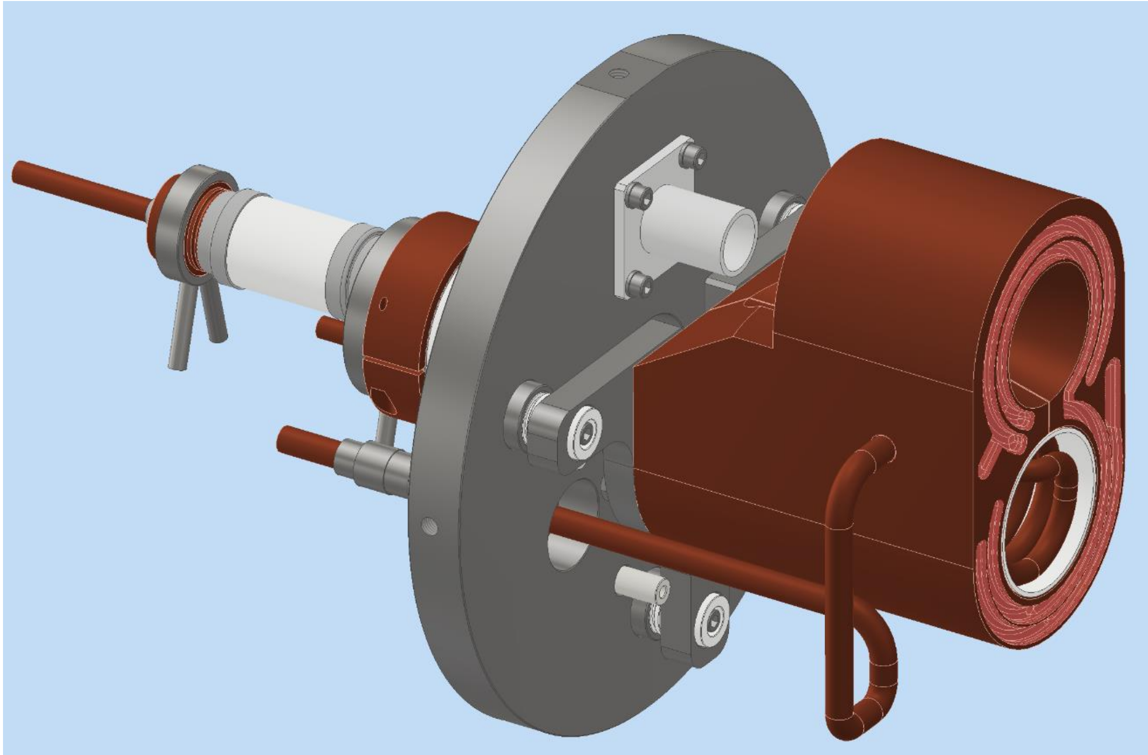




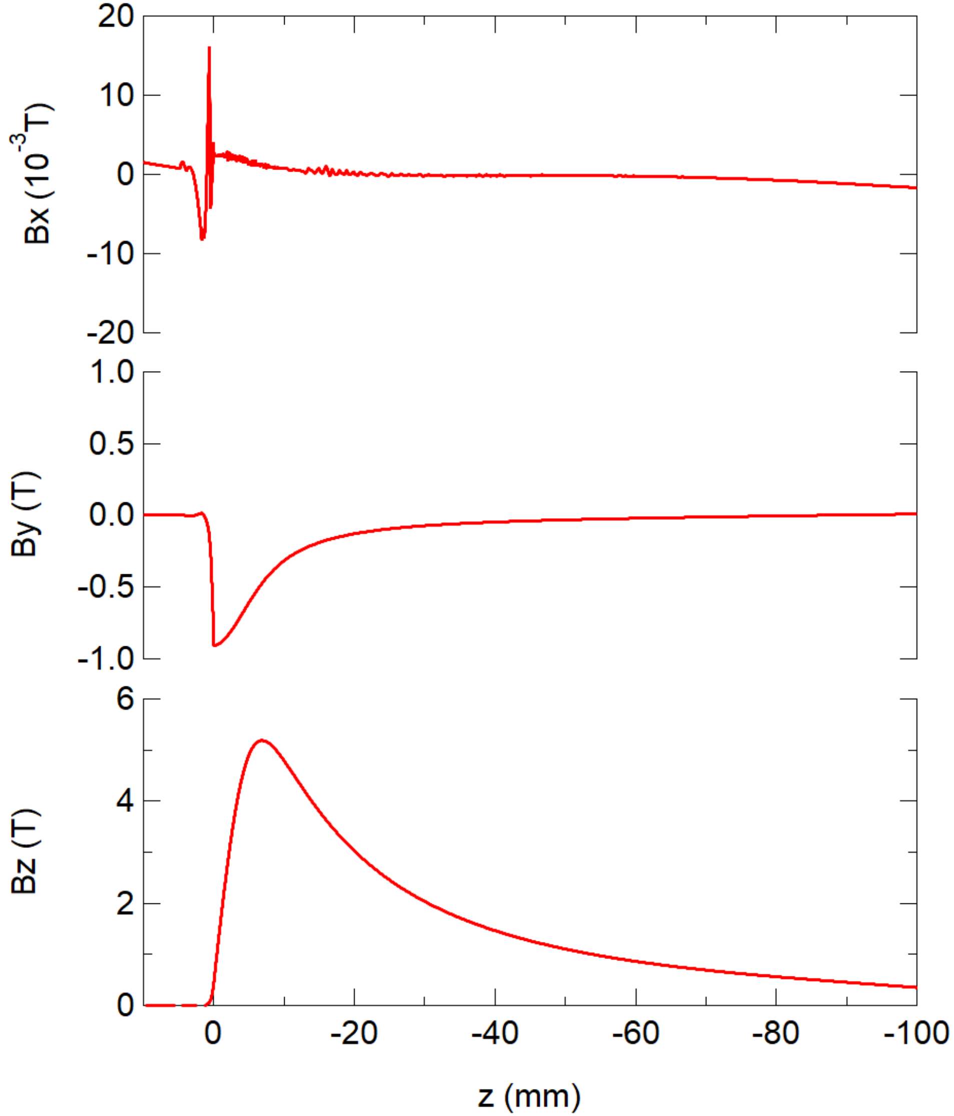
FC

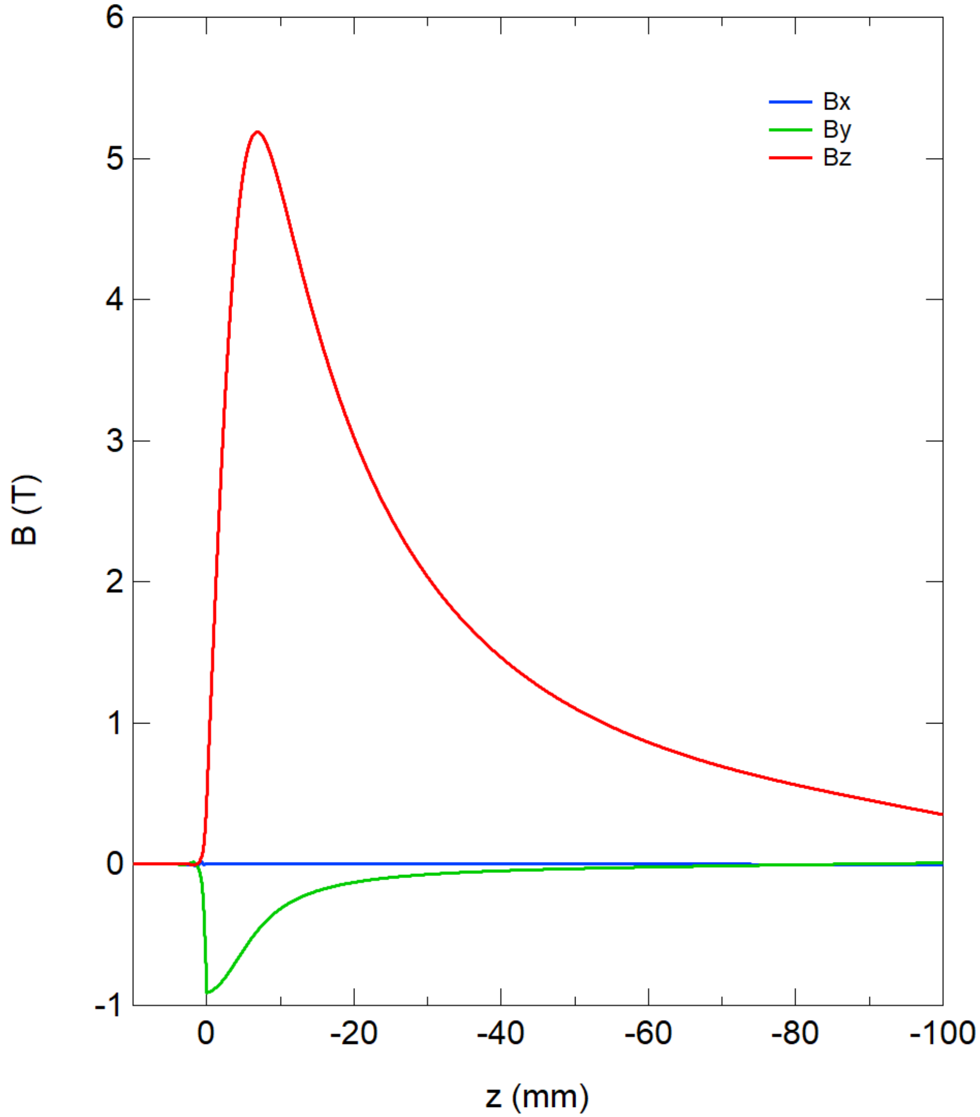
- EM-thermal simulation using CST with engineering model
  - Evaluation method was established in SuperKEKB design
  - Transient magnetic solver
  - Steady state thermal solver
  - Transient thermal solver
- Large Ohmic loss is expected
  - Optimize parameters
    - Aperture
    - Current waveform (pulse width)
    - Material
    - Slit width
    - Inlet radius
    - Cooling water path



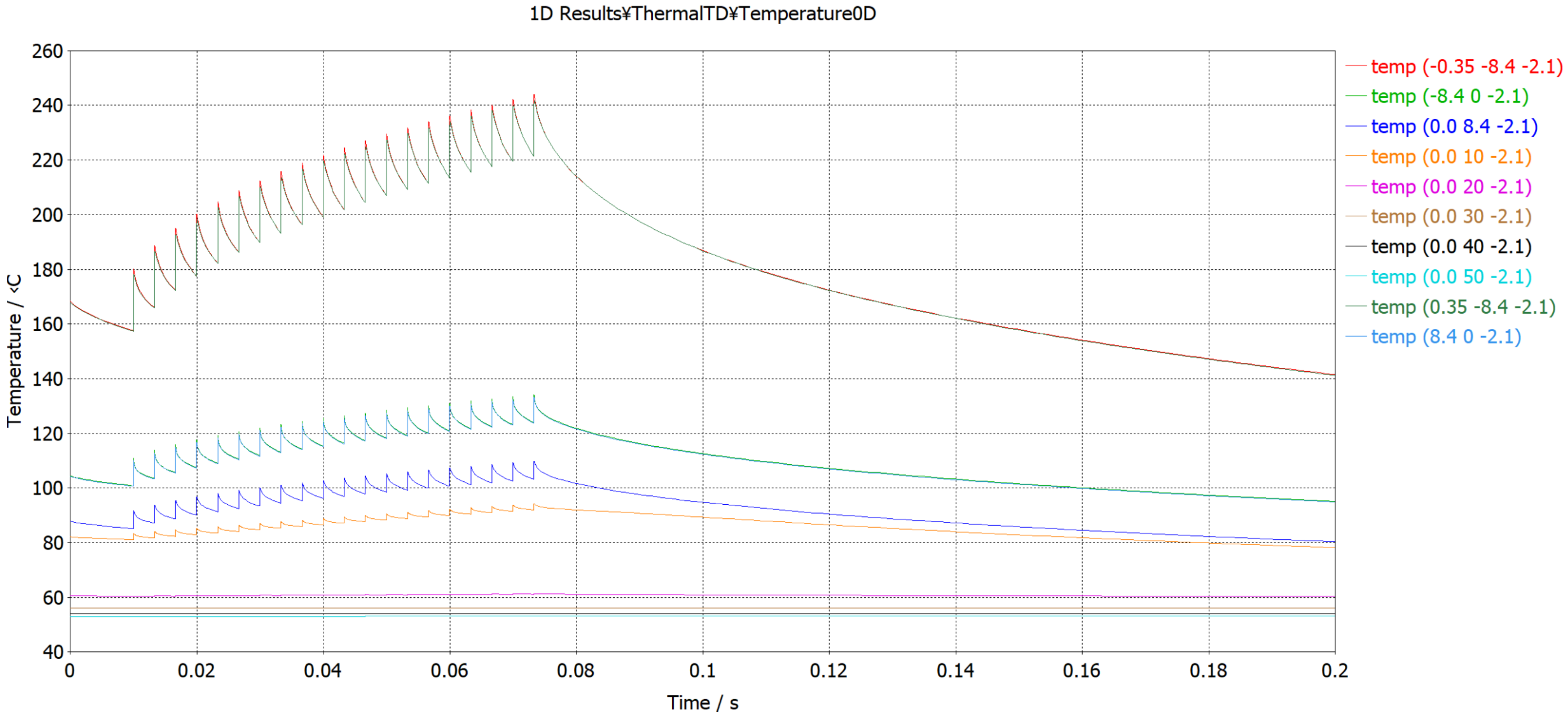
	SuperKEKB	ILC
Peak Bz	3.5 T	5 T
Aperture	7 mm	16, 12 mm
repetition	50 Hz	100 Hz
Pulse width	5 us	10 ～ 25 us
Ohmic loss	0.5 ～ 0.8 kW (measured)	Around 10 kW (depend on aperture and pulse width)

Magnetic field

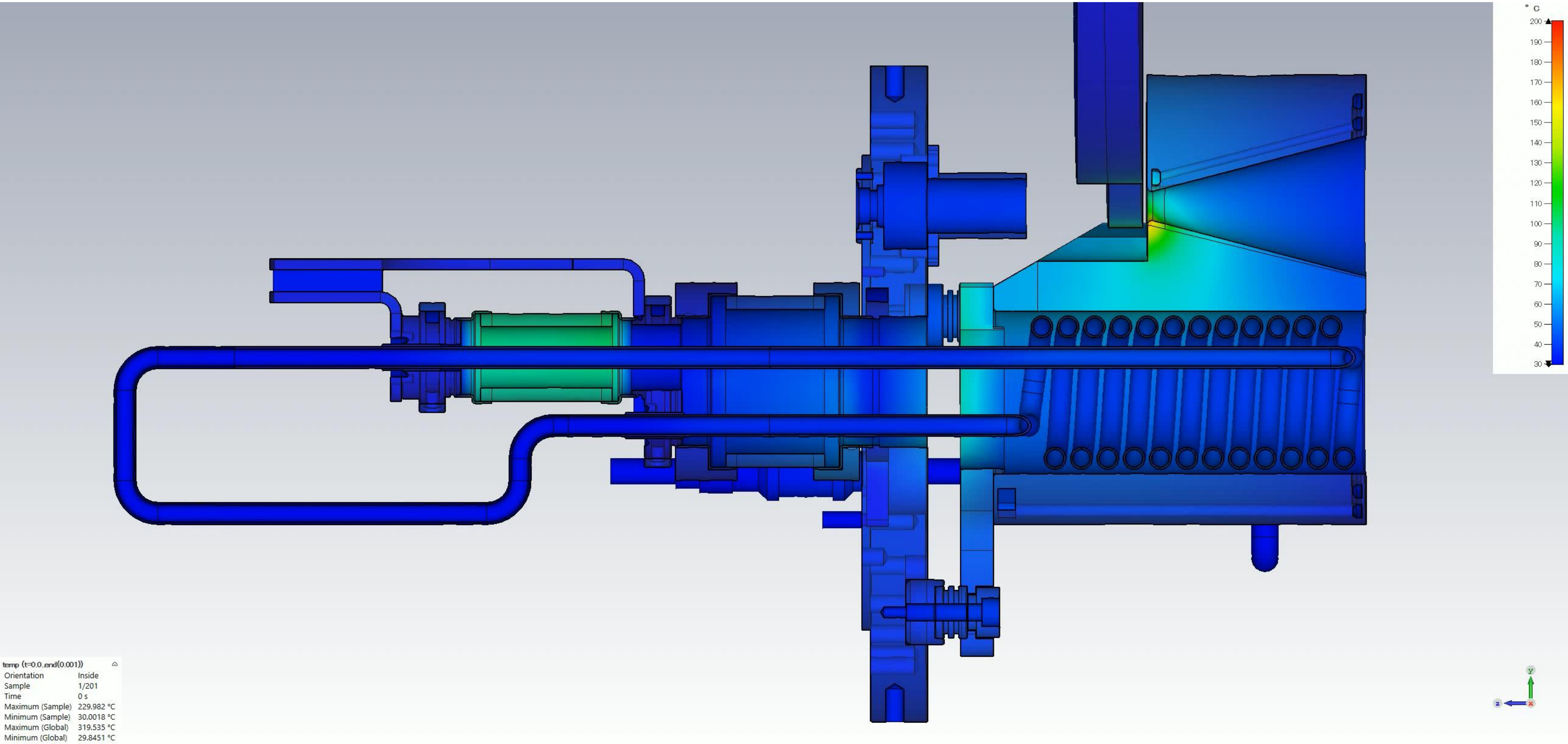




Transient temperature rise



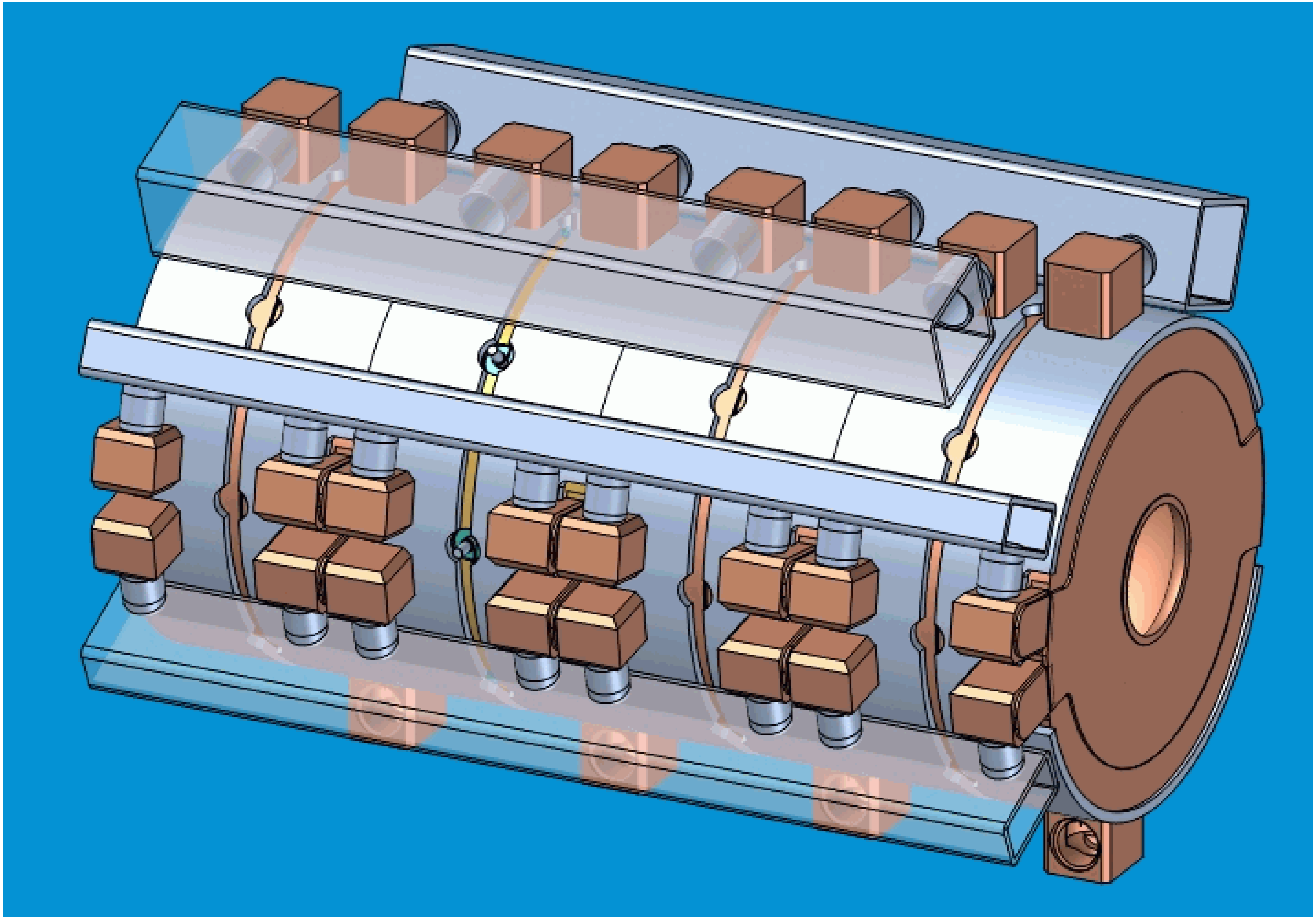
Transient temperature rise



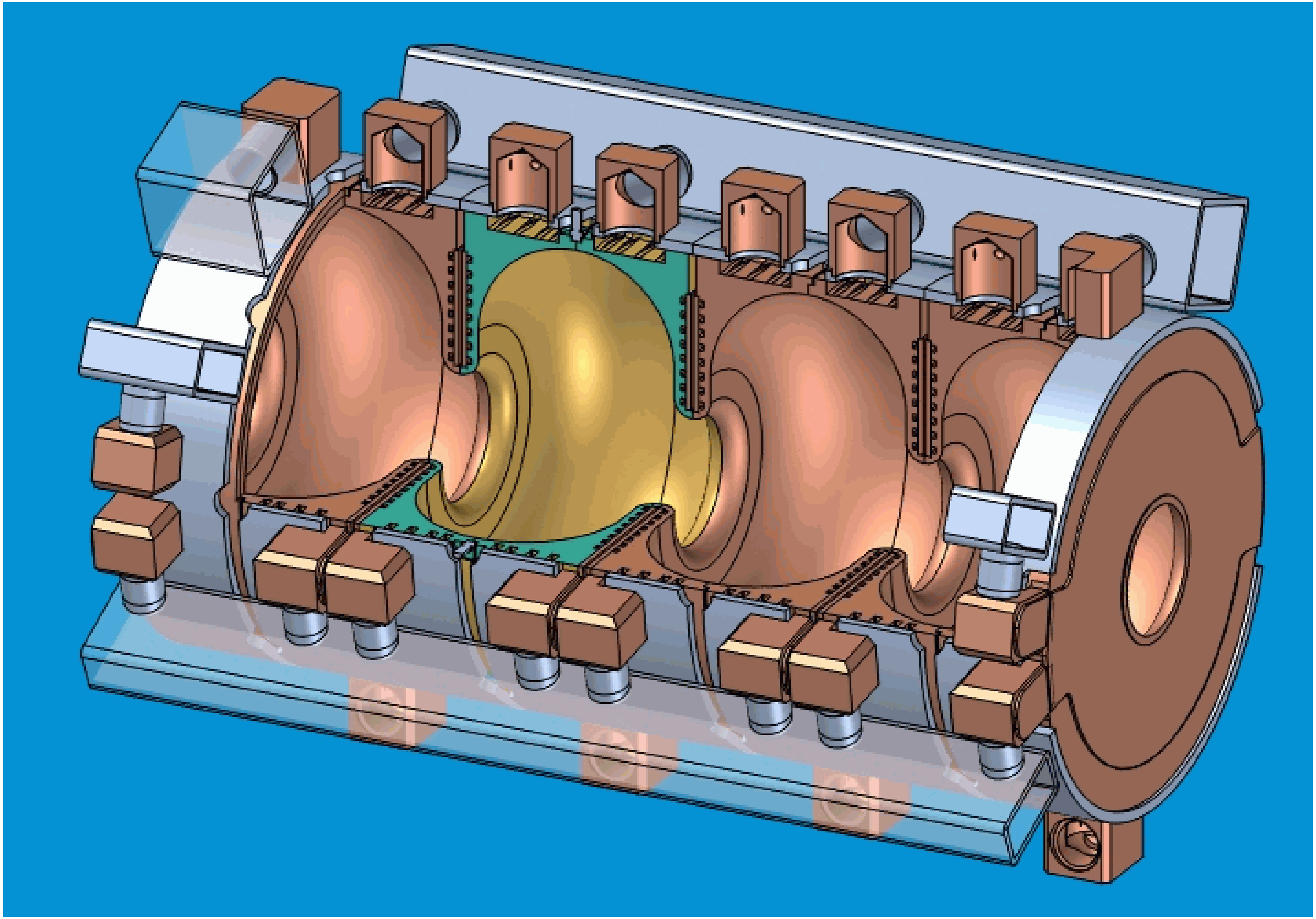
Acc. structure

- Reference design by SLAC (15 years ago)
- 500L/min. cooling water for 1.4 m L-band structure to reduce temperature rise by shower

SLAC model



SLAC model



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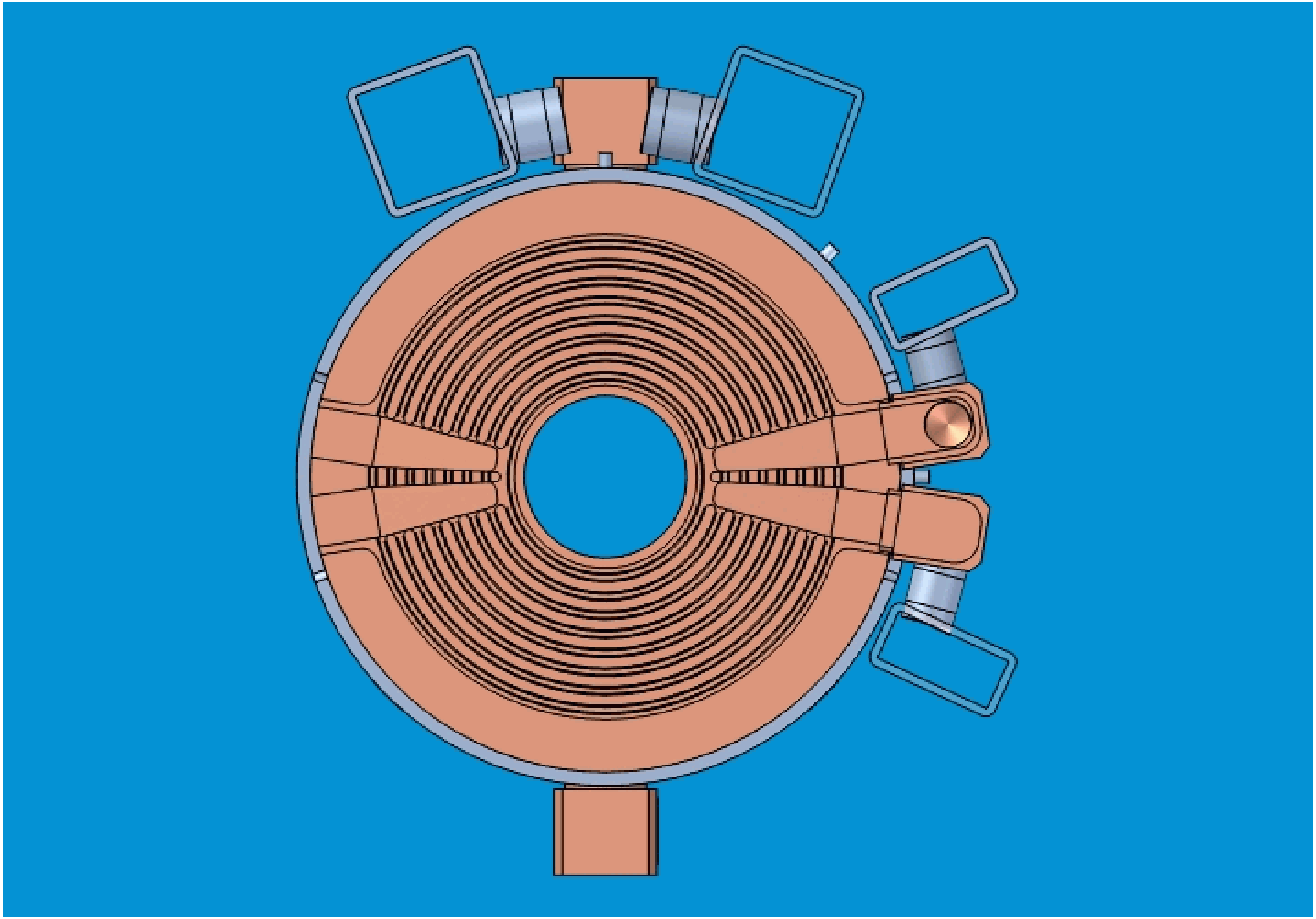
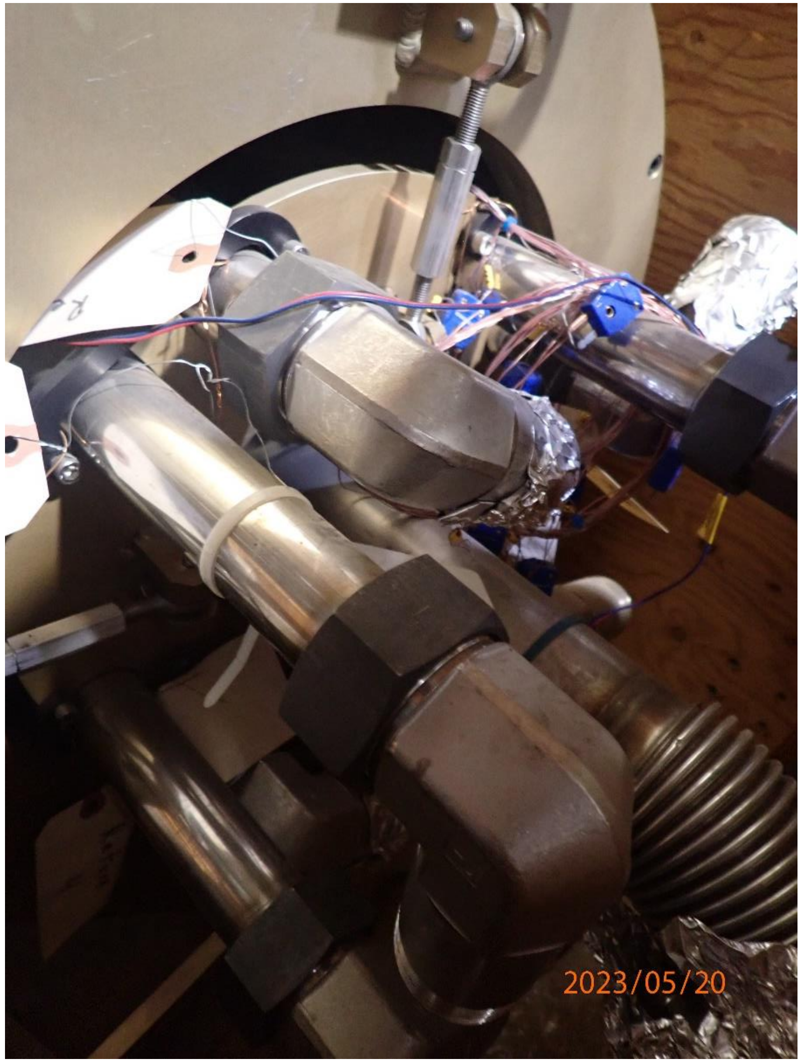


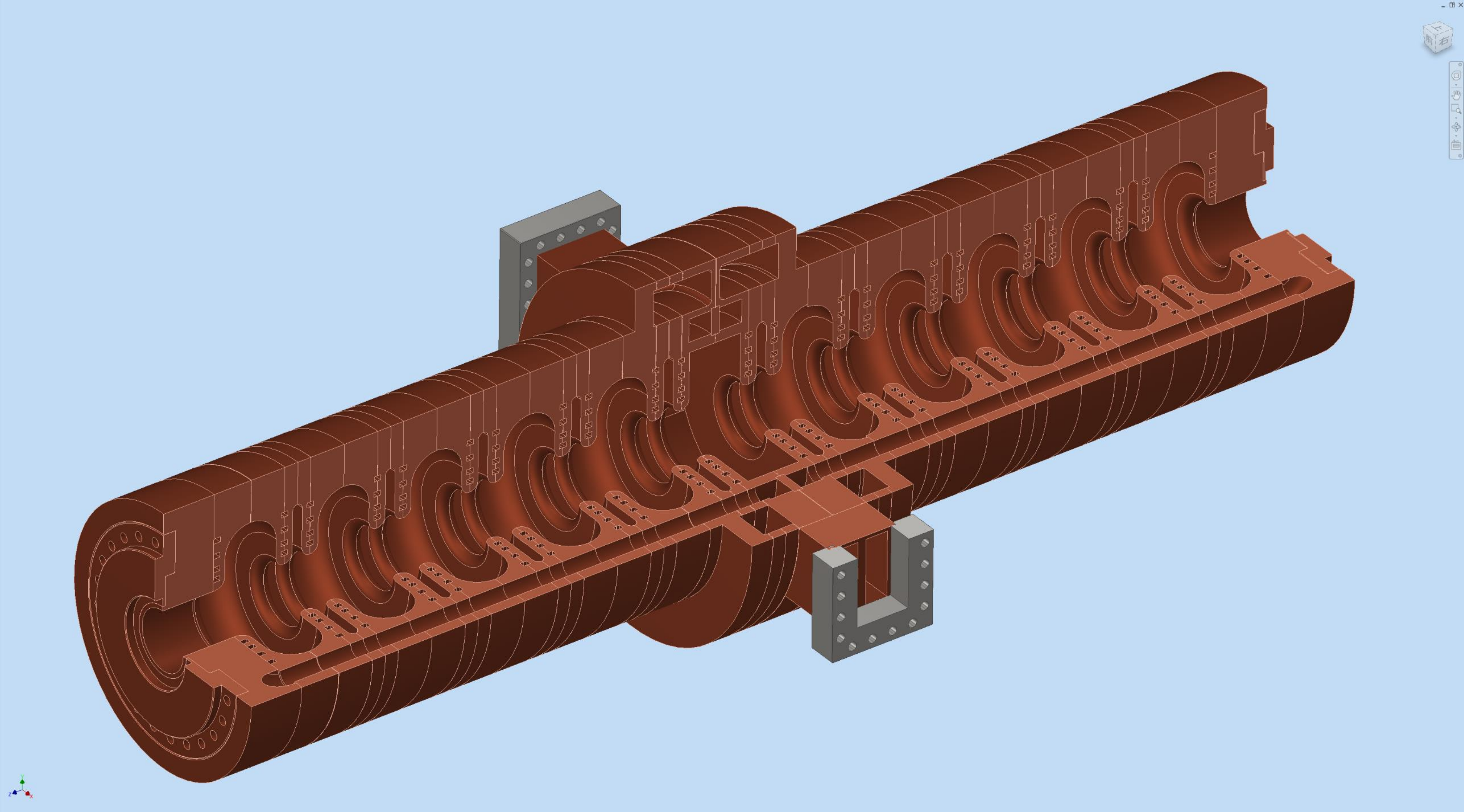
Stored prototype in SLAC



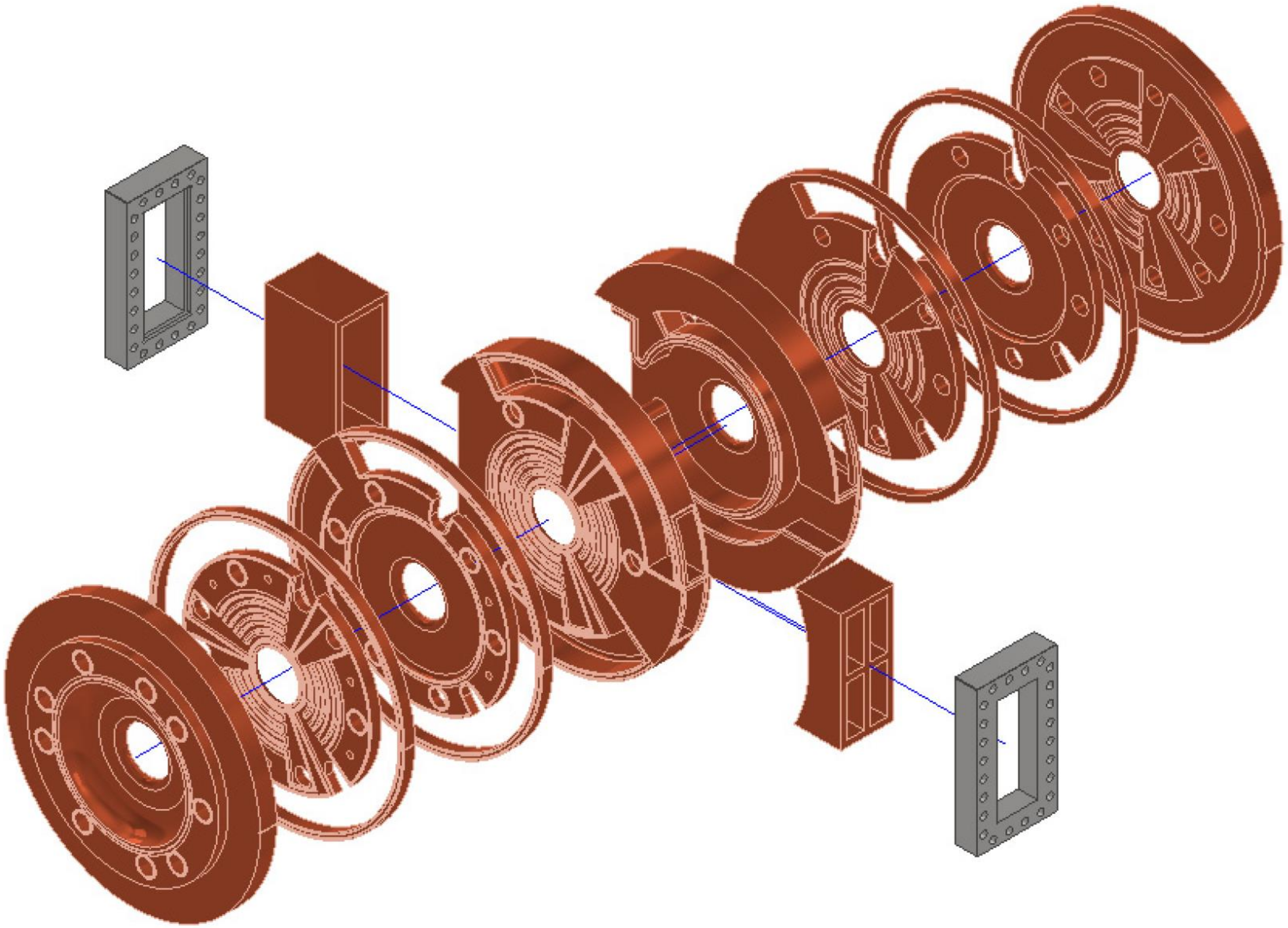
Design goal

- Large aperture
  - Increase positron yield
  - Standing wave cavity was selected
  - 70 mm
- High Vg ang coupling
  - Overcome heavy beam loading due to multi bunch operation
  - APS was selected
- High cooling capacity
  - Suppress temperature rise of cavity less than 1℃ (∼10^{-5} thermal expansion) under a few kW heat load for each cell from beam shower
  - 500 L/min. is expected
  - place cooling Water path near the iris as much as possible
- Round and small outer shape
  - No bump is acceptable for installation

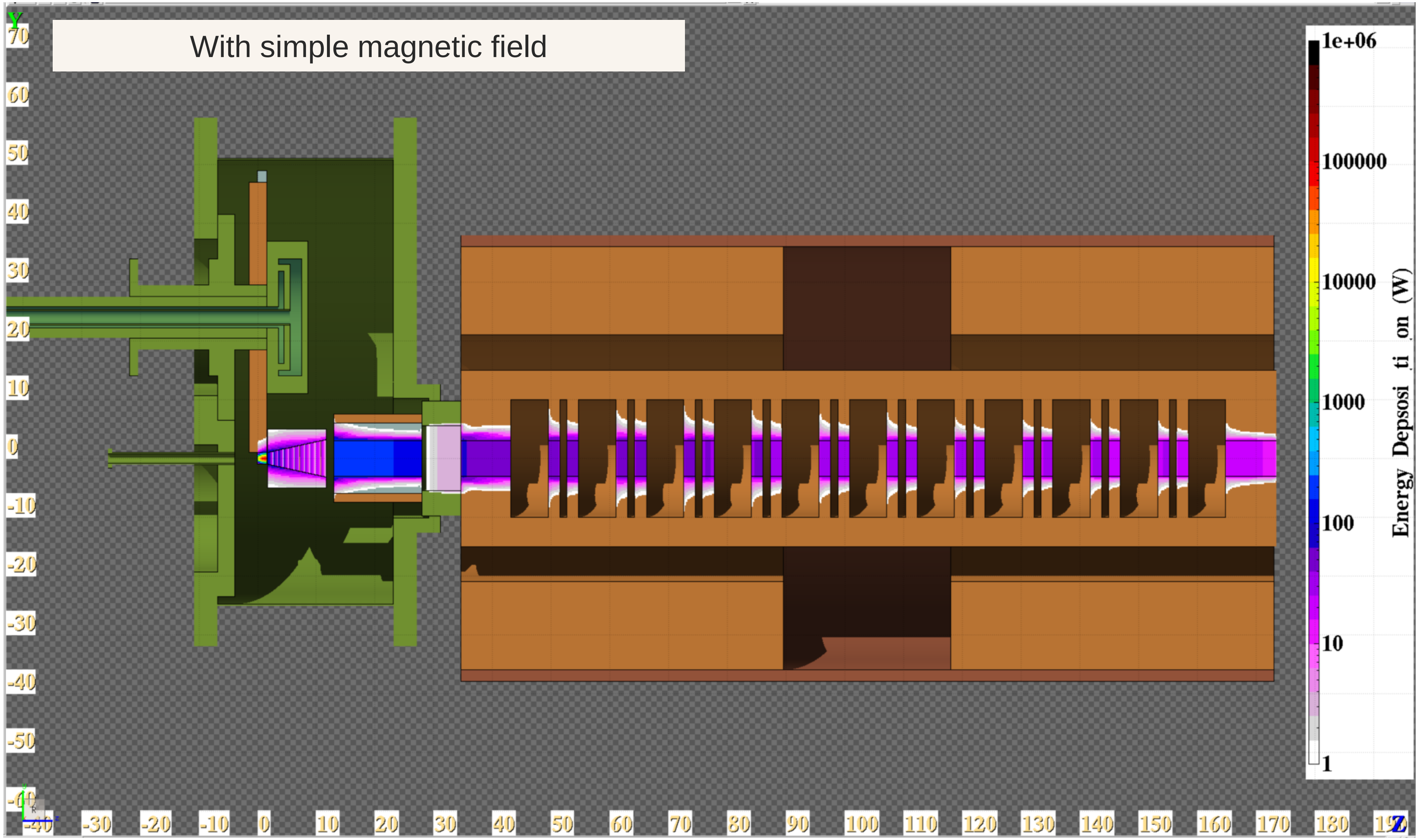
Latest 3D model



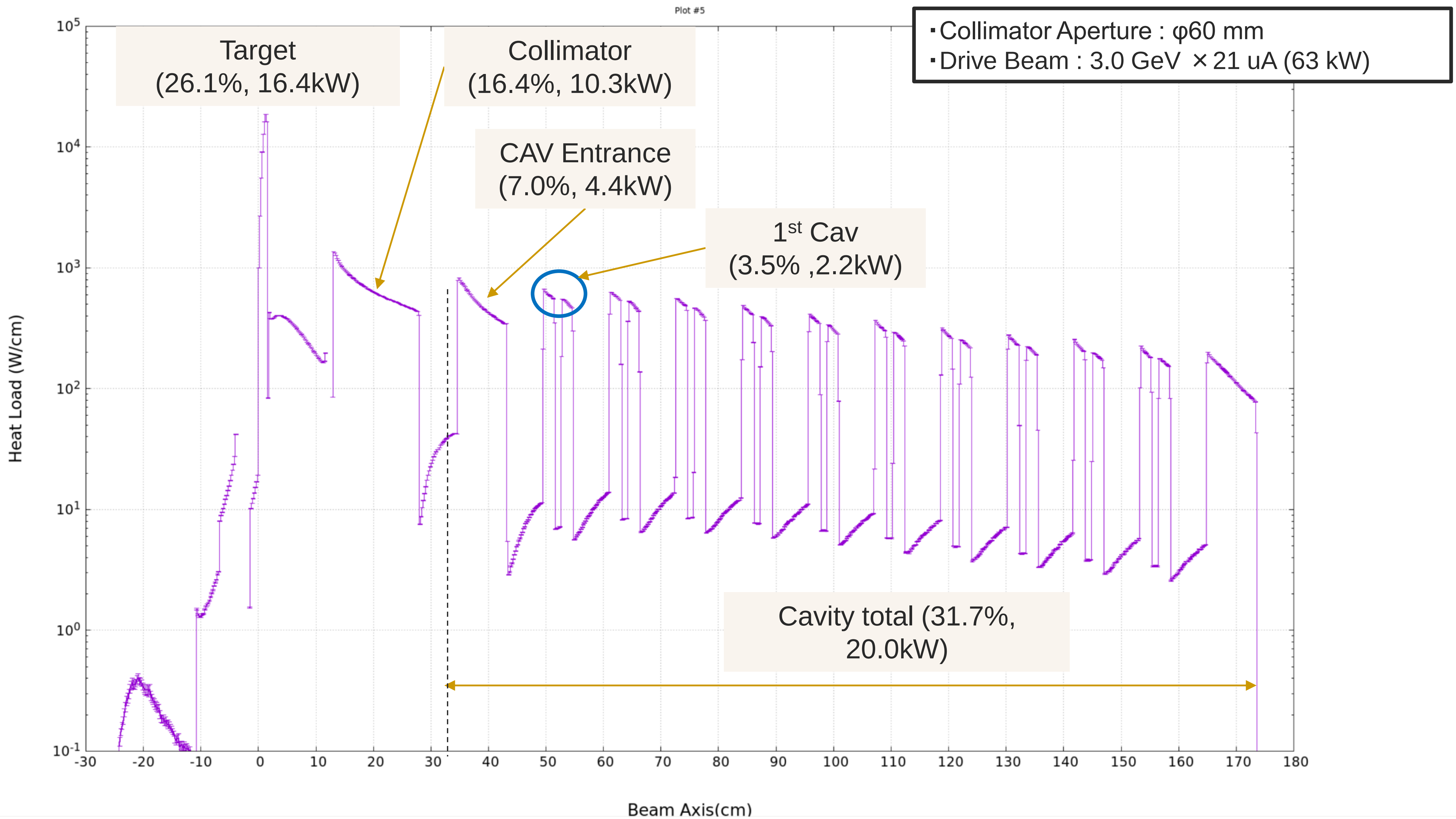
Latest 3D model (coupler)



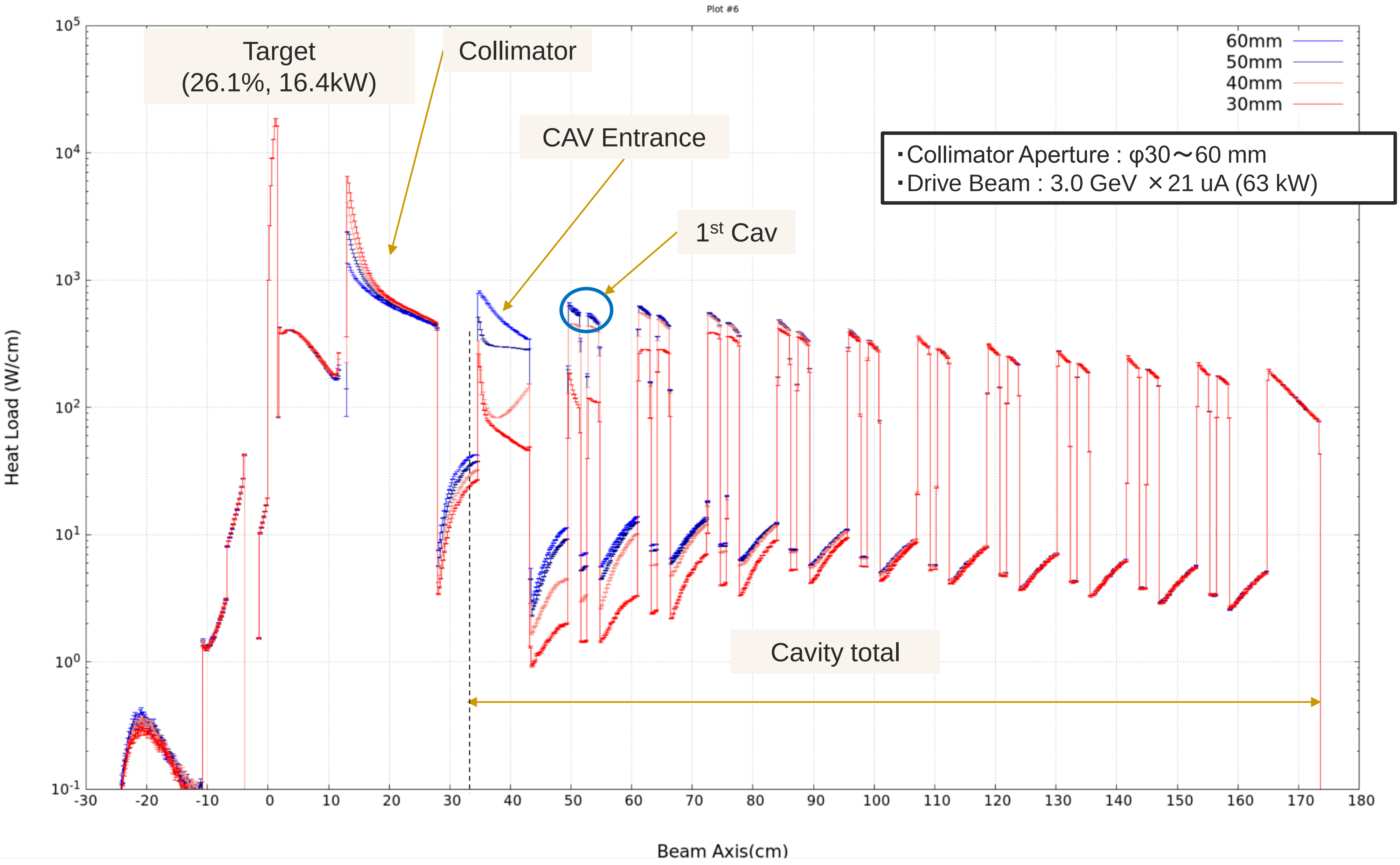
Energy deposition simulation by Fluka



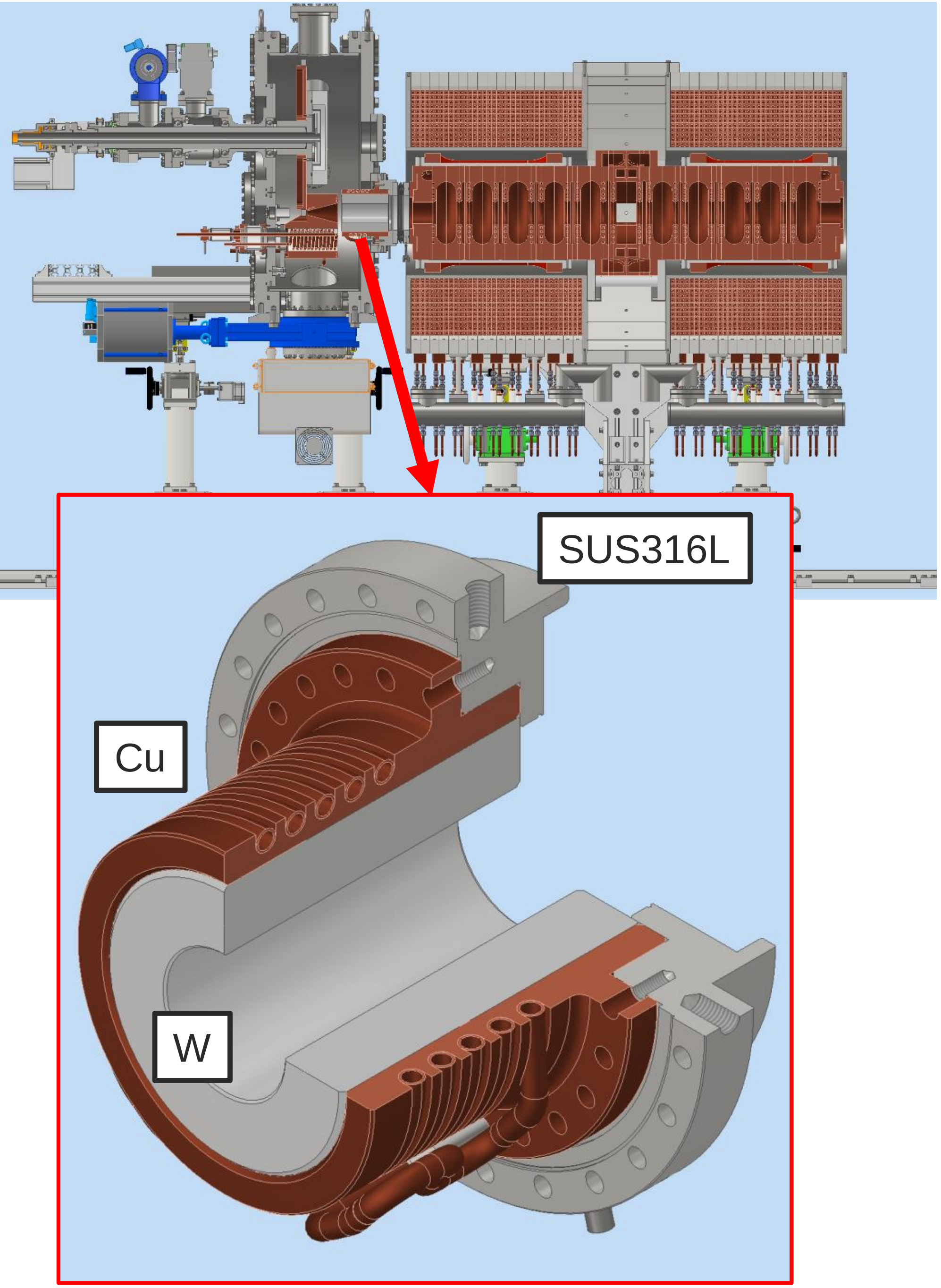
Integrated deposition along beam axis



Collimator diameter dependence of heat load

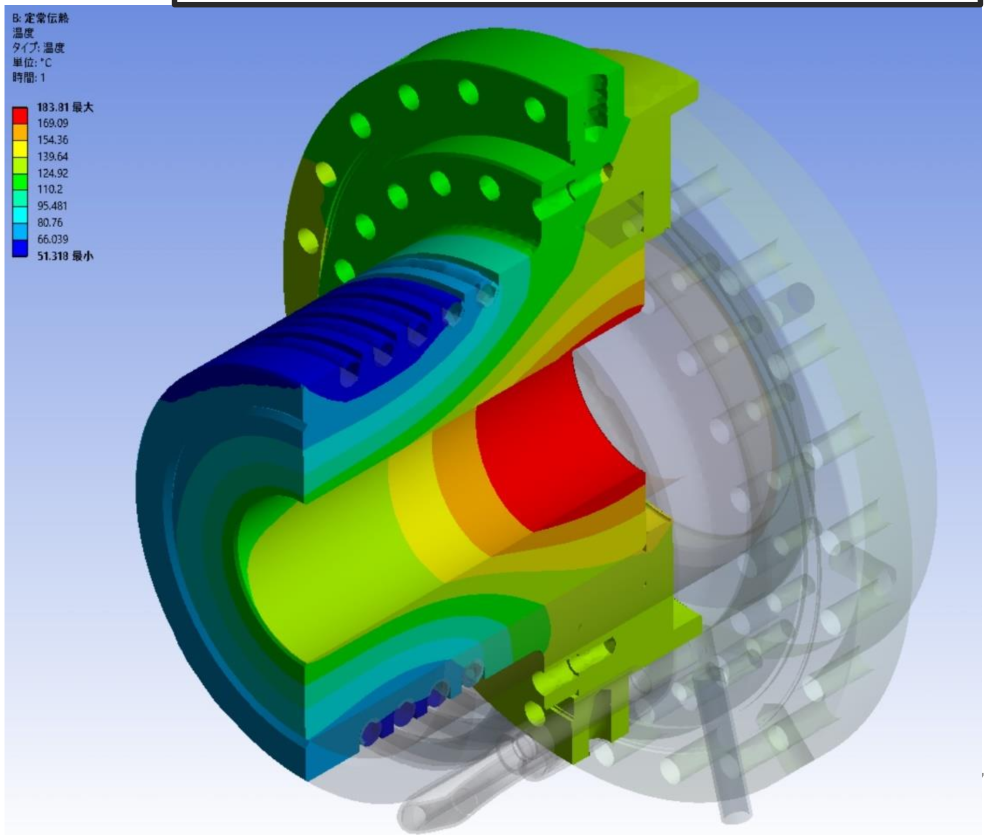


Steady state temperature simulation by ANSYS

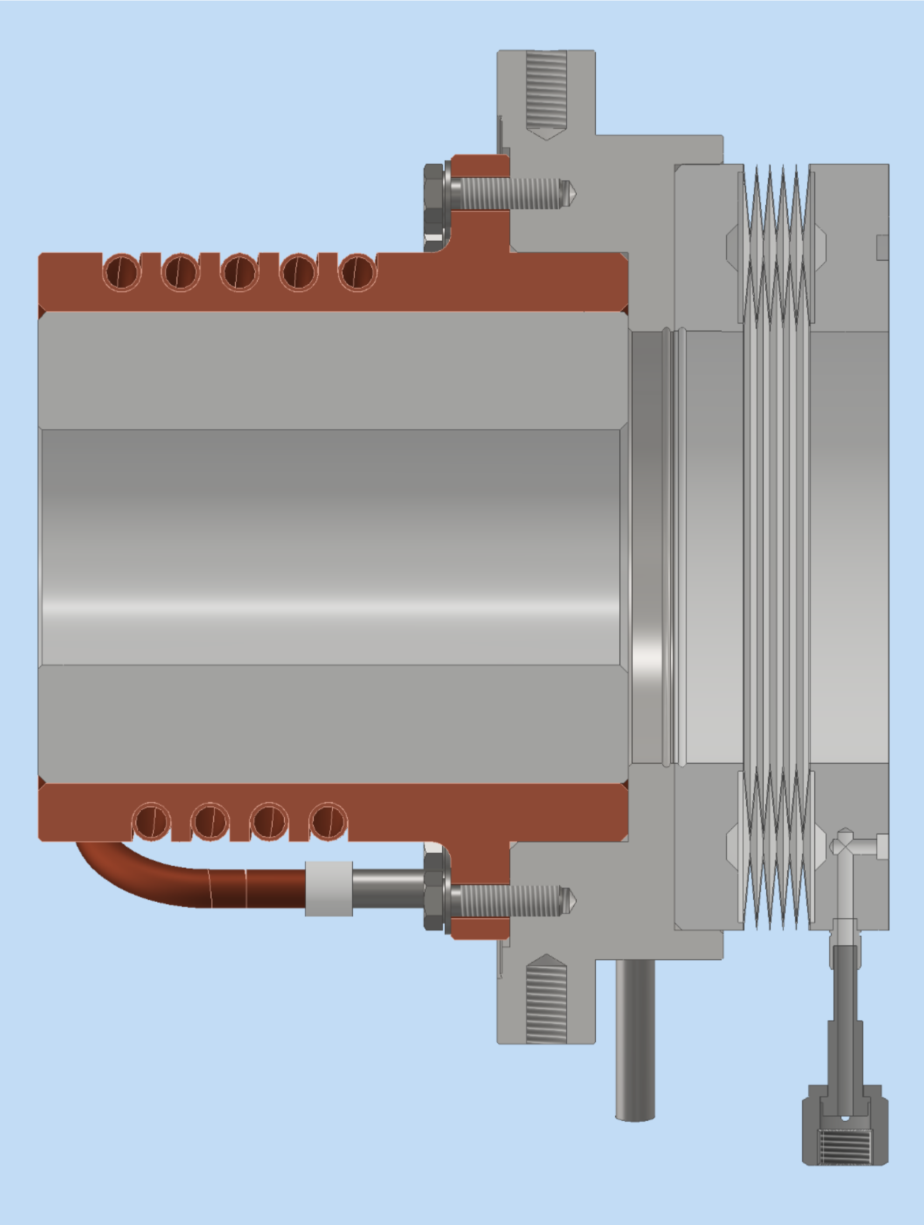


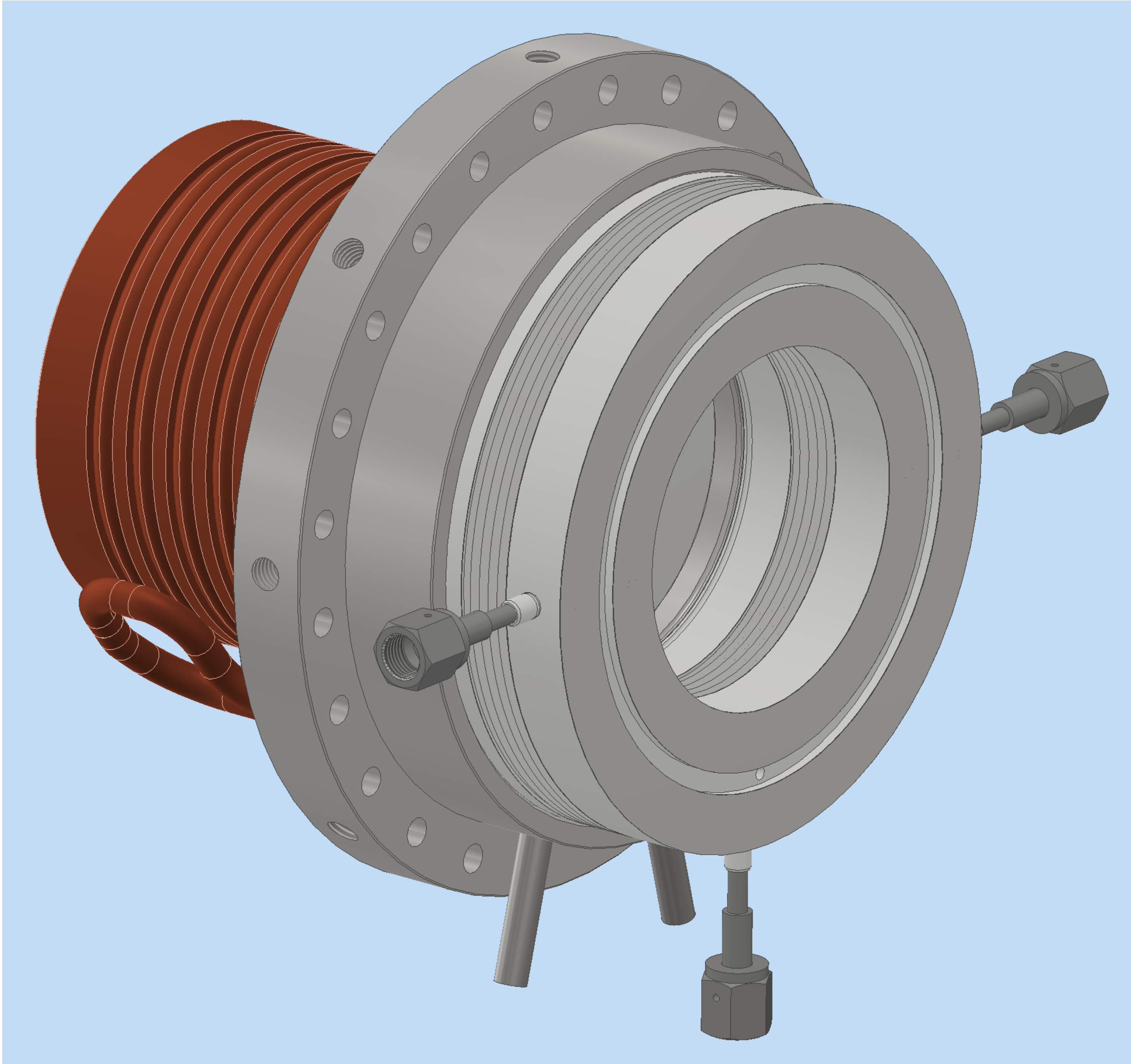
- 1st version design
  - Max. temp 180℃
  - Assuming 5000 W/m^{2}K for water cooling
- Further optimization is possible to reduce temperature

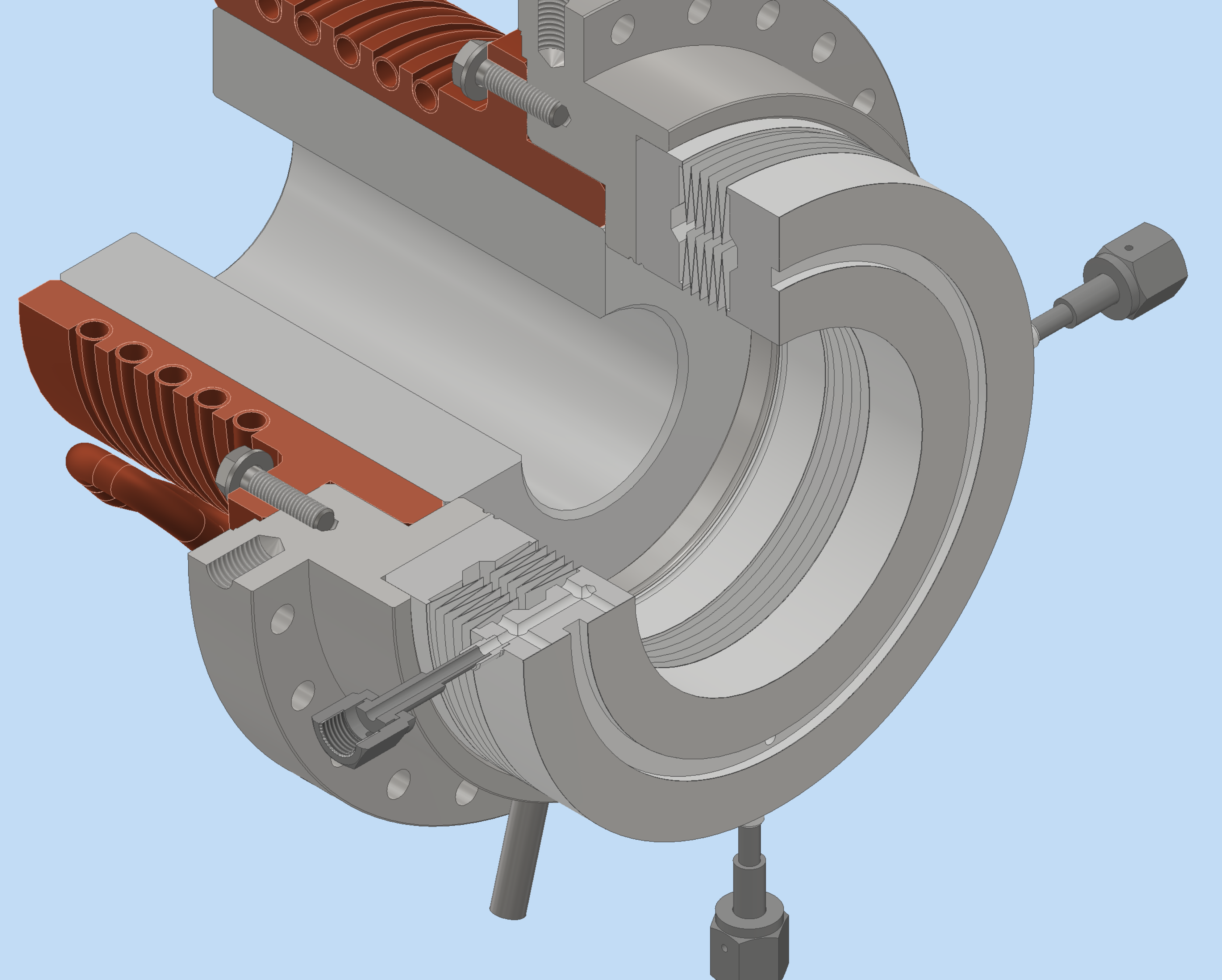
・Collimator Aperture : φ60 mm
・Drive Beam : 3.0 GeV ×21 uA (63 kW)

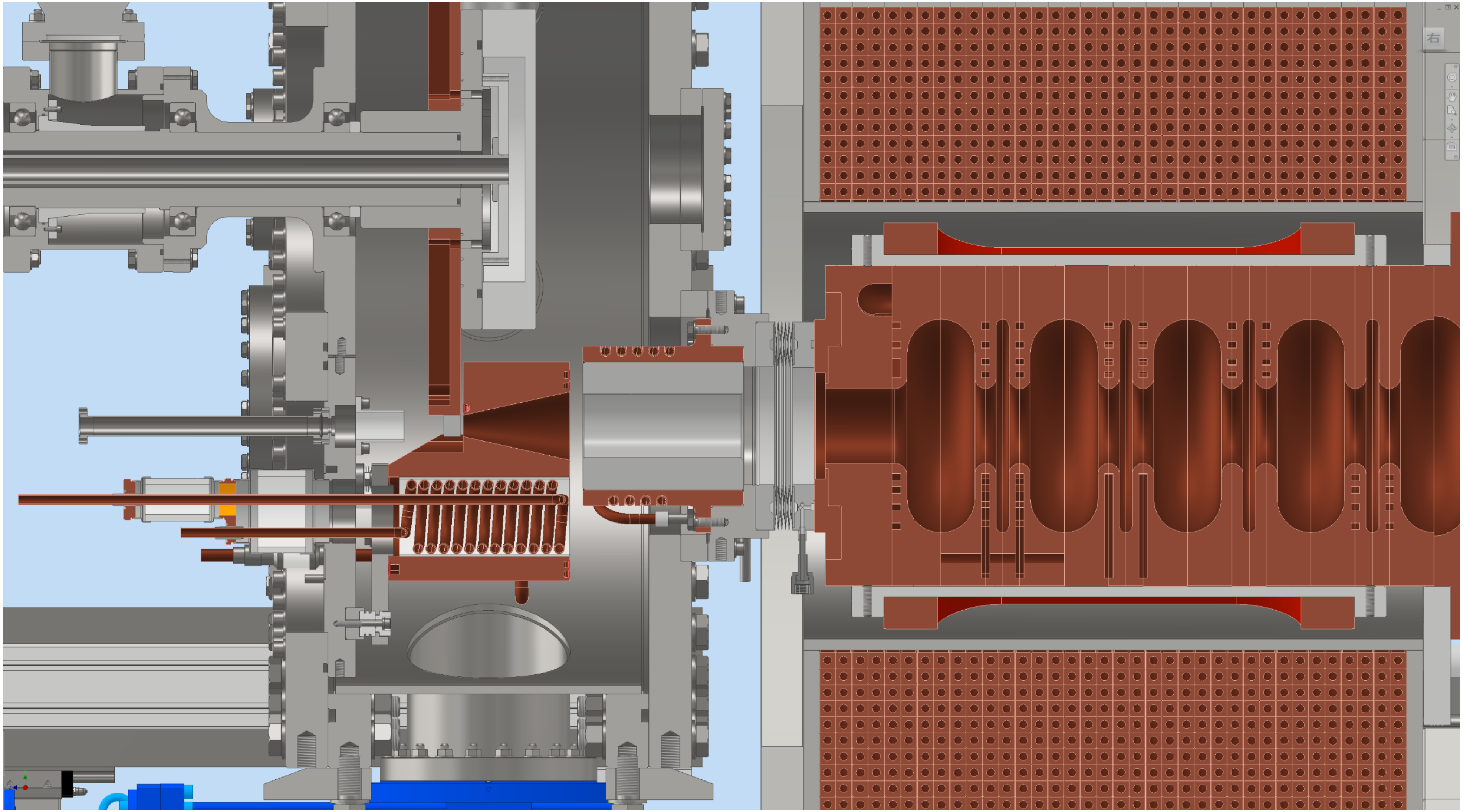


Pillow seal with collimator

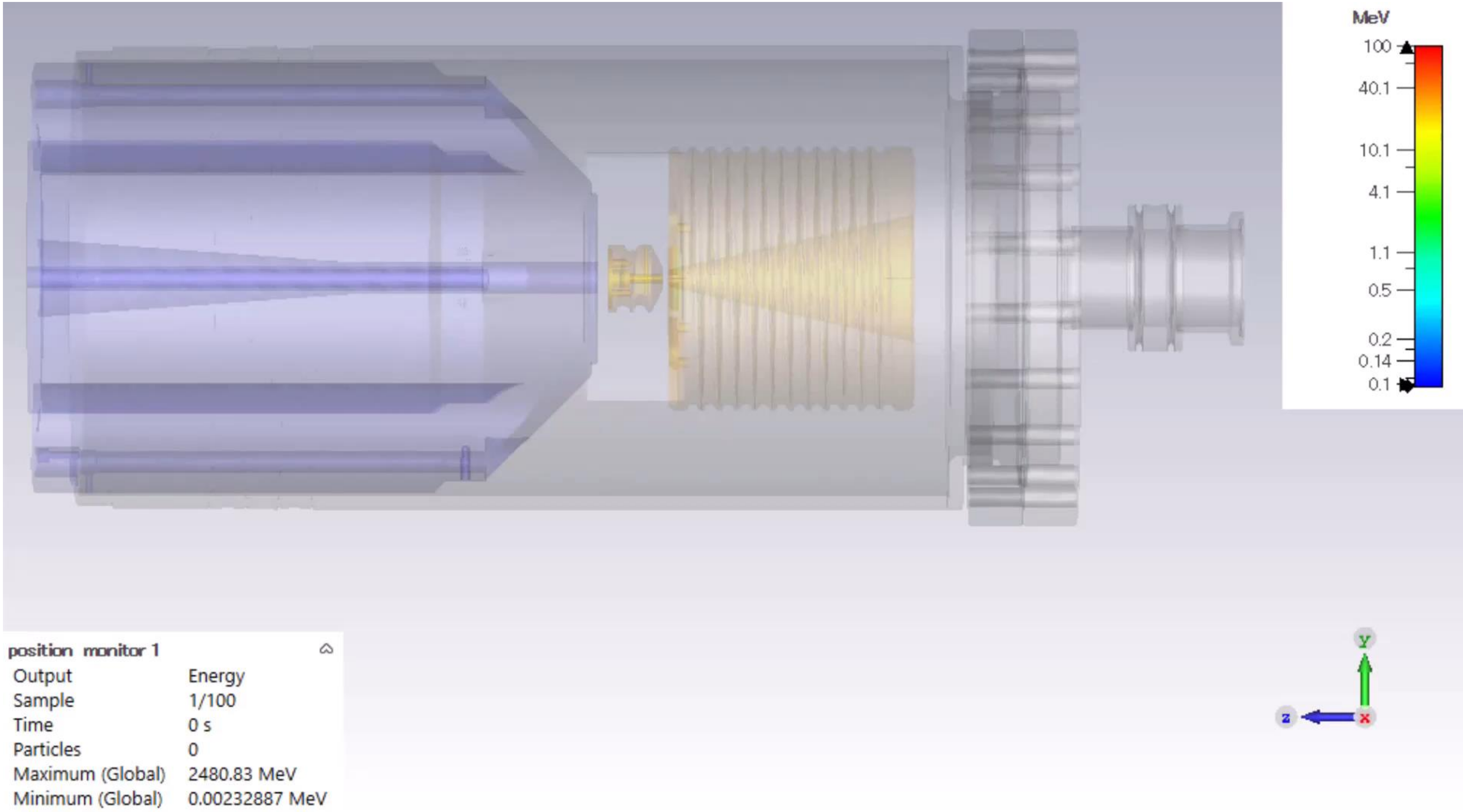


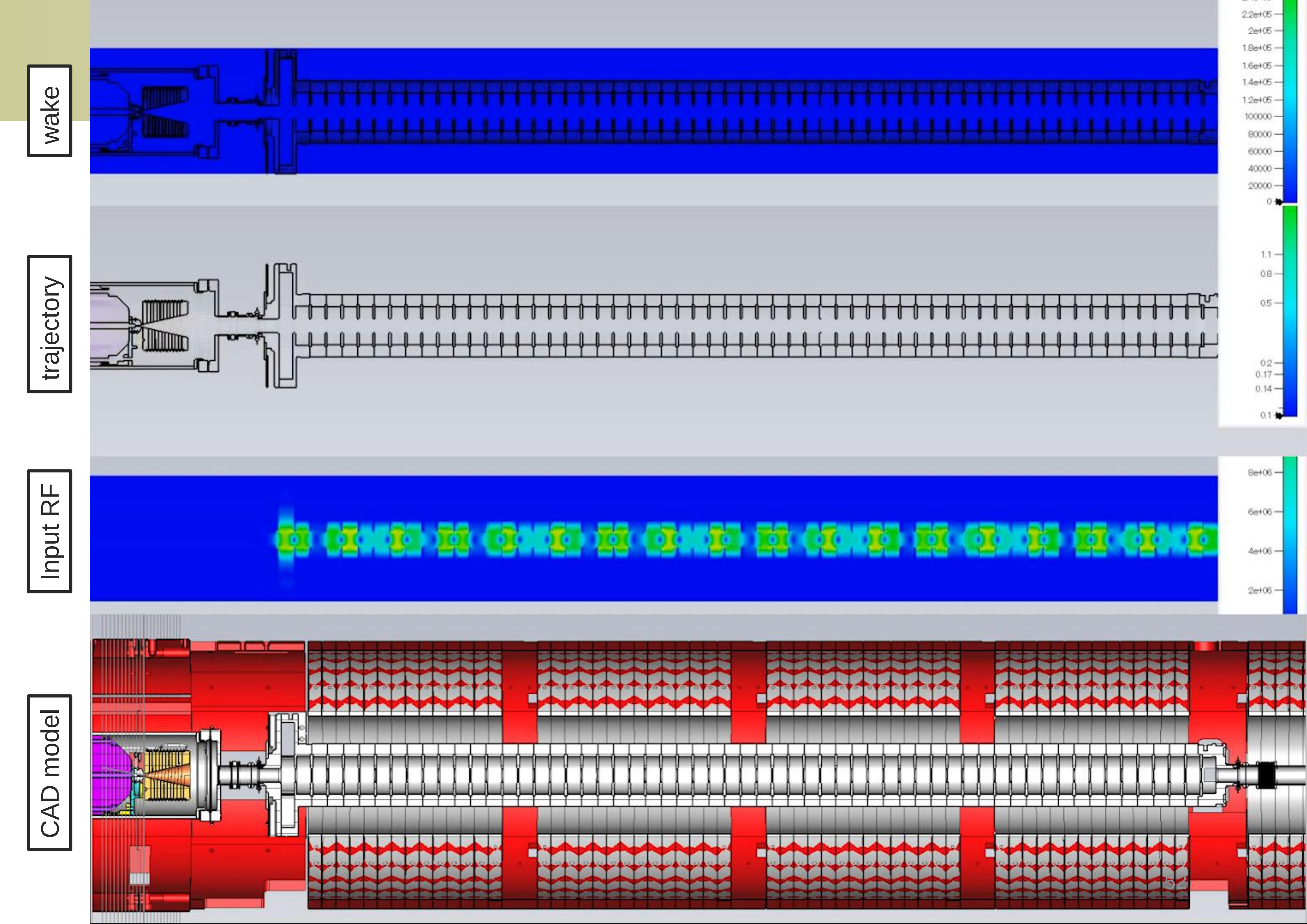


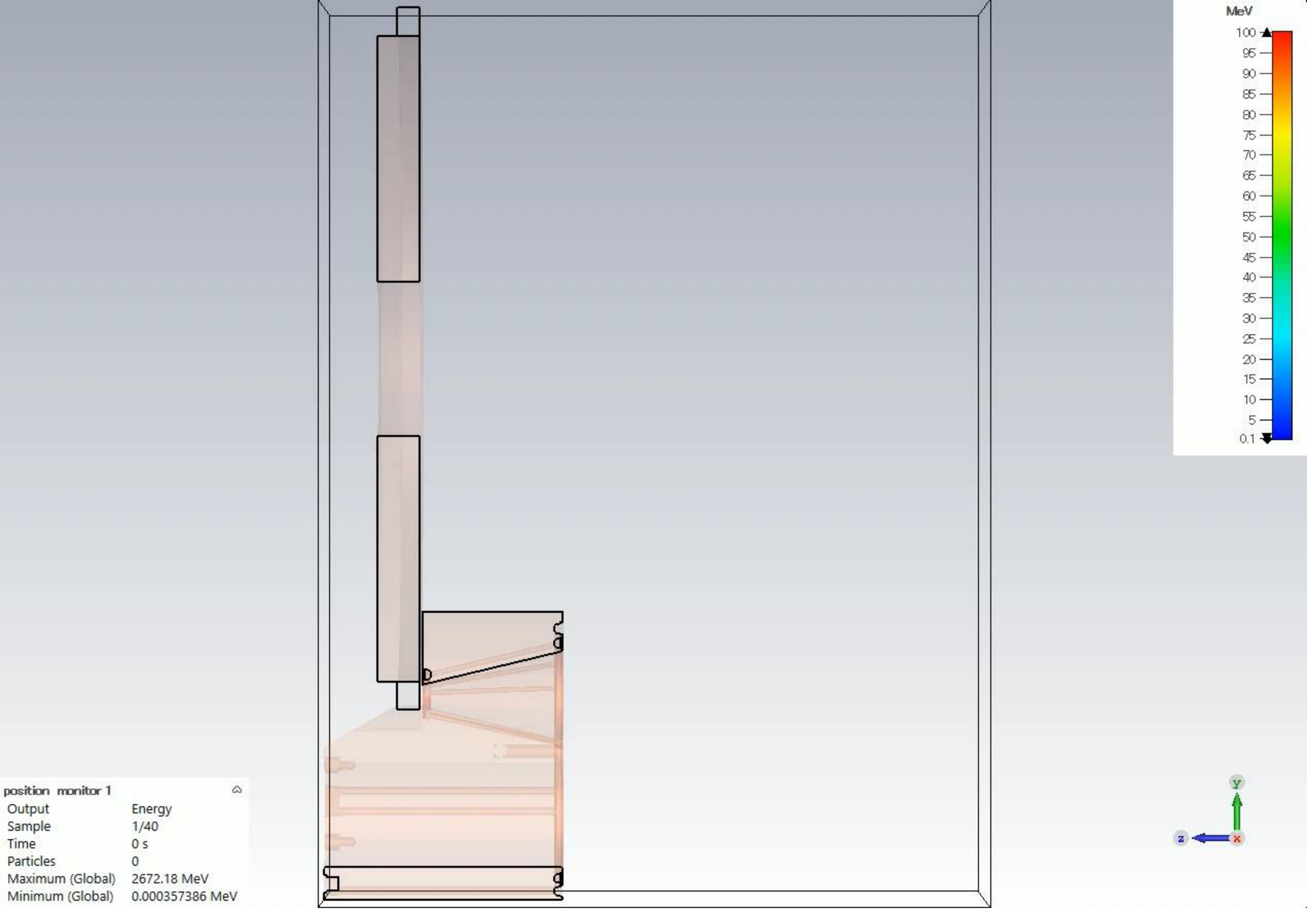



右

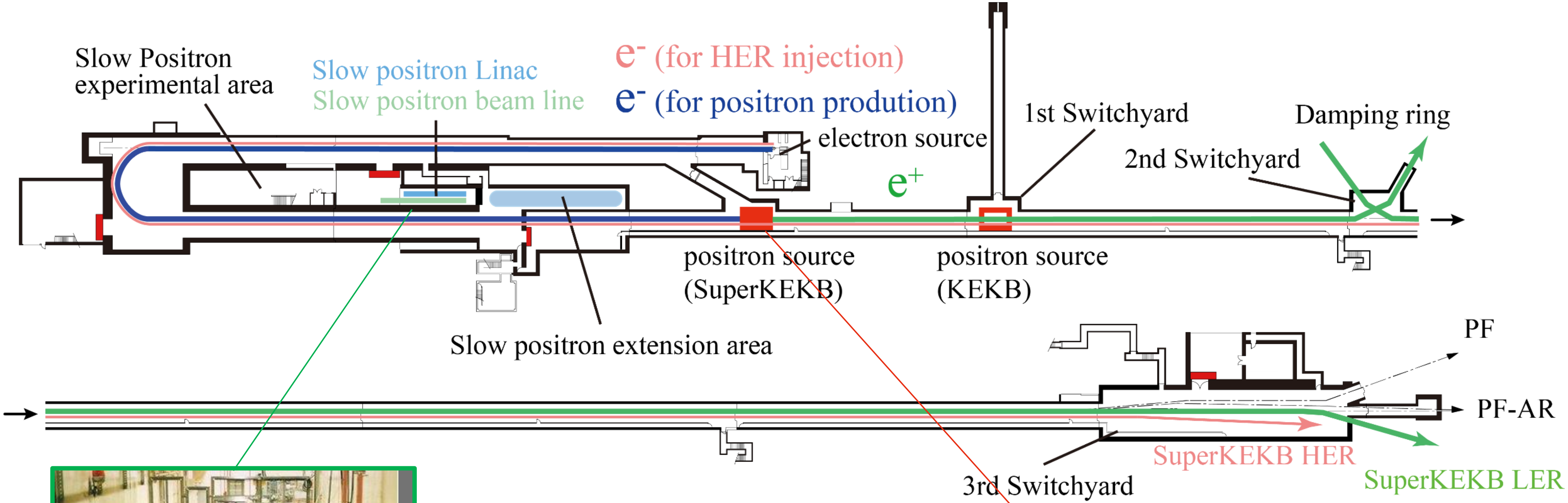
Particle tracking from targe to 1st acc structure

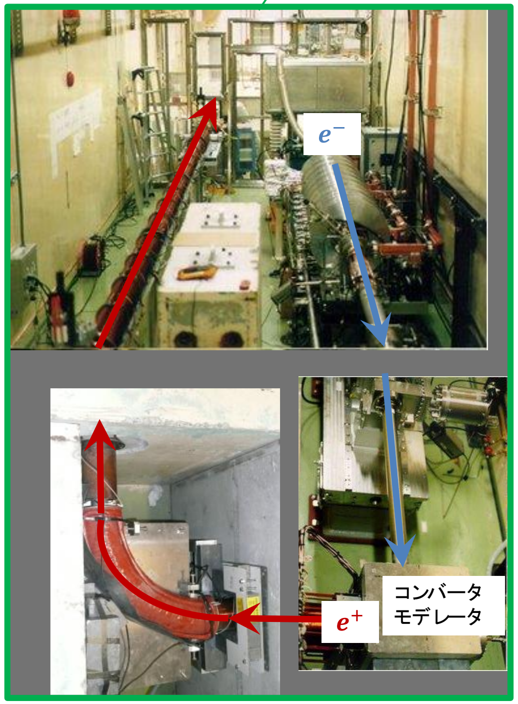



wake
2.2e+05
2e+05
1.8e+05
1.6e+05
1.4e+05
1.2e+05
100000
80000
60000
40000
20000
0
trajectory
1.1
0.8
0.5
0.2
0.17
0.14
0.1
Input RF
8e+06
6e+06
4e+06
2e+06
CAD model


MeV
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0.1
position monitor 1
Output Energy
Sample 1/40
Time 0 s
Particles 0
Maximum (Global) 2672.18 MeV
Minimum (Global) 0.000357386 MeV
Y
Z
X

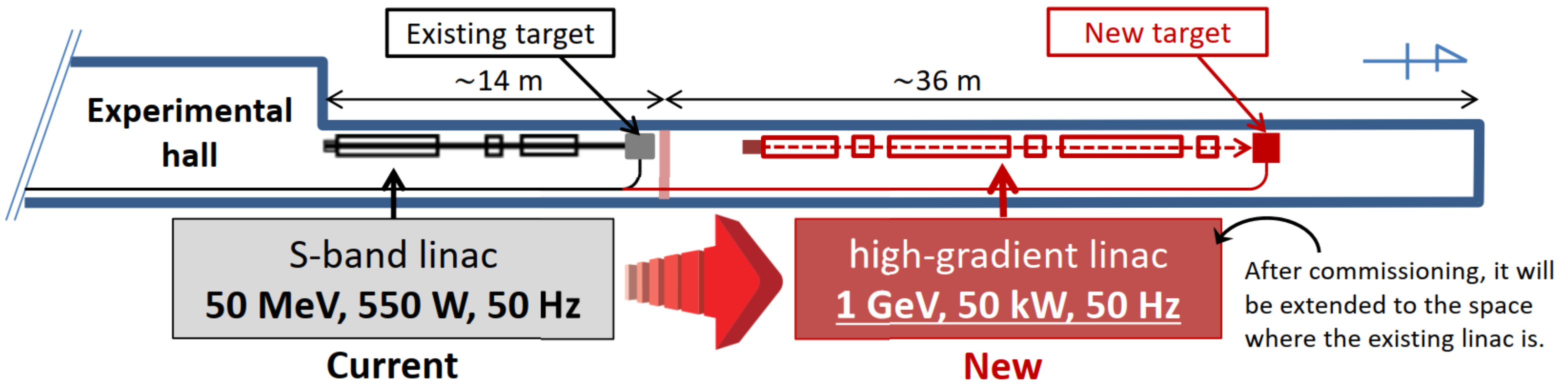
KEK injector linac and SPF





Only a few tens meter
In the same tunnel

SPF upgrade plan



Low-energy High-current / High-energy

Similar parameters

	Current SPF (achieved)	SuperKEKB (design value)	SLC (achieved)	ILC (conventional) (design value)	LLNL (design value?)	Present (design value)
energy	0.05 GeV	3.5 GeV	33 GeV	**3 GeV**	0.1 GeV	**1 GeV**
Beam power	0.50 kW	3.5 kW	27 kW	**74 kW**	45 kW	**50 kW**
Repetition	50 Hz	50 Hz	120 Hz	**100 Hz**	300 Hz	**50 Hz**
Pulse width	1 μs	Single x2	Single	**Single x 66**	3 μs	**4 μs**
Ave. current	10 μA	1 μA	0.8 μA	**24 μA**	450 μA	**50 μA**
Slow-e+ intensity	1 x 10^8 /s				100 x 10^8 /s (not achieved)	100 x 10^8 /s

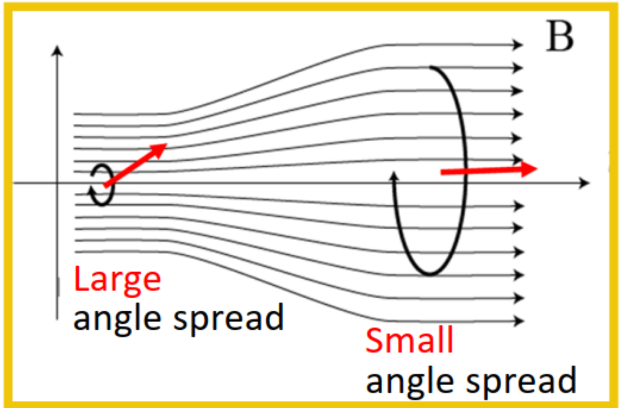
extrapolation/simulation

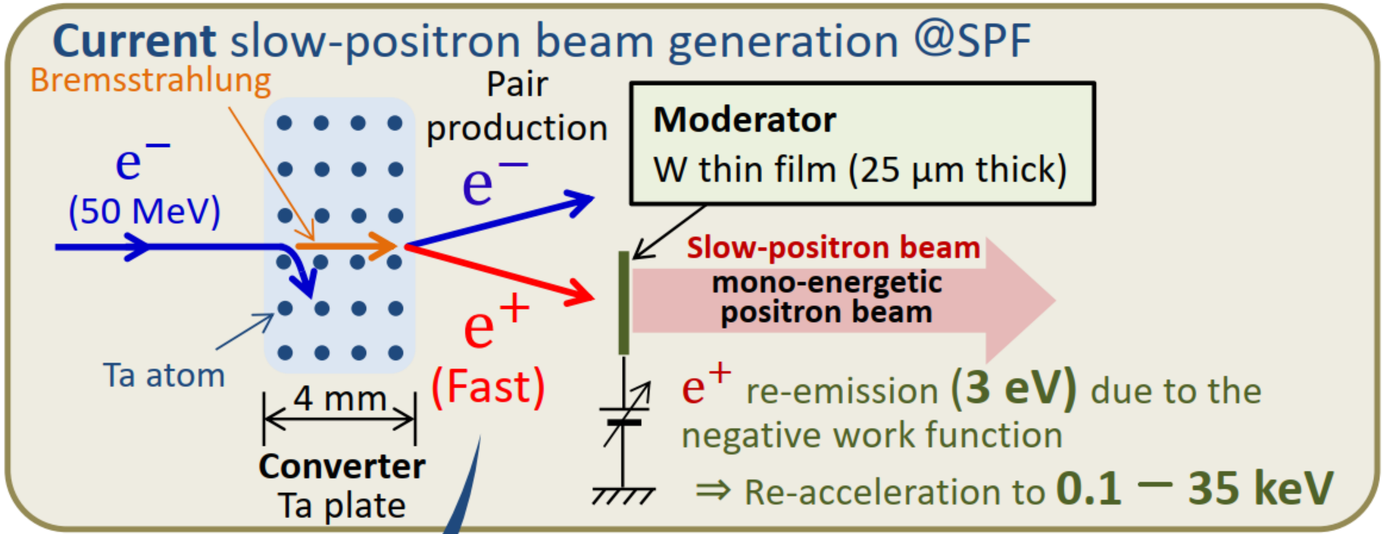
- $16M plan proposed for mid-term project in KEK in 2021
- Strong support from user and community
- Many synergy with ILC and HE accelerator
- One of best test bench for high-gradient accelerator
- Not approved

Application of the SuperKEKB positron source technology

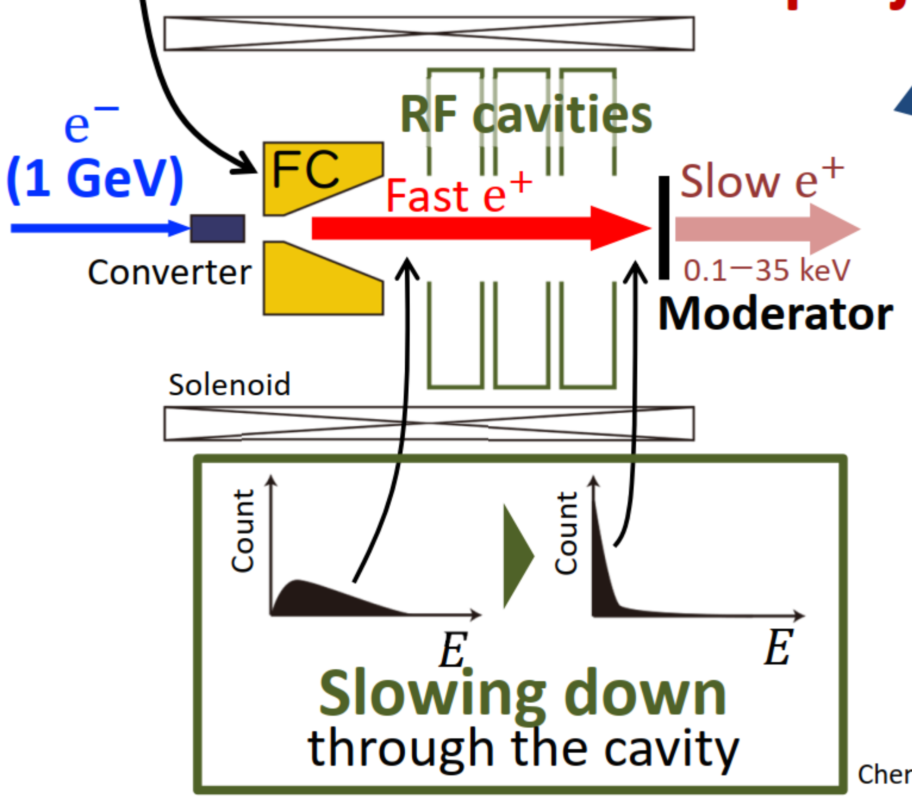
Courtesy of K. Wada

Reducing the angular spread by a **flux concentrator (FC)**





In this project ...



We will first Slow down the fast positrons **in the same way as SuperKEKB** and then let them go into the moderator

Improving the slow-e$^+$ conversion efficiency of the moderator **by a factor of ~50**

Historic breakthrough in the slow-positron beam technology!

Chemerisov et al., International Workshop on Positrons at Jefferson Lab, AIP Conf. Proc. 1160, 87 (2009)

SPF in AIST

- AIST (National Institute of Advanced Industrial Science and Technology), 10 km from KEK, has another slow positron facility.
- Collaborating and proposing development of small positron source to replace isotope

From SuperKEKB to ILC, FCC, CLIC, C3, CEPC…

- There are many common and similar tasks.
  - Experience in SuperKEKB will be useful for designing positron source for ILC.
  - Since the number of people in this field is not large even all over the world, collaboration with other projects like, FCC, CLIC, CEPC etc. is important.
  - Collaboration with non-accelerating institute is also important.
- A new group launched in KEK in Sept. 2022
  - Positron source and beam dump for ILC
- 5 year grant for ILC time-critical component will be start from FY2023
  - So-called pre-pre-lab
  - SRF, nano-beam, particle source
- Partners
  - JPARC (muon, hadron target), RIKEN (heavy ion target)
  - NIFS (SPS)
  - US-Japan program with SLAC and JLab
  - FJPPL
  - ITN (international technology network)
  - Another framework?