Chapter 5:
Introduction of Cryomodule

Typical operating temperature of SRF cavities is 1.8 K~4.5 K

Helium circuit:
SRF cavities are immersed in liquid helium (helium vessel)
Helium supply and return lines are connected to helium vessel
Helium vessel can be pumped down to get lower temperature

Thermal design:
Minimize thermal loss
Typically uses multi-layer insulation and intermediate temperature boundary in a vacuum chamber

Power coupler: Couples RF power to a cavity

Mechanical tuner
Keeps a cavity on resonance or within a certain range of detuning

HOM coupler: Couples HOMs→ damp and extract HOM

Magnetic shielding: Reduces ambient magnetic field

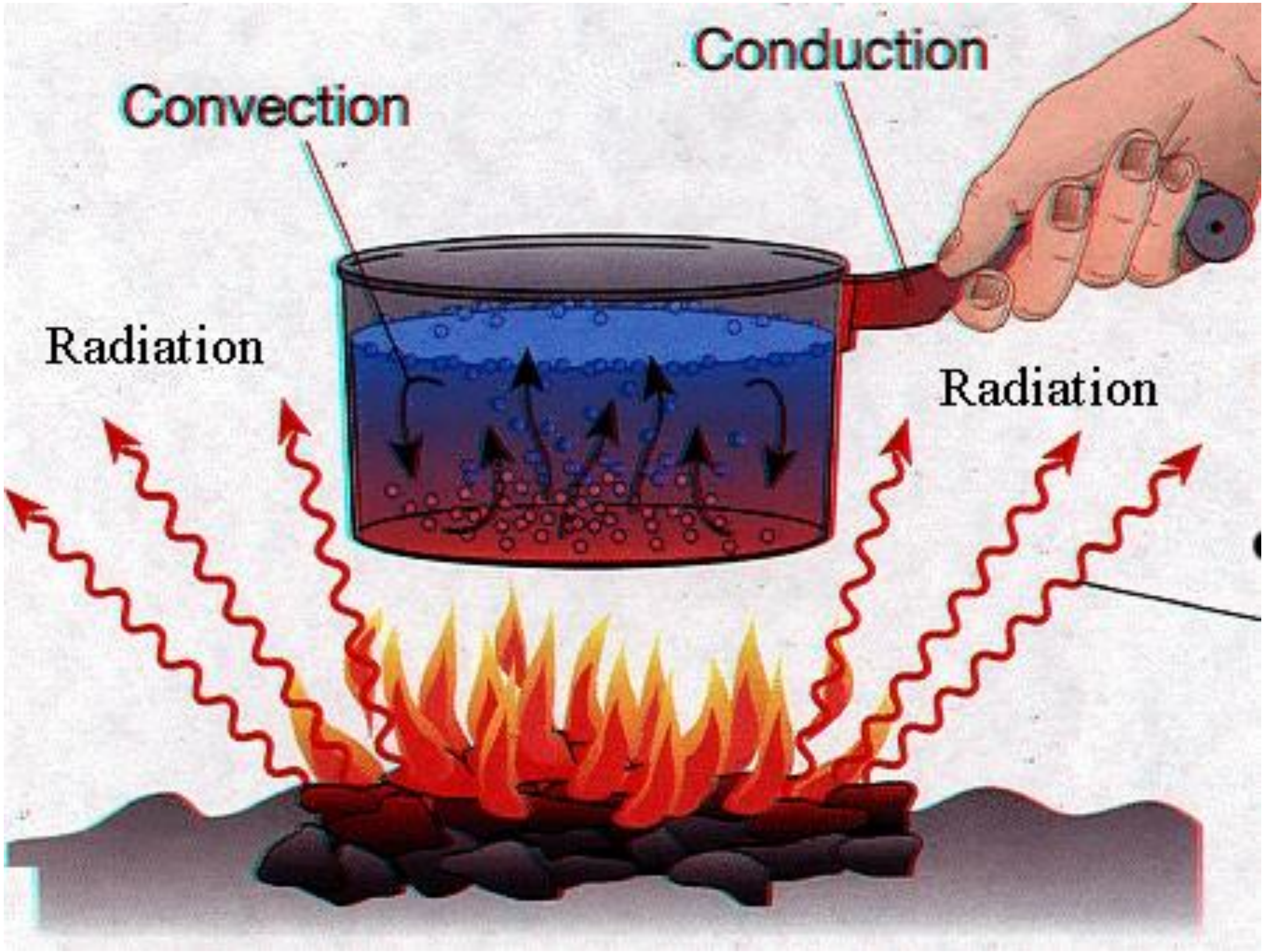
Keep cold efficiently

One of the major concerns in cryomodules.
Large scale refrigeration plant is also one of major challenges for large scale machines

Need a very careful consideration in thermal and safety points of view.
- thermal: minimize thermal loss or optimize operating condition
- safety: cryogenic incident (machine protection, personnel protection)

Insulation: reduce thermal heat transfer
- convection: vacuum chamber
- conduction: penetrations, supporting structures
- thermal radiation: Multilayer insulation (MLI), thermal shield

Heat Transfer



Conduction heat transfer

When a temperature gradient exists in a body or between objects that are in physical contact, there's an energy transfer from the high temperature region to the low temperature region.

The heat transfer rate is proportional to area, temperature gradient

$$q = -kA\frac{\partial T}{\partial x}[W]$$

$$\text{where } A : \text{area for conduction}$$

$$k : \text{ proportional constant called thermal conductivity (material property)}$$

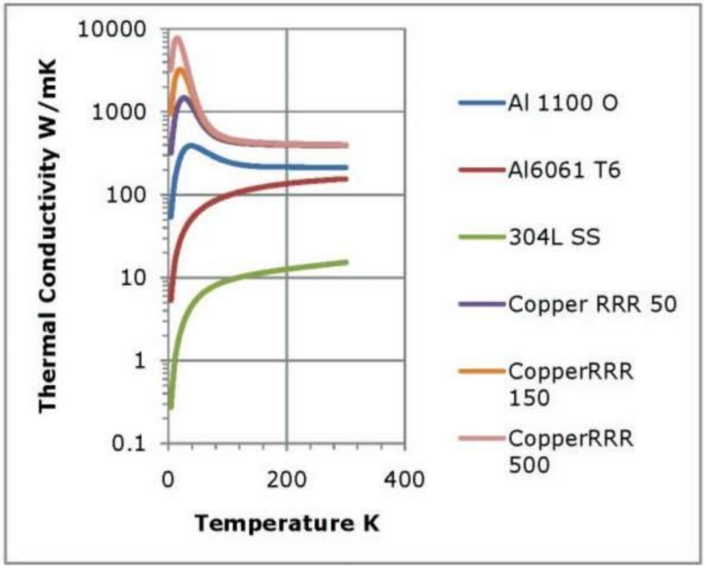
$$\text{function of a temperature}$$

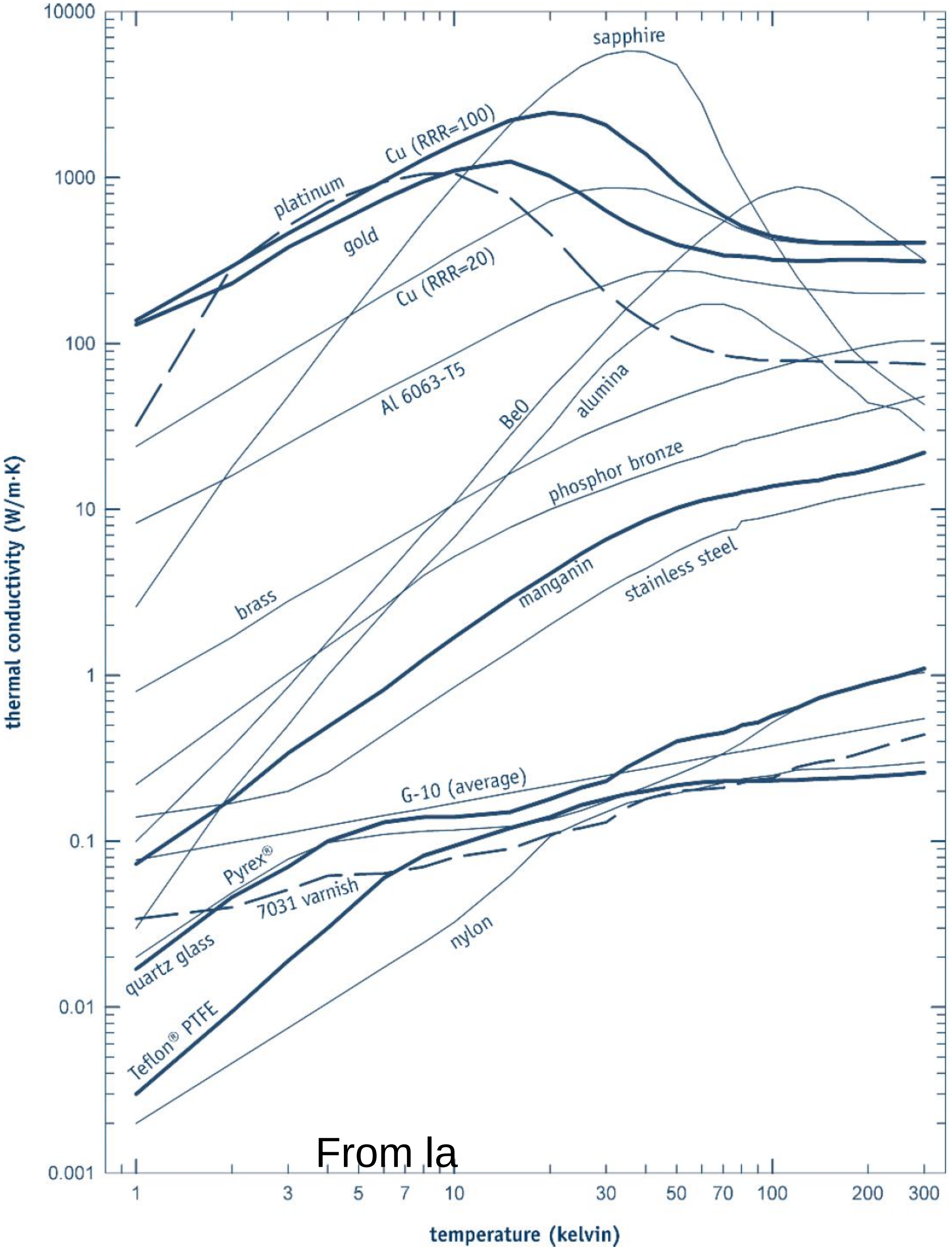
$$\frac{\partial T}{\partial x} : \text{temperature gradient}$$

Ex. Each end of rod (2cm dia. And 0.5m long) is connected to thermal boundaries at 4K and 300 K.
Stainless steel: assume constant *k*=3 W/mK → q=1*π*1e-4*296/0.5=0.568 W
Copper: assume constant *k*=300 W/mK → q=1*π*1e-4*296/0.5=56.8 W

Thermal conductivity is a function of material

When one performs a thermal analysis in large temperature range,
non-linear analysis is essential using a FEM code.





From Ia

Convection heat transfer

Heat transfer occurring due to the bulk motion of fluid (gas, liquid).

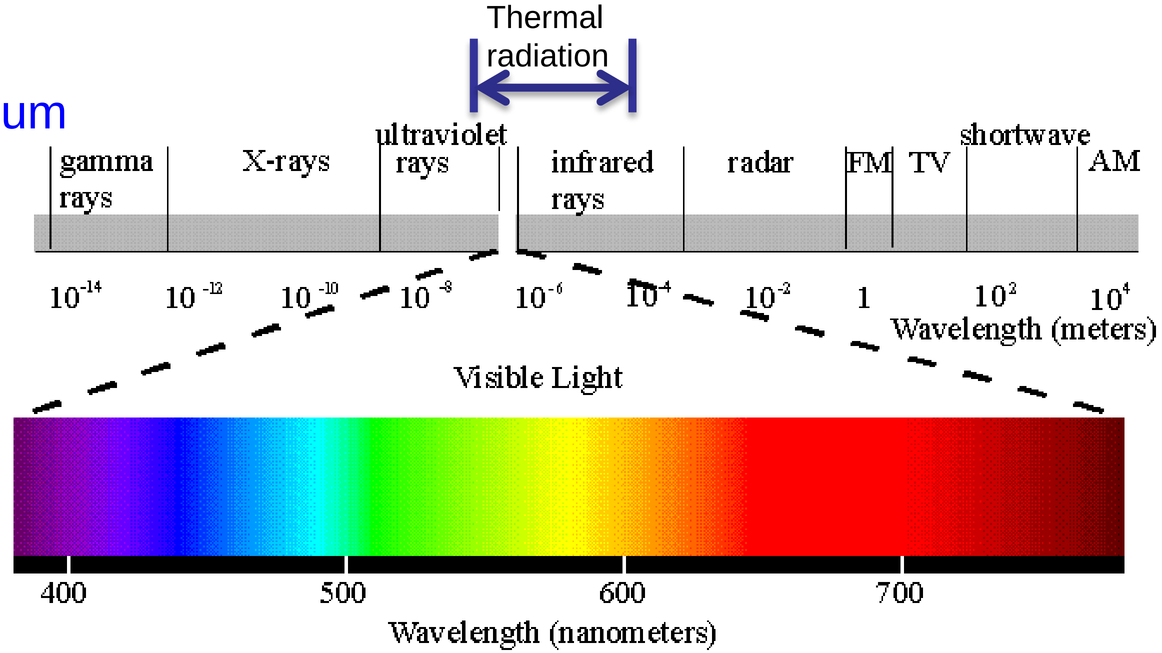
The transfer of energy between an object and its environment, due to fluid motion.

Pressure < 10^{-4} torr: negligible effect

Radiation heat transfer

The transfer of energy to or from a body by means of the emission or absorption of electromagnetic radiation

Electromagnetic Spectrum



Energy radiated per unit time and per unit area by the ideal radiator is given by the Stefan-Boltzmann law:

$$E_b = \sigma T^4 \quad \text{where } \sigma \text{ is the Stefan - Boltzmann constant, } 5.669\times 10^{-8}\ \mathrm{W/(m^2\cdot K^4)}$$

Ex.) Heat exchange between non-blackbodies

1) Two infinitely parallel plates→ $$q/A = \frac{\sigma(T_1^4 - T_2^4)}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}$$

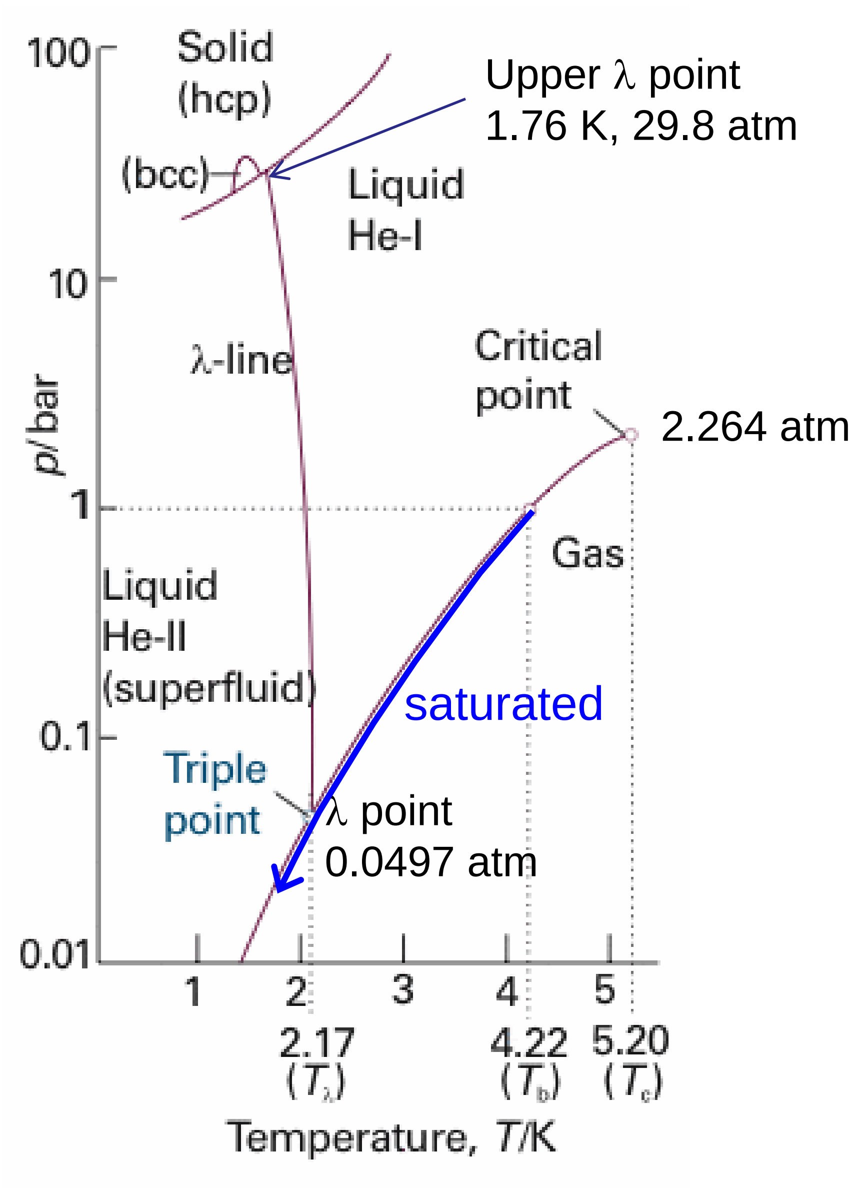
2) Two long concentric cylinders→ $$q = \frac{\sigma A_1(T_1^4 - T_2^4)}{1/\varepsilon_1 + (A_1/A_2)(1/\varepsilon_2 - 1)}$$

Inner cylinder: T_1, A_1, ε_1
Outer cylinder: T_2, A_2, ε_2

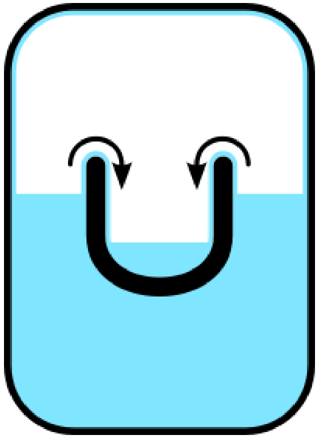
3) layers of low emissivity material and insulators.

Ideally $(q/A)_{\text{with shields}} = (q/A)_{\text{without shield}}/(1+n)$, n=number of layers

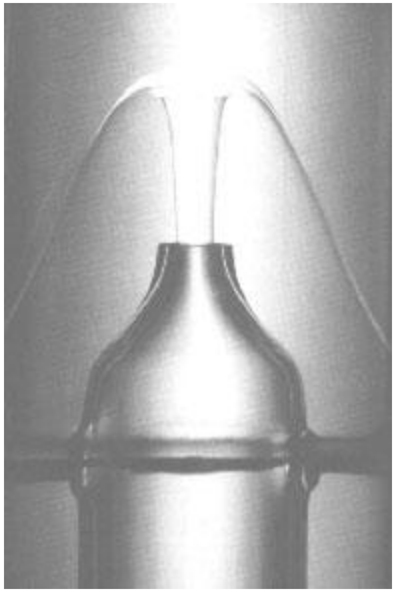
Phase diagram of ^{4}He



Superfluid:
A phase of matter in which viscosity of a fluid vanishes.
Discovered in 1937 by Kapitza, Allen, and Misener.
L. Landau won the Novel Prize in Physics ‘phenomenological and semi-microscopic theory of superfluidity of ^{4}He’.



Film creeping



Thermo-caloric effect

Cryogenic efficiency

Ideal Carnot efficiency

$$\eta_{\mathrm{ideal}} = \frac{T_{\mathrm{op}}}{T_{\mathrm{ambient}} - T_{\mathrm{op}}}$$

Ex. Ideal case: η_{ideal}=0.345 for 300K→77K,

η_{ideal}=0.014 for 300K→4.2K

In practice, actual efficiency is much lower than this ideal case.

$\eta/\eta_{\mathrm{ideal}} = \eta_{\mathrm{ratio}}$ typically ranges 0.1~0.35 (<0.1 in small systems)

Smaller machine has lower efficiency.

As technologies improve, efficiencies are getting higher.

Some reference numbers for scaling

Room temperature power/power at 4.5 K: 250~350

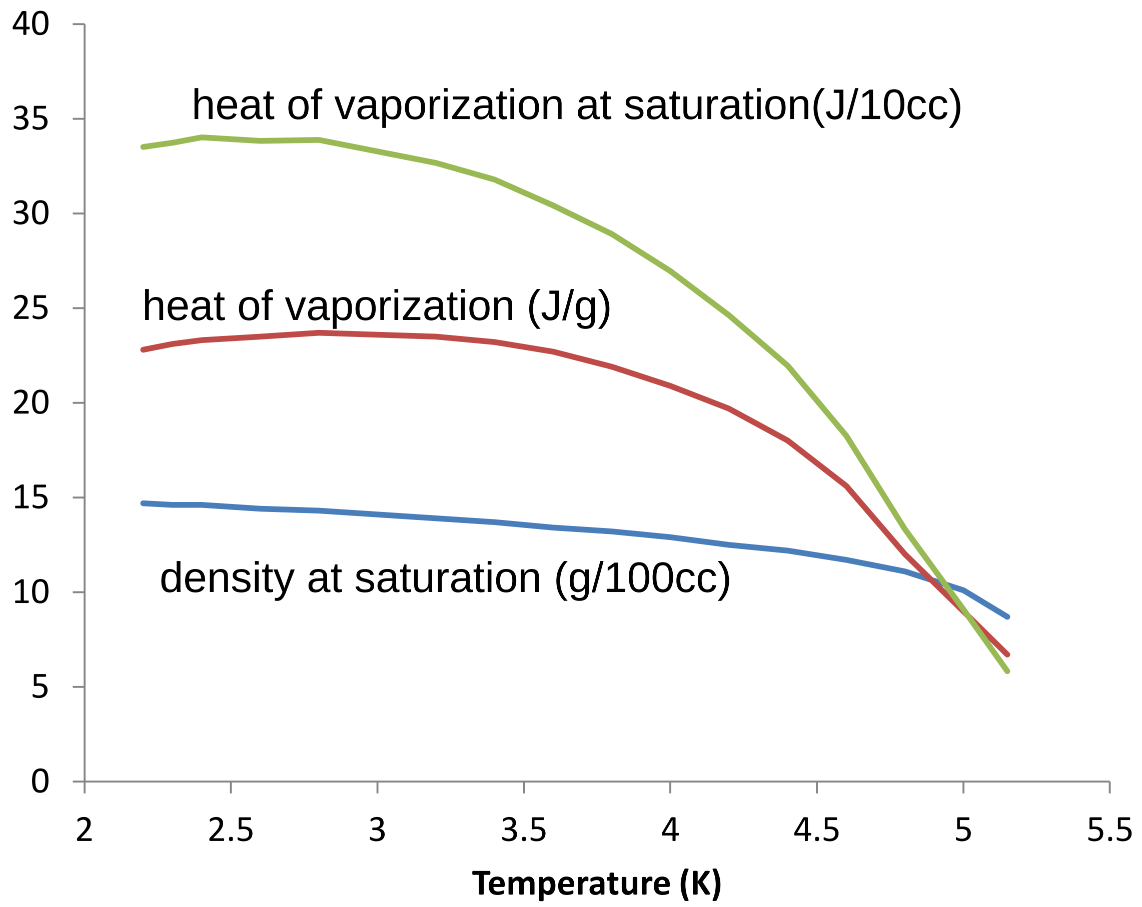
Room temperature power/power at 2 K: 1100~1300

Rough scaling:

If we have 100 W load at 2 K → we need ~120 kW cryogenic system at least.

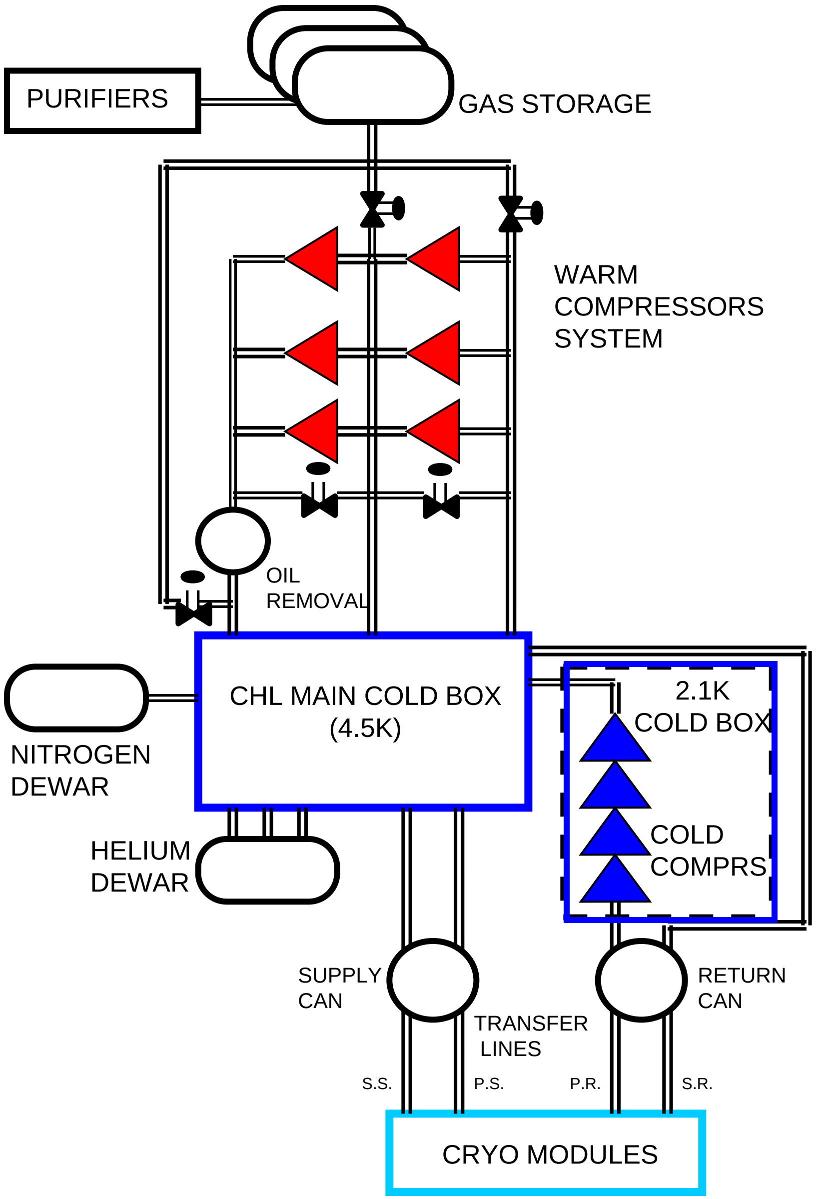
(we will re-visit this concern for machine efficiency estimation in Chapter 7)

Helium properties at saturation



Low efficiency + small heat capacity + expensive: need very careful design

Ex. SNS Refrigerator System



Helium Refrigerator System

2400 Watt Capacity@ 2.1Kelvin and

8300 Watt Shield Load @ 38/50Kelvin

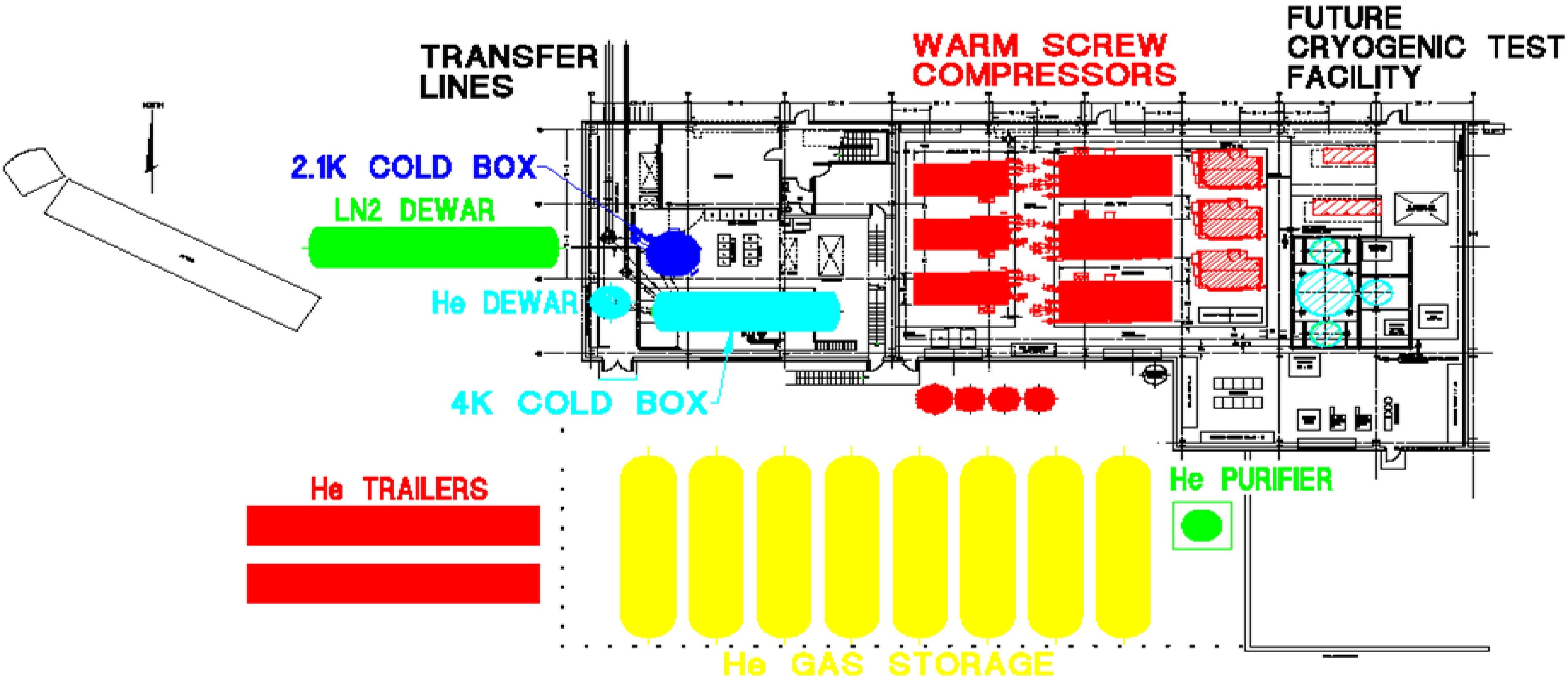
15g/s Liquefaction at 4.5Kelvin

80g/s Liquefaction Mode

Cryogenic Transfer Line System
4.5K & 38K Helium Supply and
4.0K & 50K Helium Return

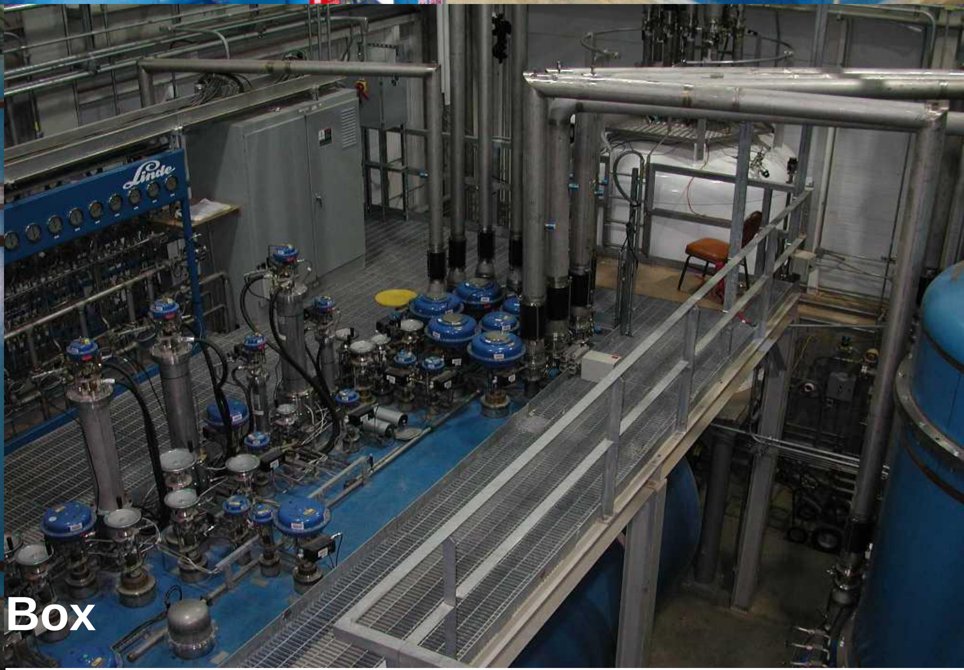
Whole system consumes >3 MW electricity

SNS CHL layout



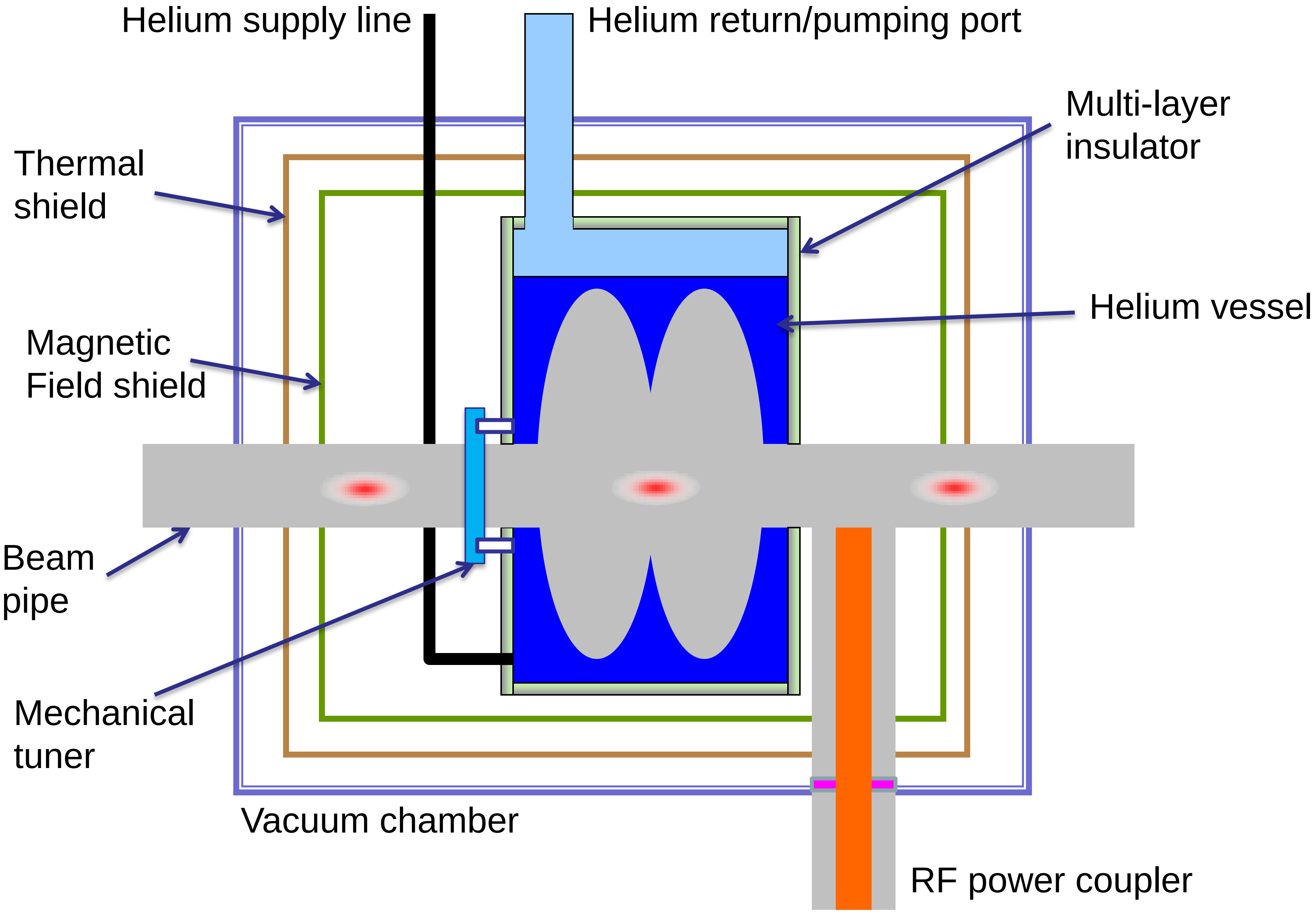
2 K Cold Box

Warm Compressor



4 K Cold Box

Schematics of cryomodule



Helium supply line

Helium return/pumping port

Multi-layer insulator

Thermal shield

Helium vessel

Magnetic Field shield

Beam pipe

Mechanical tuner

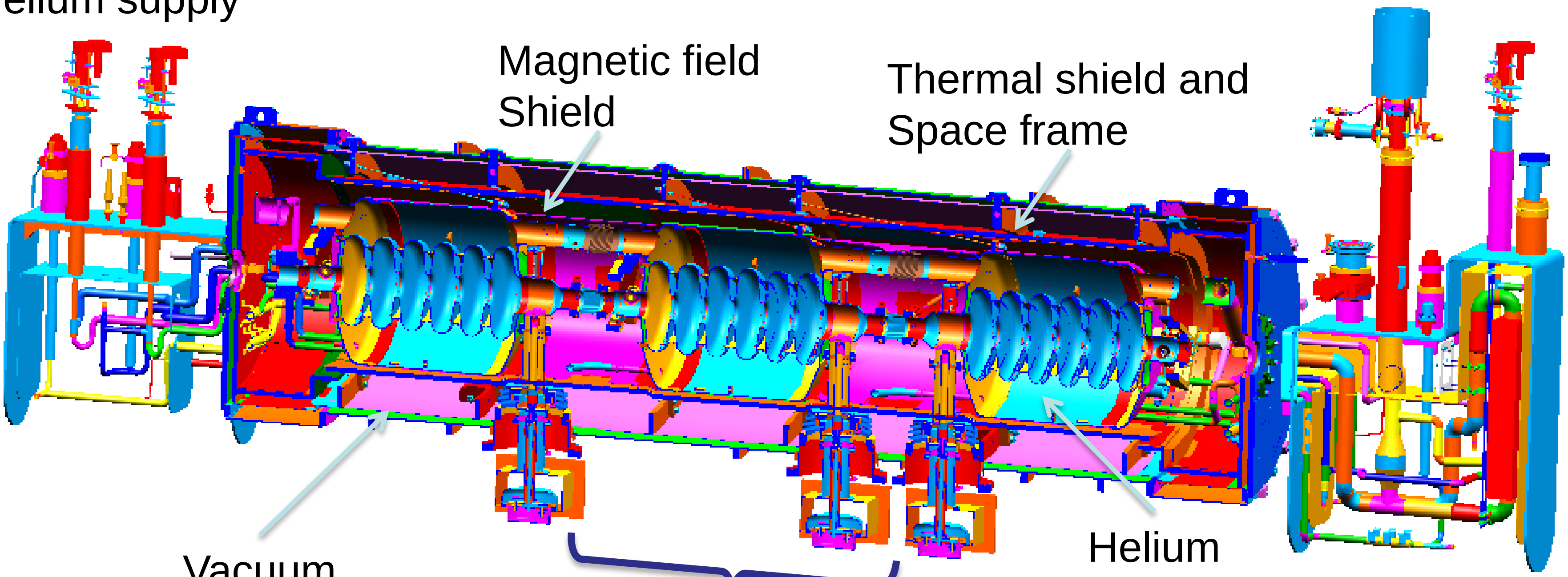
Vacuum chamber

RF power coupler

Space frame and thermal shield

Cavity string

Ex: SNS Cryomodule



End can for
Helium supply

Magnetic field
Shield

Thermal shield and
Space frame

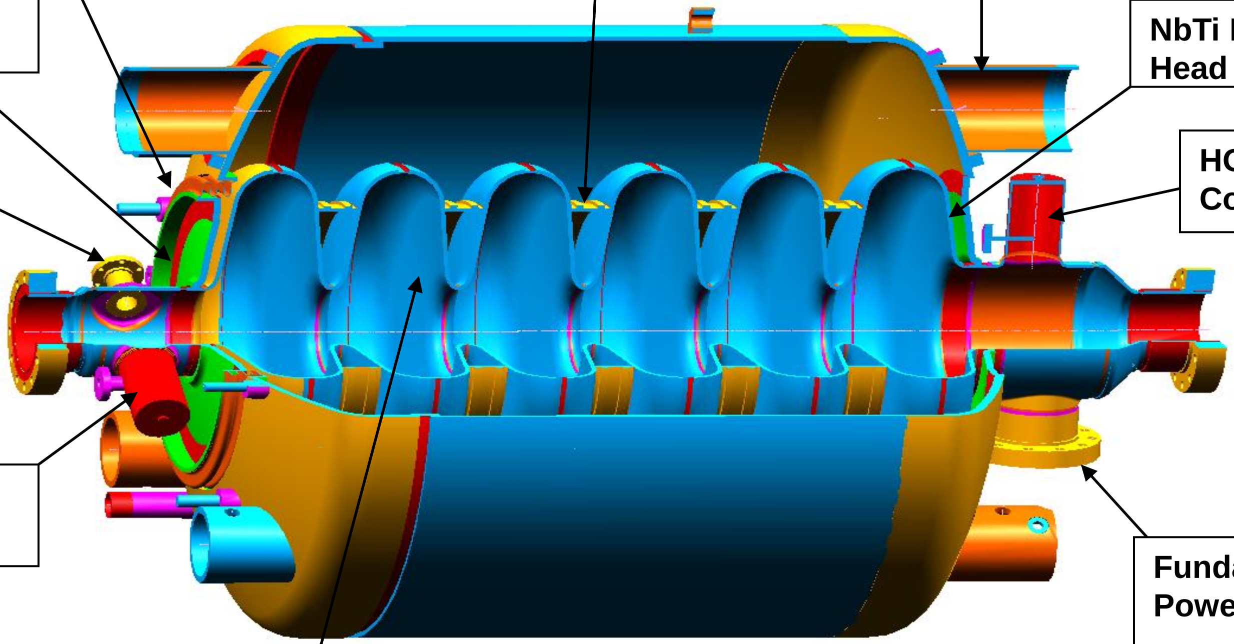
End can for
Helium return

Vacuum
Chamber

Power couplers and
waveguide transitions

Helium
vessel

Ex. SNS Cavity Assembly



Stiffening Rings

Titanium Bellows

2 - Phase Return Header

NbTi Dished Head

NbTi Dished Head

Field Probe

HOM Coupler

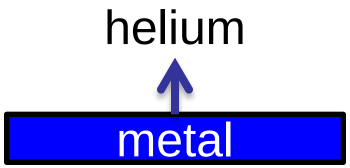
HOM Coupler

Fundamental Power Coupler

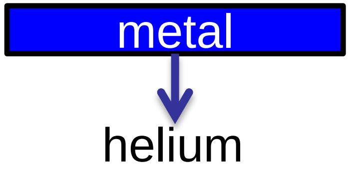
Medium Beta Cavity

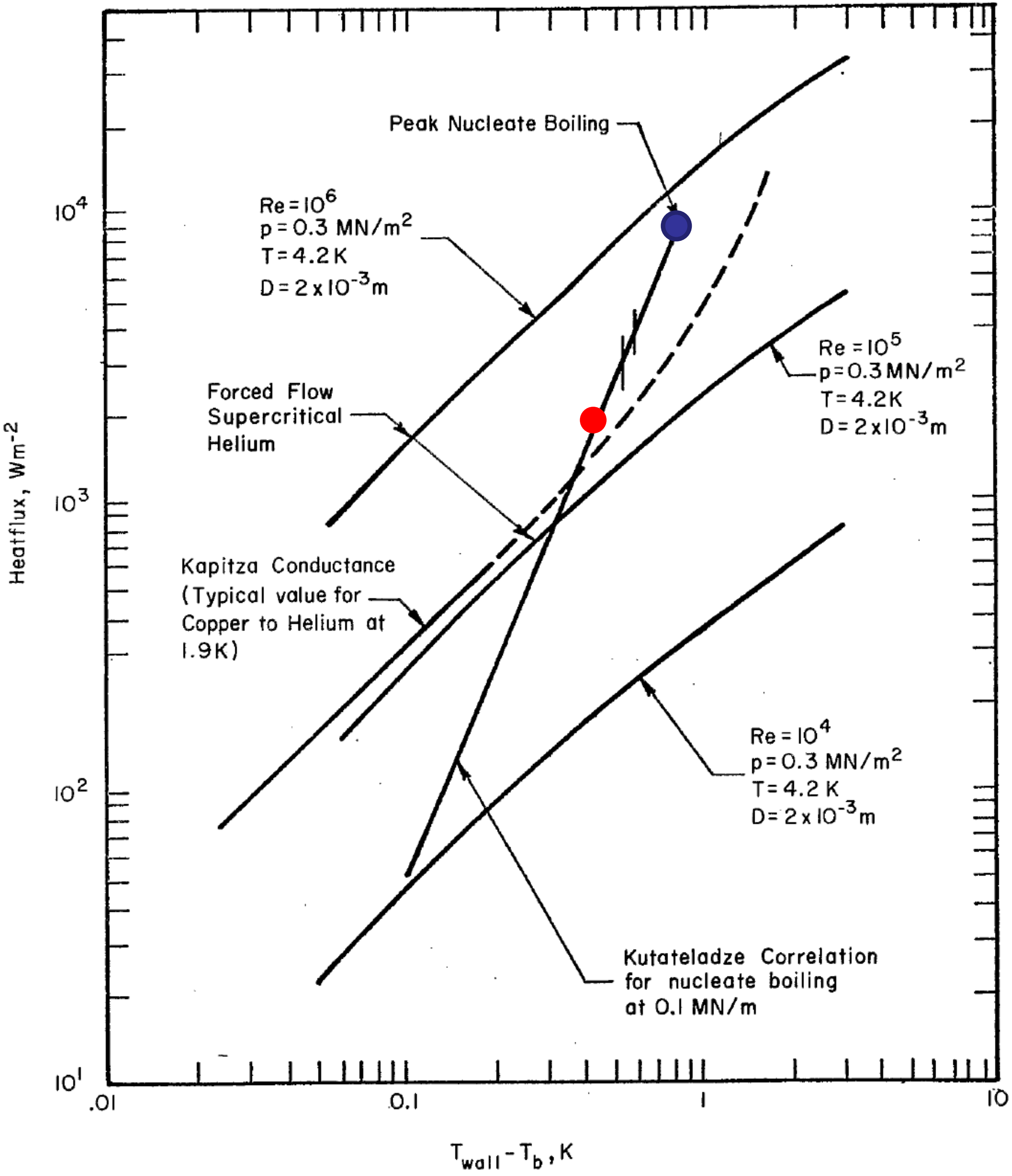
Comparisons of various modes of helium heat transfer

● Downward:



● Upward:





Resonance frequency control

Slow tuner (mechanical tuner):

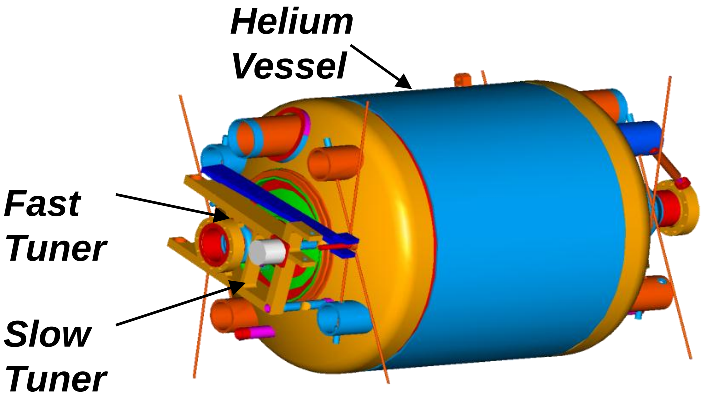
Compensate static or quasi-static detuning
(initial offset or slow drift of resonance frequency)

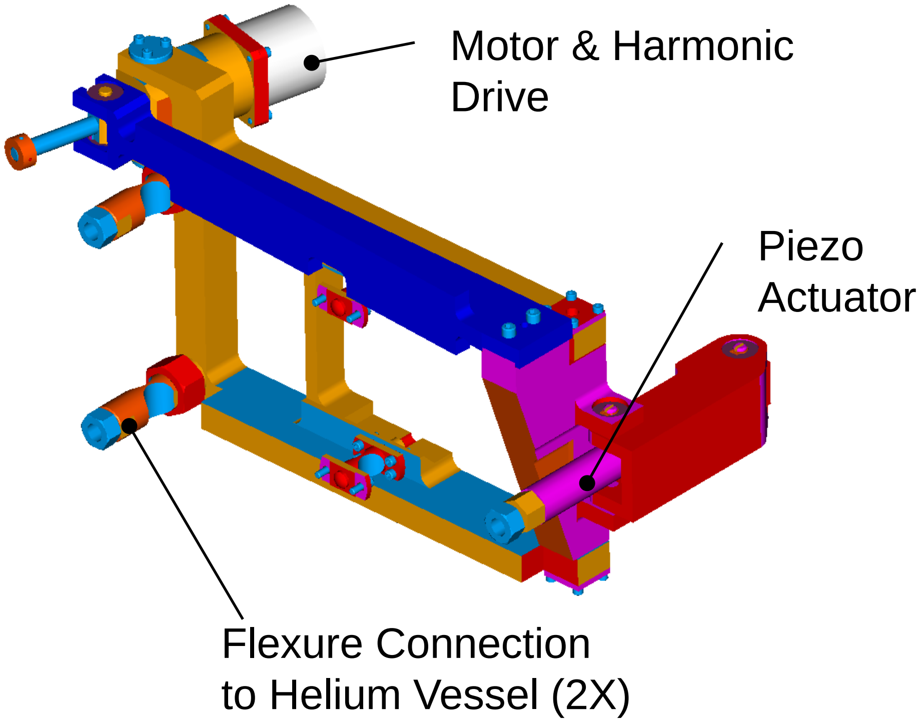
Compress/expand cavity length typically using stepper motor

Coarse tuning: usually put the resonance frequency in the allowable band

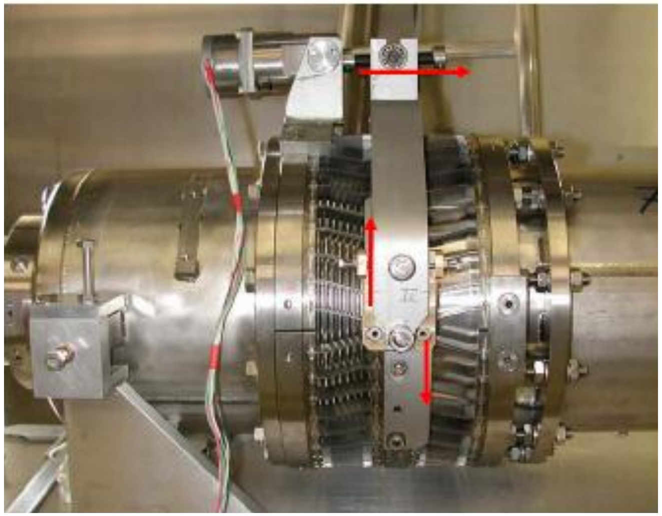
Typical tuning range: about +/- few mm

Types:
CEA/Scalay tuners
blade tuner (DESY, INFN)
side jack tuner (KEK)

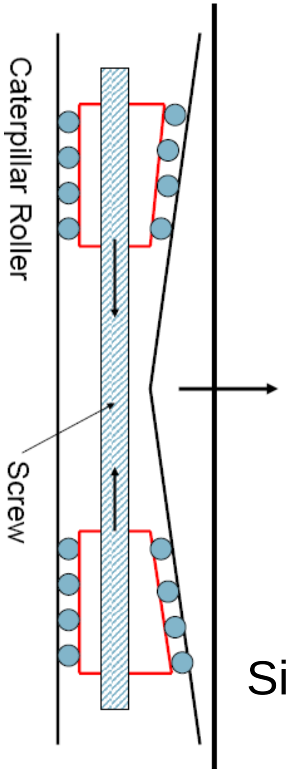


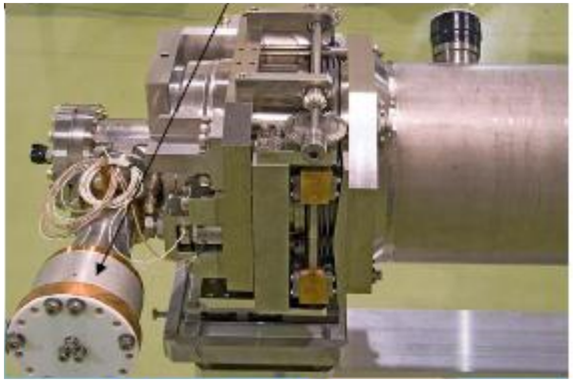


SNS tuner (saclay-TTF generation I type)



INFN, Blade tuner for ILC





Side Jack tuner (KEK)

Fast tuner:

Fine & fast tuning

Pulsed operation: Compensate Lorentz force detuning within RF pulses

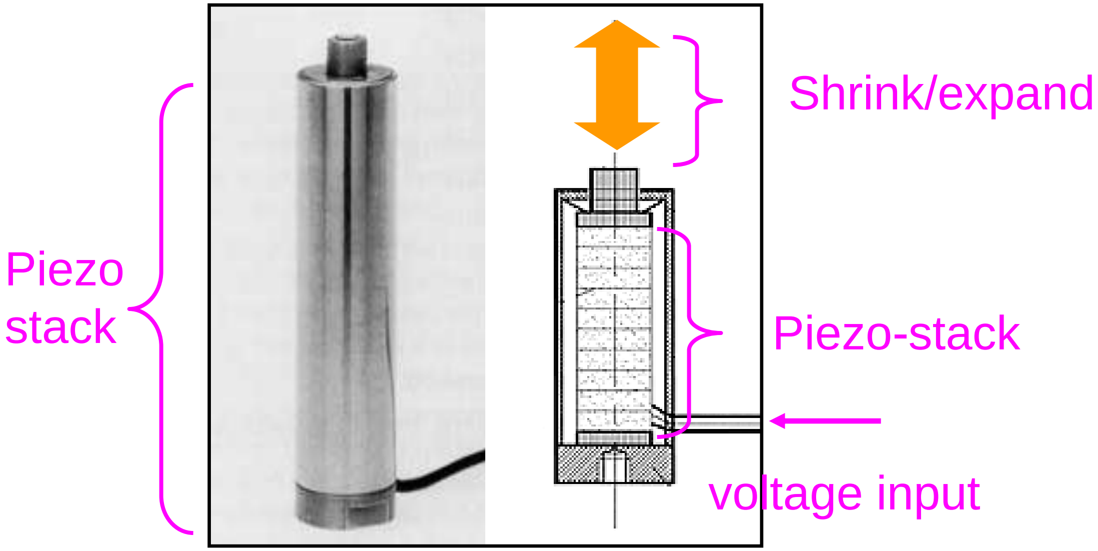
High Q_{ext}: Compensate microphonics

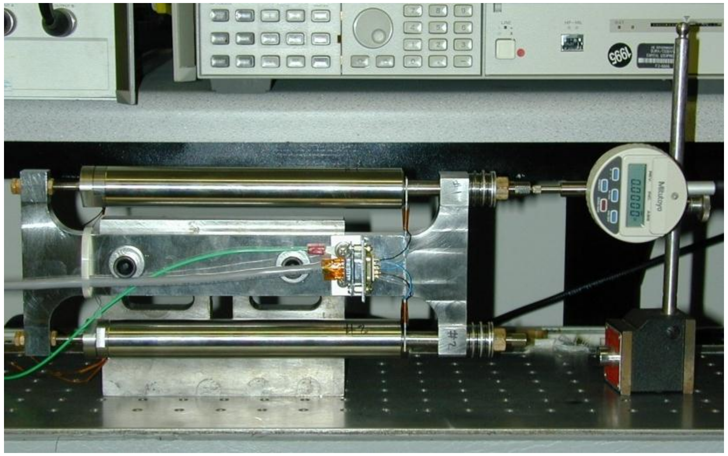
- Piezoelectric actuators: electromechanical actuator. Linear electromechanical interaction between the mechanical and the electrical state in piezoelectric materials.
  typical tuning range: few to several μm

- magnetostrictive actuator: solid state magnetic actuator. A current driven coil surrounding the magnetostrictive rod generates the expansion of the rod.

Piezoelectric actuator

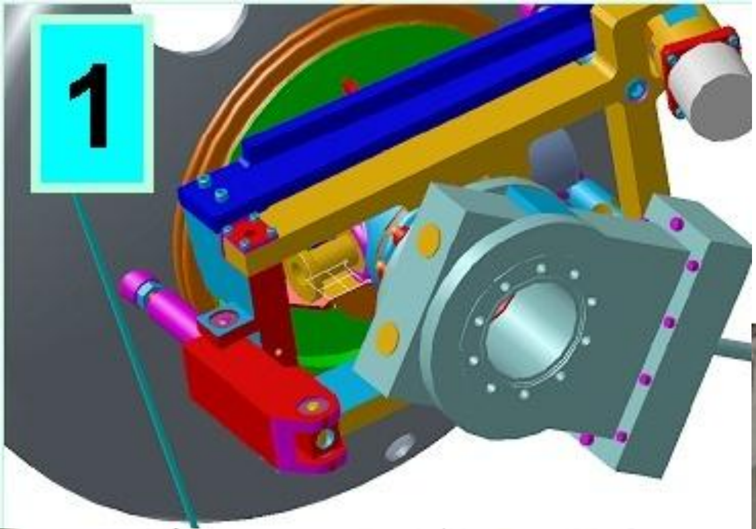
Voltage is applied to the piezoelectric actuator device which make the piezo stack shrink/expand





Typically
Stroke: 70~80 mm for 100 mm stack at room temperature
stroke at cryogenic temperature→ 5~10 % of that at room temperature
Resolution: ~Hz

Model vs. Reality



1. On the CAD Model

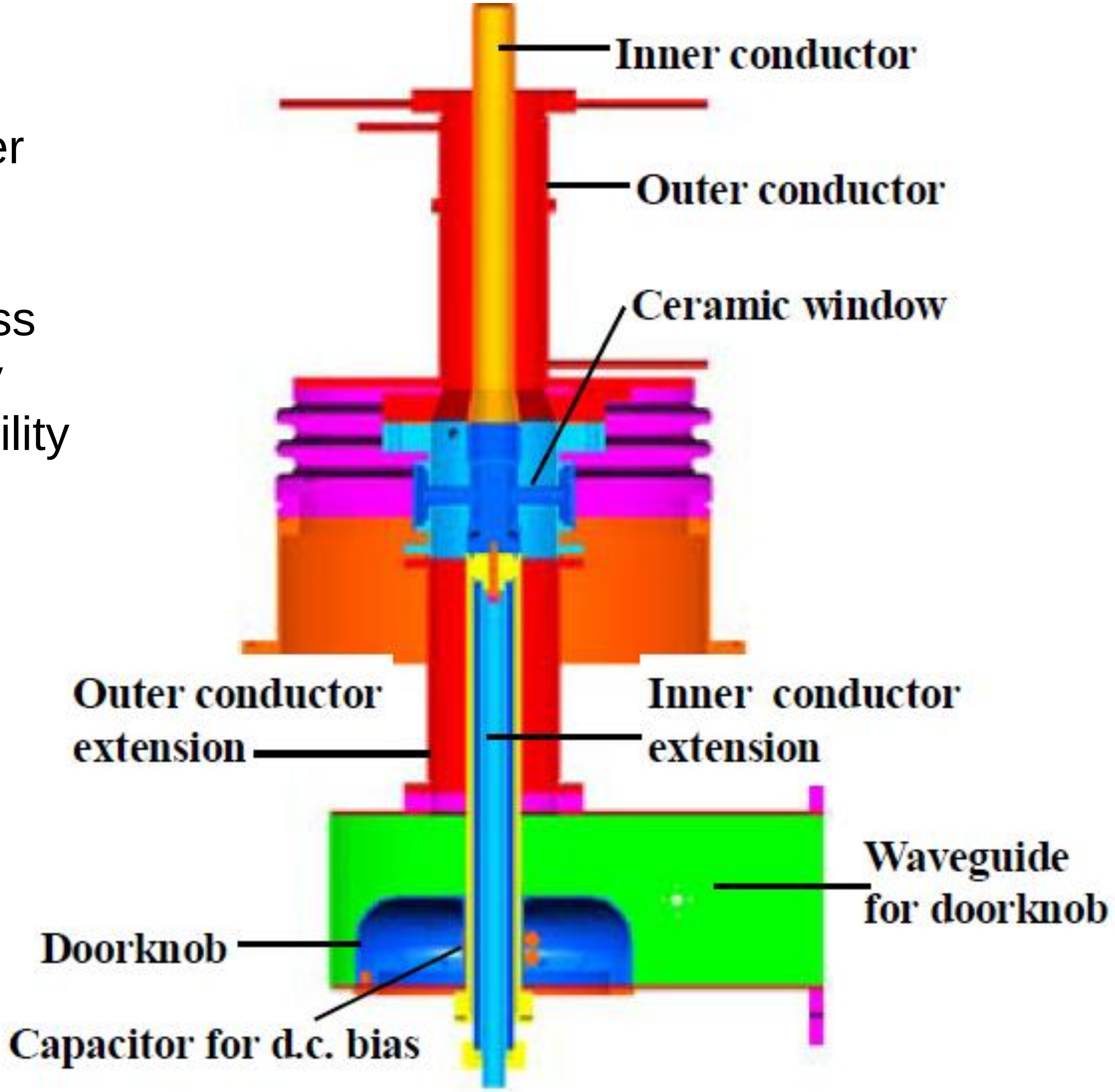
3. Reality – Pretty Complicated

Power Coupler

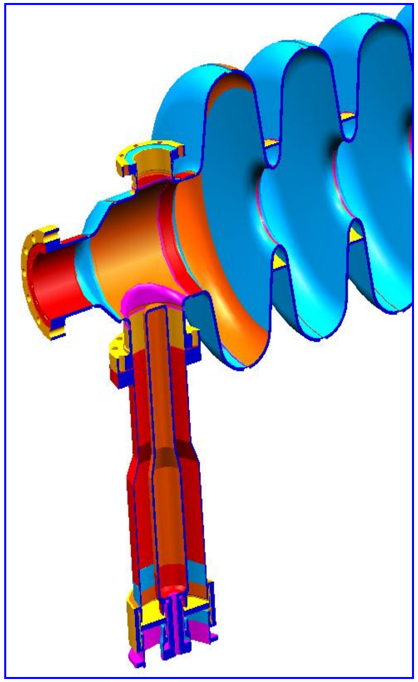
Function:
- Deliver RF power
- Coupling → Q_{ex}

Concerns:
- Transmission loss
- Thermal stability
- Mechanical stability
- Simplicity
- Reliability
- Cost
- Multipacting

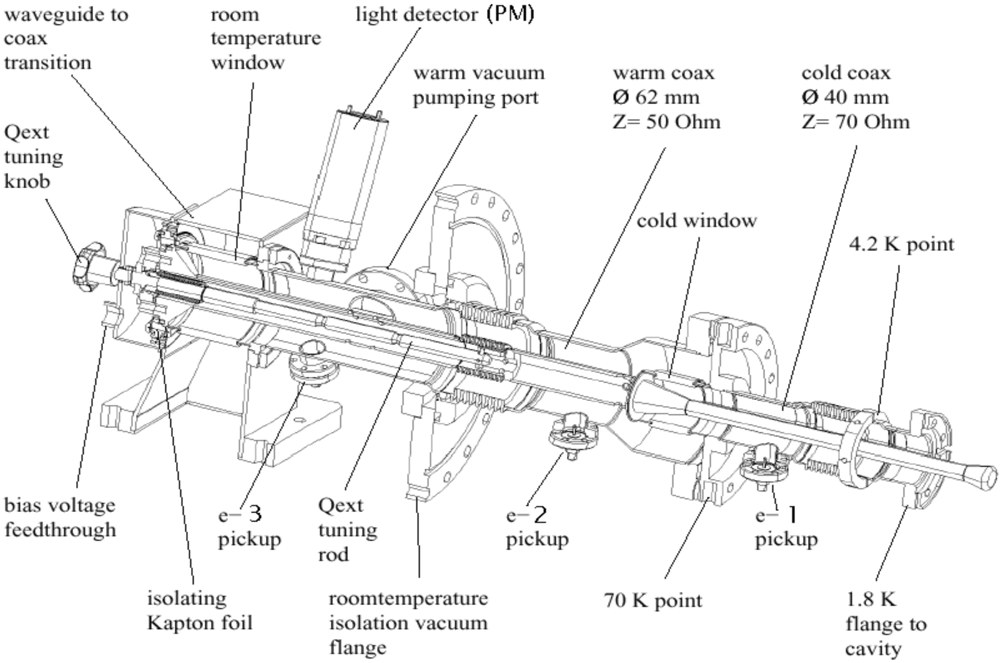
- Frequency
- Power needed
- Coupling
- Types
- Cooling
- Window



Coaxial

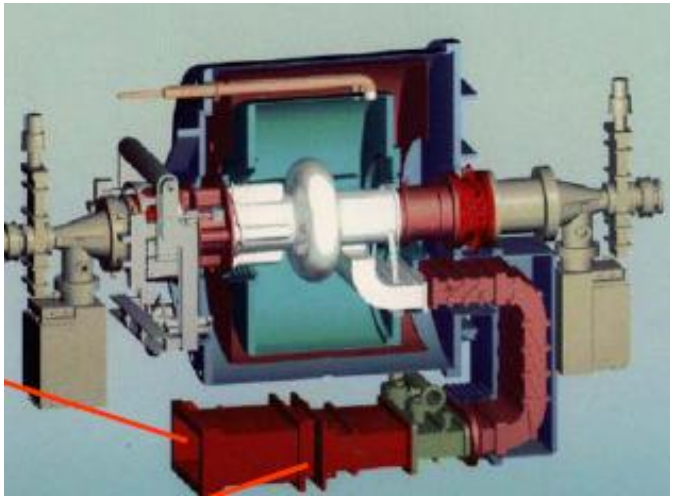


SNS power coupler

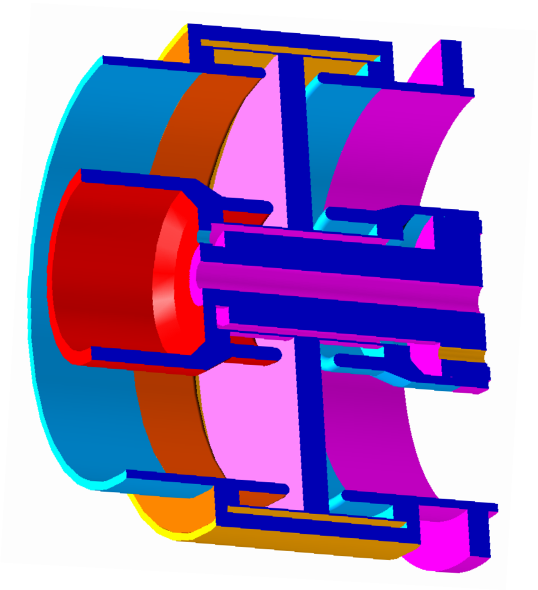


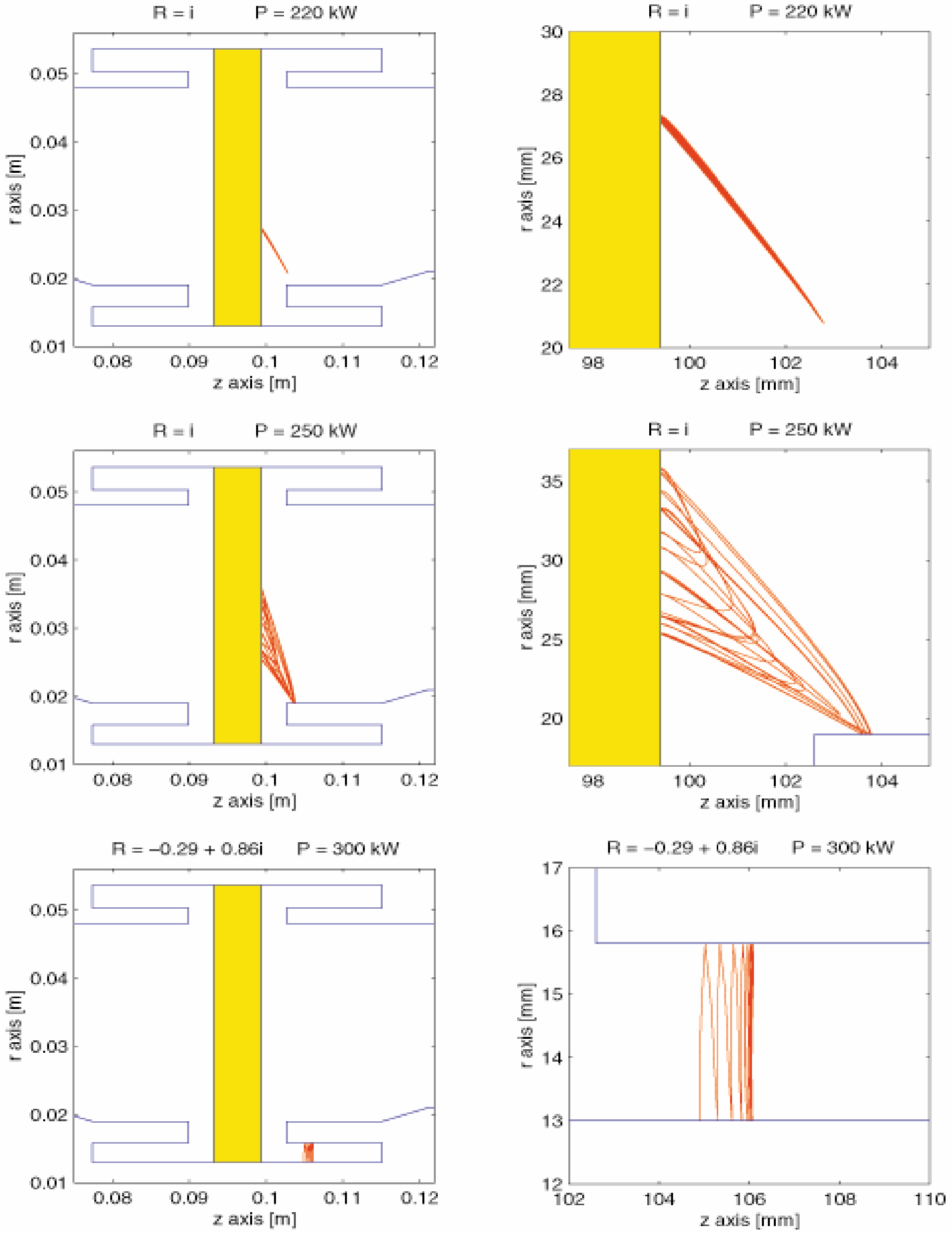
TTF3 coupler (ILC)

Waveguide



Multipacting simulations around ceramic window





Coupler conditioning