Room temperature structure development for high-current applications

- Introduction
- Constraints on CW high power designs
- Few comments on SC options
- RT structure choice with projects feedback

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Introduction

- High power beam becomes true since a few years. 10 to 125mA under constructions, some of them in CW mode
- Significant increase in production of secondary particles
  - Kaon
  - Neutrons
  - Muons
  - Neutrinos
  - Radioactive beam
- Discussion on intermediate cavities, RFQ and others (β=0.07- 0.5)

Projects requiring high beam power

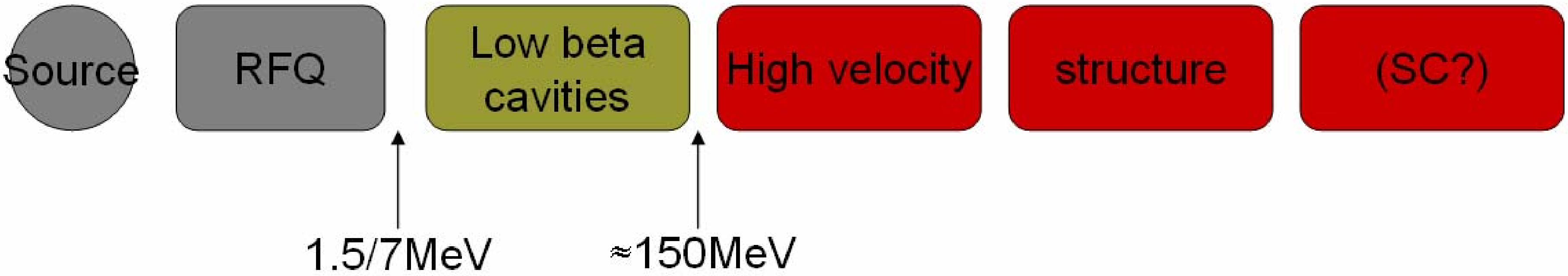
- Multipurpose projects (J-PARC –Japan –*P/HI/C*, KOMAC-PEFP – Korea – *CW-P/HI/C*, LANSCE – US – *LP/HI/R*)
- Neutron Spallation sources (SNS –US – *P/HI/R*, CSNS – China – *P/HI/C*, ESS – Europe –*P/HI/P*, ISIS - UK – *P/HI/R*
- Irradiation tool (IFMIF, IFMIF-EVEDA –Europe/Japan – *CW/VHI/Pr-C*)
- Muon and neutrino production (LINAC4-SPL - Swiss – *P-LP/HI/P*
- RIB (SPIRAL 2 – France – *CW/C*, Eurisol – Europe – *CW/P*, SPES – Italy – *CW/P*, SARAF – Israel – *CW/C*, RIA now AEBL –US *CW/P*
- ADS (TRASCO – Italy *CW/HI/C-P*, EUROTRANS – Europe *CW/P*, ADS – China – *P/HI/C*

- In the past, high-intensity linac designs were also developed for tritium production (APT in US, TRISPAL in France…)

- P: pulse, LP: Long Pulse (>10%DF), CW
- HI: >15mA, VHI>100mA,
- Pr: Project, C: under construction/commissioning, R: runing

High power constraints on intermediate velocity structure

- Typical LINAC designs:



- High beam current, but still the same loss level ➔ better understanding of the halo formation or halo handling (transverse and longitudinal)
- High power CW machine:
  - Beam handling
  - Engineering difficulties (alignment, complexity, RAMI)
- Shunt impedance, accelerator length
- Economical aspect

Beam handling

- Need strong focalization
- Need tight tolerances
- Diags are fundamental for the control, but often interceptive
- Difficulties arise in
  - engineering,
    - 20 to 50 W/cm²
    - Hot spot up to 150/250 W/cm²
  - cooling
  - stabilization of the cavity under operation
- Need serious calculation
  - Beam dynamics
  - 3D RF simulation
  - Thermal deposition
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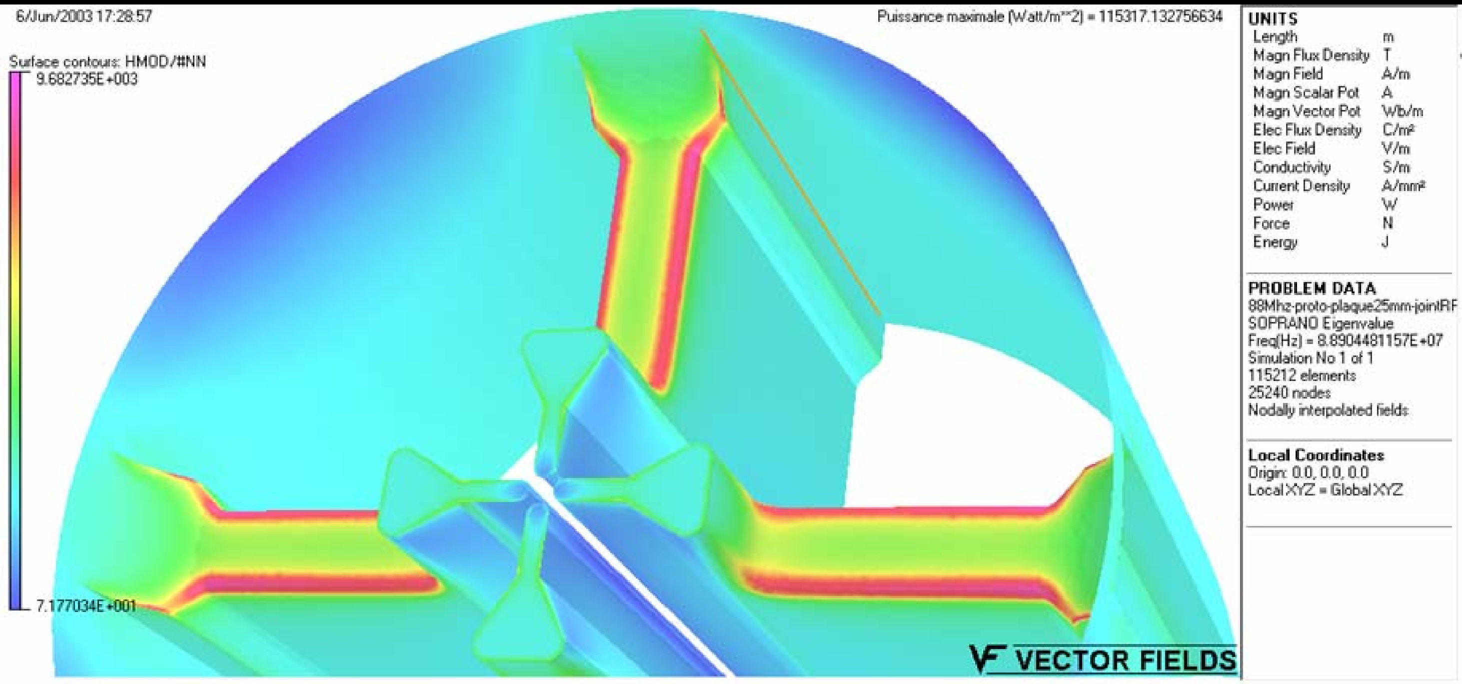
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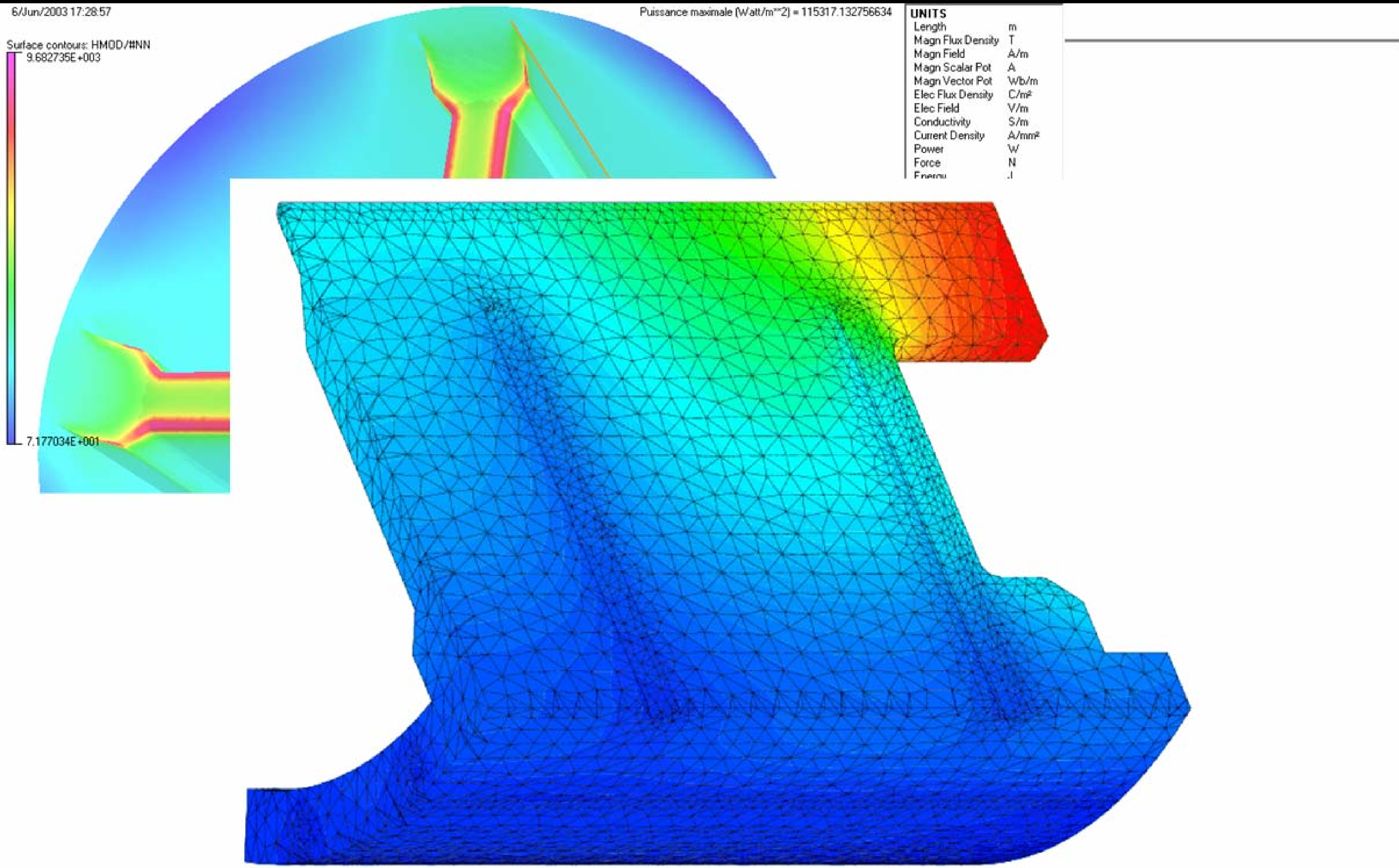
7.177034E+001
VECTOR FIELDS
UNITS
Length m
Magn Flux Density T
Magn Field A/m
Magn Scalar Pot A
Magn Vector Pot Wb/m
Elec Flux Density C/m²
Elec Field V/m
Conductivity S/m
Current Density A/mm²
Power W
Force N
Energy J
PROBLEM DATA
88Mhz-proto-plaque25mm-jointRF
SOPRANO Eigenvalue
Freq(Hz) = 8.8904481157E+07
Simulation No 1 of 1
115212 elements
25240 nodes
Nodally interpolated fields
Local Coordinates
Origin: 0.0, 0.0, 0.0
Local XYZ = Global XYZ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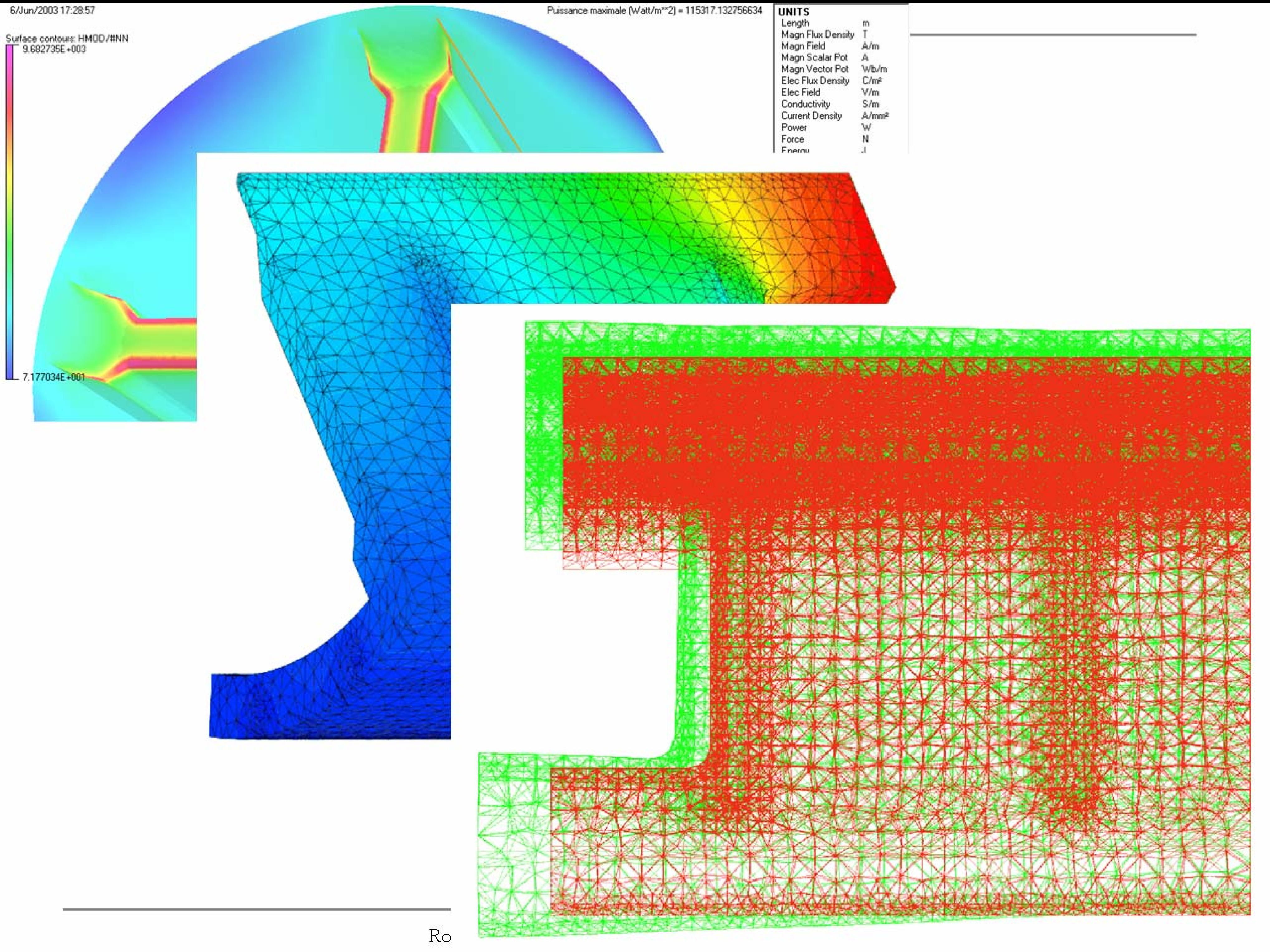
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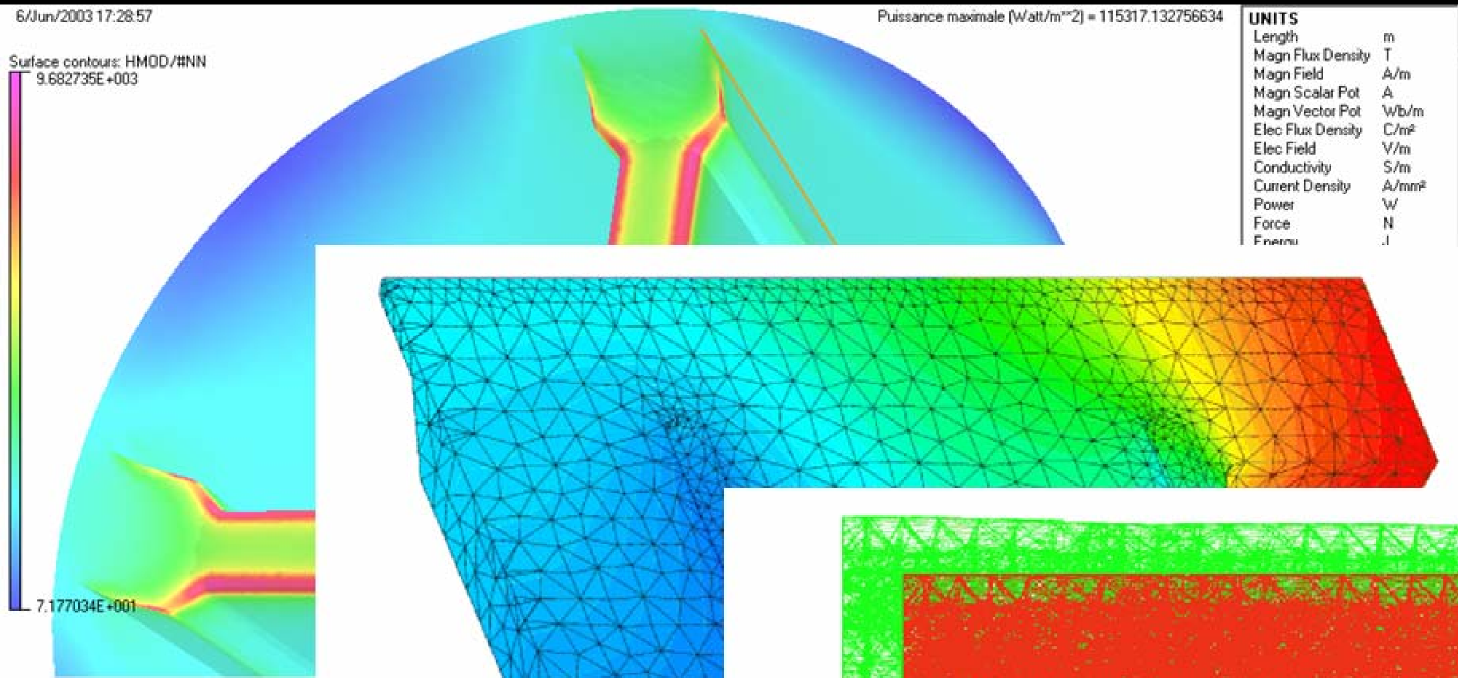
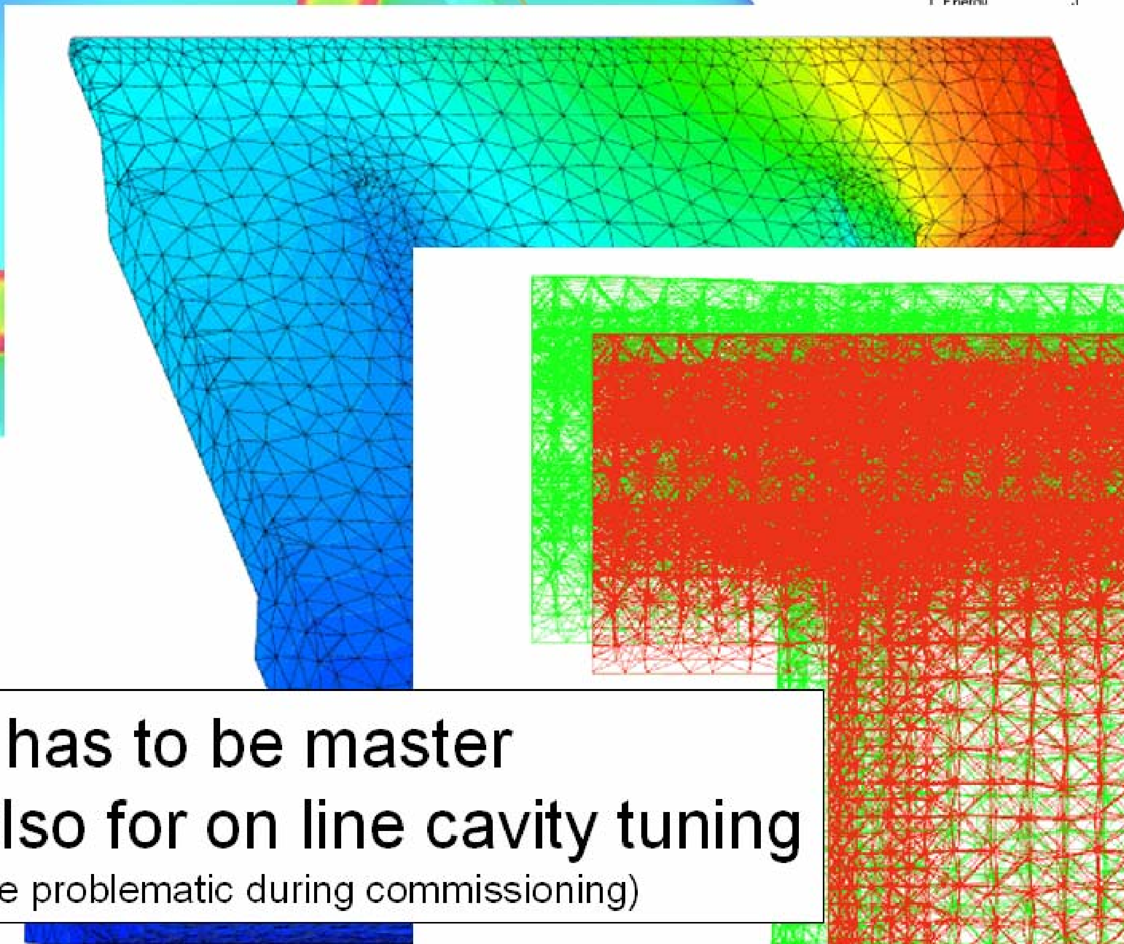
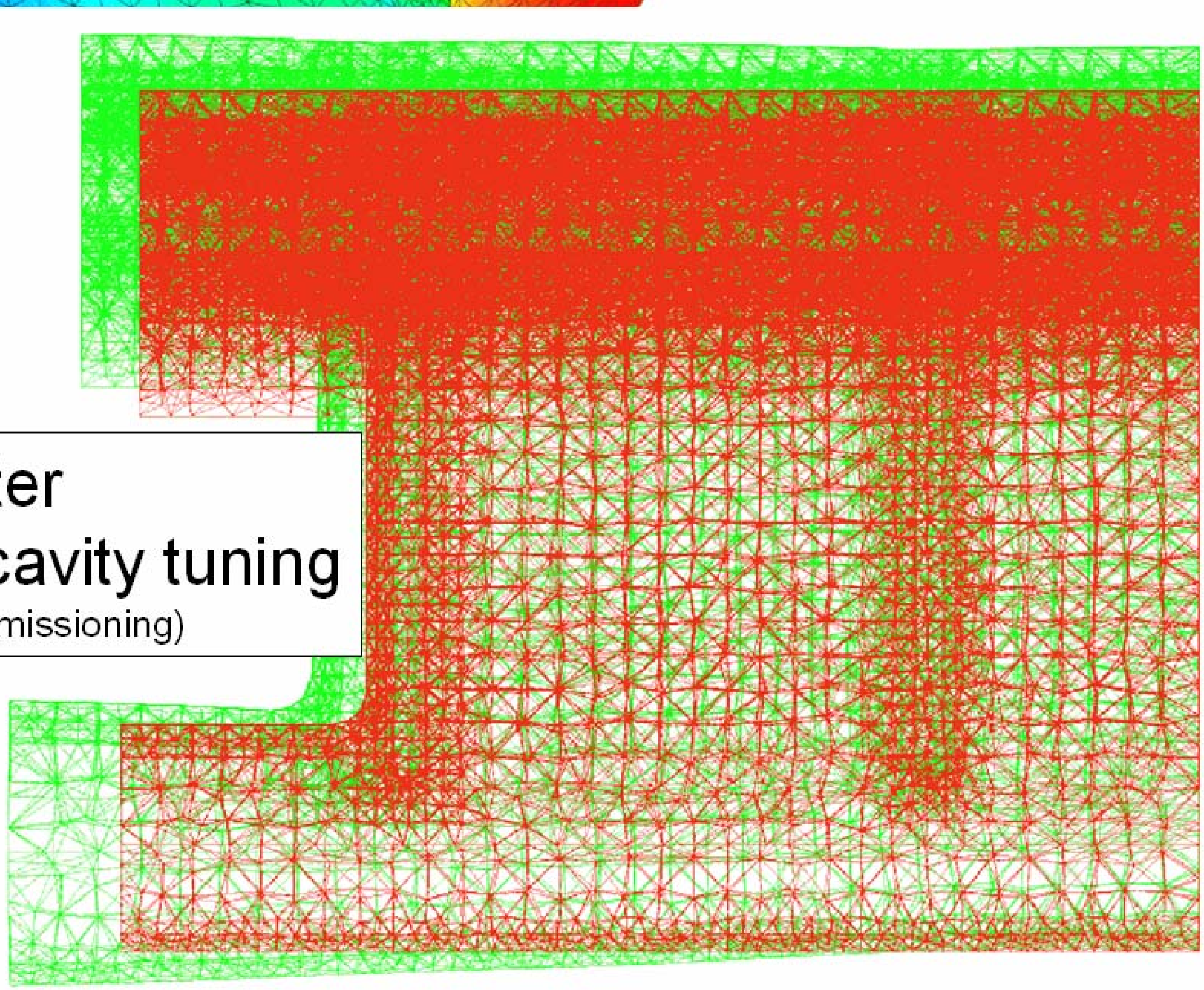




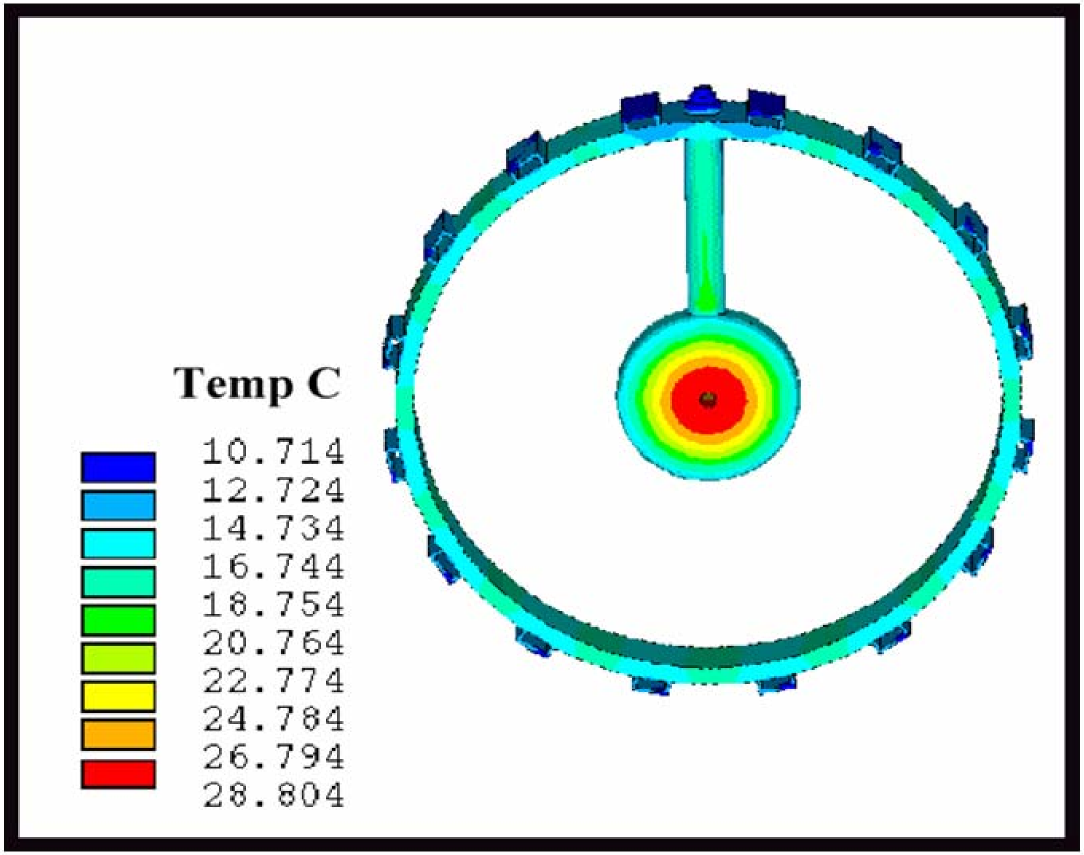


Heating has to be master

Useful also for on line cavity tuning

(Could become problematic during commissioning)

CW DTL example



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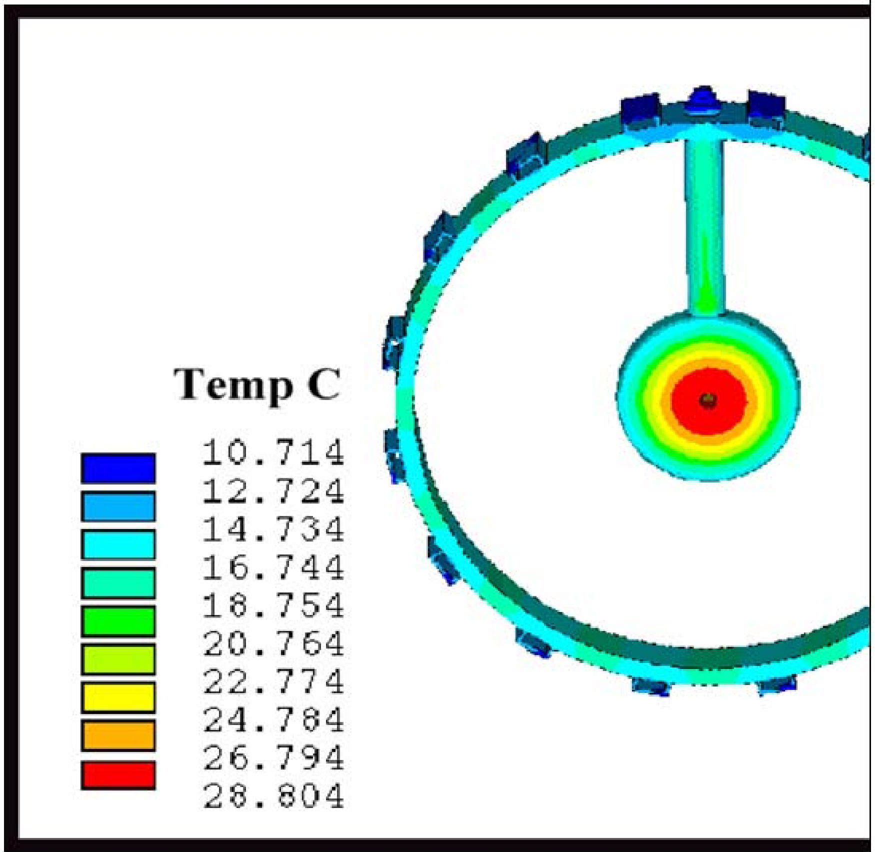
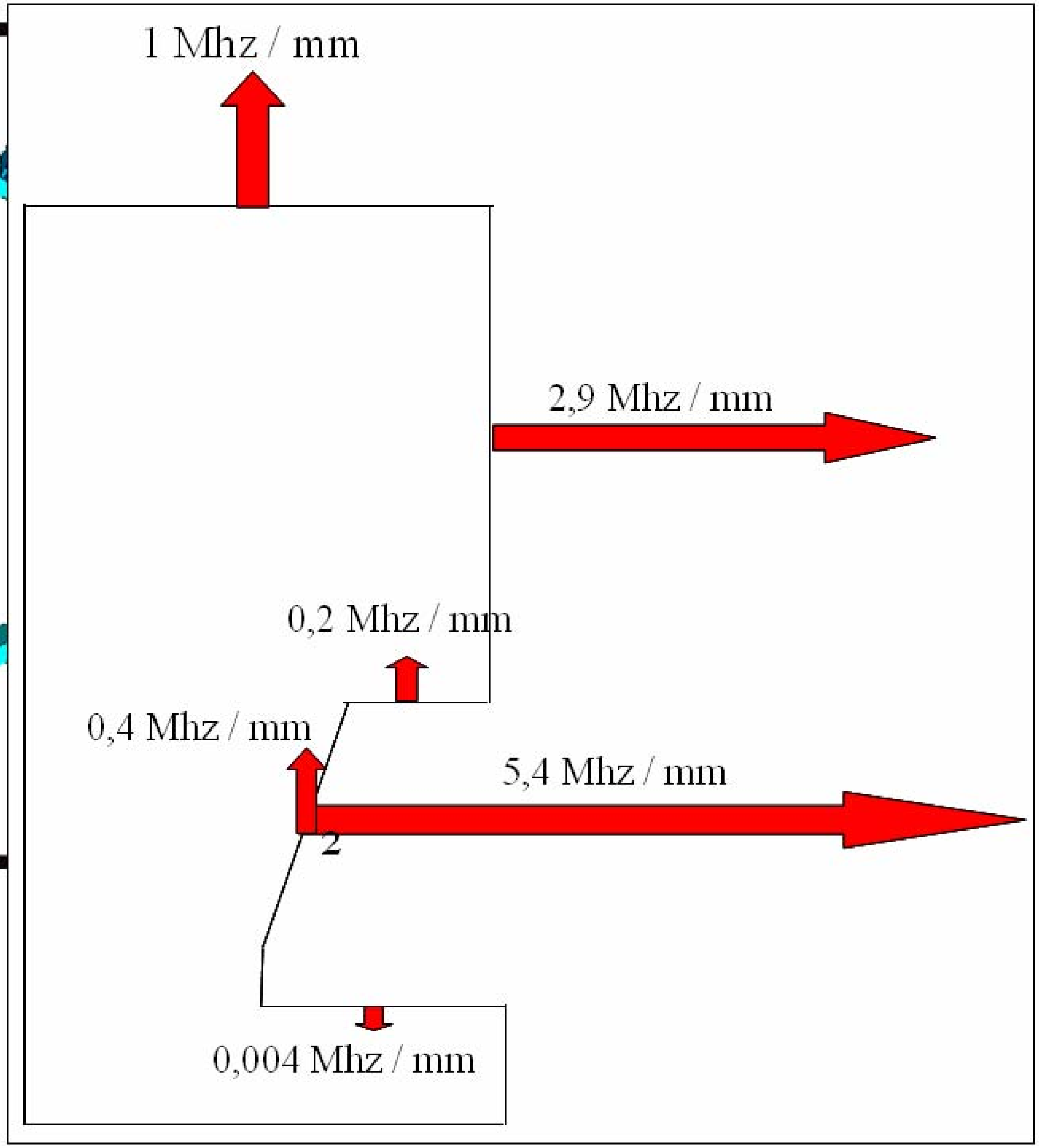




Comments

- The challenge:
  - Minimize activation
  - Minimize the cost
  - Maximize the availability
- Specs on beam intensity and energy not enough: time structure, emittance versatility, RAMI specifications
  - Huge RF sources allow capital saving but are the weakness point of the system in case of failure
- Never a unique solution
  - Choice between SC and Room temperature
  - Choice between different RT cavities
  - Depends more on team knowledge or worldwide solution

SC alternative

- SC machine were first developed for β=1 cavities, then extended to ion beams and lower velocity beams
- SC for low beta appears 20 years ago, for CW design with low beam current (low losses)
- RAMI becomes an issue with high beam current
- Today progress are made
  - Cavity simulations
  - Beam simulations
  - Gives confidence to designers in SC solutions

Comments obtained on SC alternative

- Cost:
  - Operational : high RF-to-beam-power efficiency gives a permanent advantage
  - Capital : considered to be similar
- Flexibility
  - Bigger aperture but also lower focusing
  - Beam-to-bore-aperture ratio has to be taken as the major point.
  - Is there a bigger ratio using SC cavities?
    - Space charge dominated beam
    - Longitudinal losses will be lost whatever the bore aperture
- Availability
  - Considered to be better
  - More stable cavities
  - Design that could be fault tolerant (hardly true at very low β)
- **Development of SC cryomodule usually required more time**
  - Expertise needed
  - Attract young because of high tech
- **Accurate control on beam losses.**
  - LLRF must include feedback and feedforward loop techniques
  - Pulse SC machine must deal with microphonics or Lorentz detuning difficulties.
- **SC cavities usually provide higher gradients allowing a length reduction. Real estate gain starts after 100-200 MeV**

RT design

Frequency

- For a high-power hadron machine, 200 to 400 MHz is ideal
  - F ↗ Cavity size ↘
  - F ↗ efficiency ↗ cost of RF↘
  - shunt impedance ↗ Linac length ↘ cost ↘
- @ high frequency
  - Difficulties in the manufacturing process
  - Incorporation of focusing elements difficult
  - Tolerances might become a problem
    - Example of SNS and J-parc : 400MHz, 3MeV, electromagnet not possible => PMQs for SNS, 324MHz for J-Parc
- RF source may become a part of the frequency choice:
  - 1MW, CW diacrode @ 200MHz exist but only 1 manufacturer
  - Klystrons usually preferred to tetrode (gain, reliable, simple) but limited to 300-350MHz

Frequency in the different projects

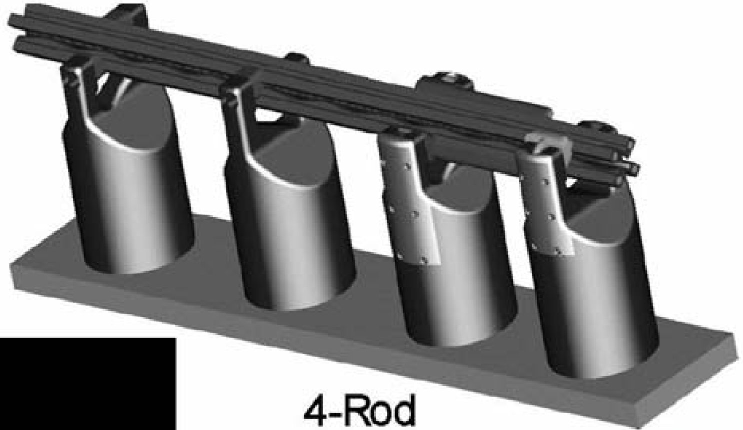
- Choice is large enough to use existing possibilities from the RF tube manufacturers
- Most of the time, the choice is more political or experience-based rather than supported by compelling technical reasons
- RF is expensive, development of new frequency even more expensive
- In Europe : based from LEP in CERN (352MHz) ➔ 88/175/352/700 MHz
- Asian project use same synergy or 324MHz for pulse machine (J-Parc, CSNS)
- US : mostly based on LANSCE experience (402MHz)

Room Temperature cavity types

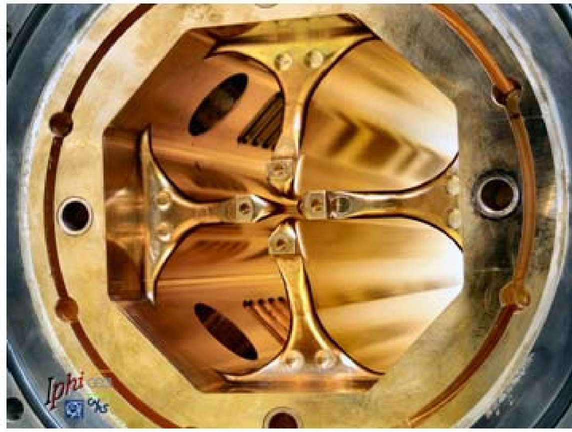
RFQ

- RFQ is not efficient cavity, is expensive, has a low RF/acceleration ratio but accelerate and bunch adiabatically
- Energy ranging from 1.5 to 7 MeV proton with excellent beam quality and relative low losses
- Final energy depend on ability to manage longitudinal field stabilization and project needs
  - Coupling plates : LEDA IFMIF TRASCO IPHI PEFP China
  - π-mode stabilizing loop : J-parc, SNS
- Input energy : lowest compatible with sources and beam transport

Different RFQ types

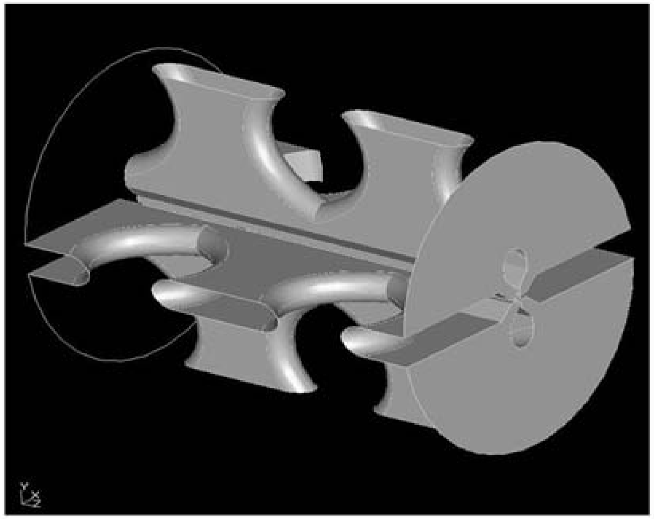


4-Rod



4-Vanes

Split coaxial



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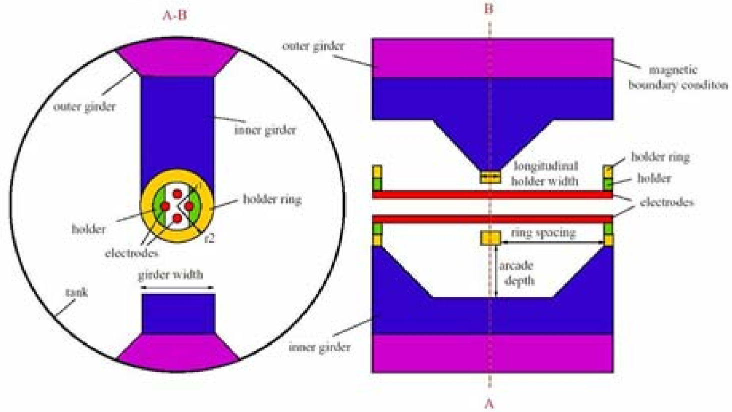
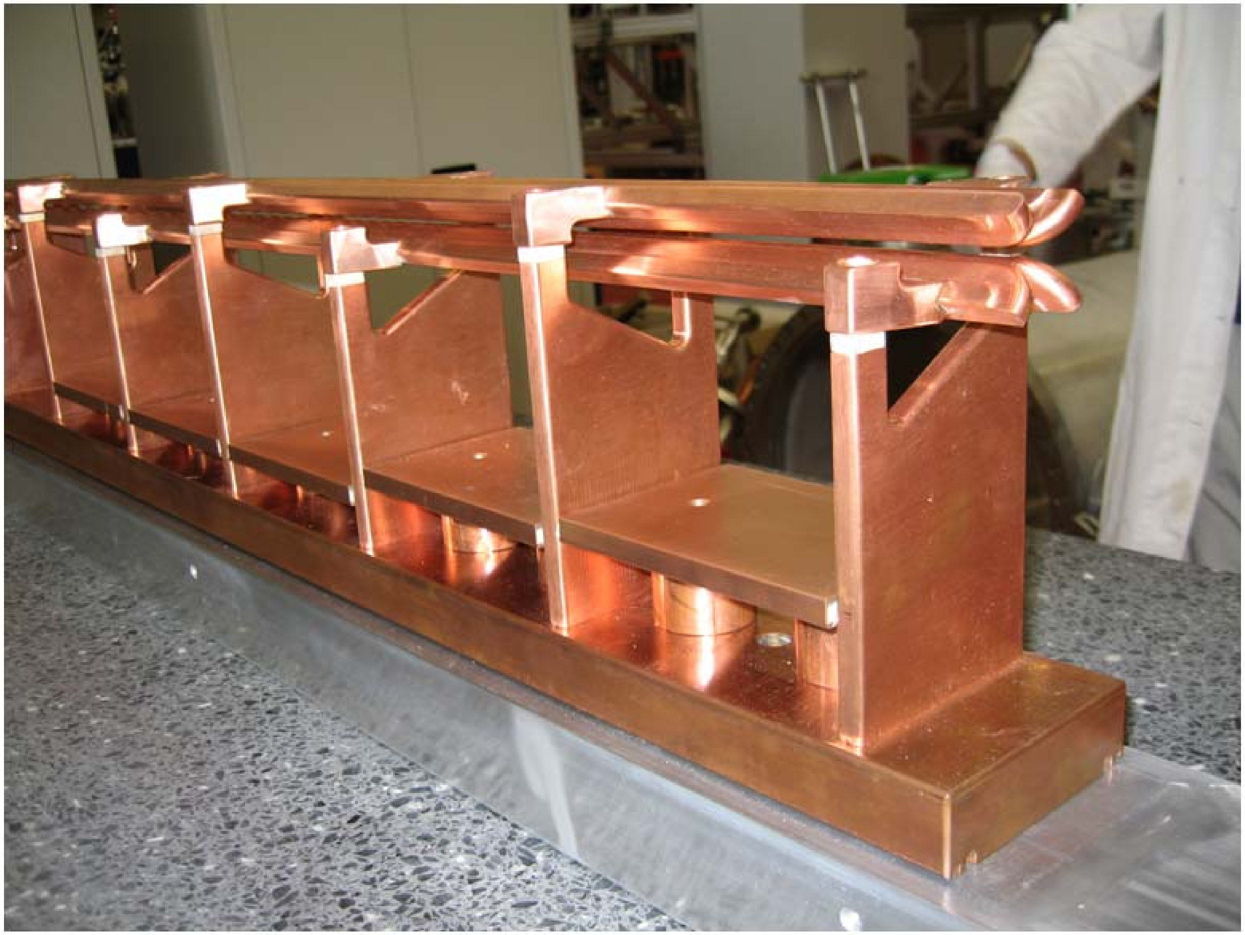
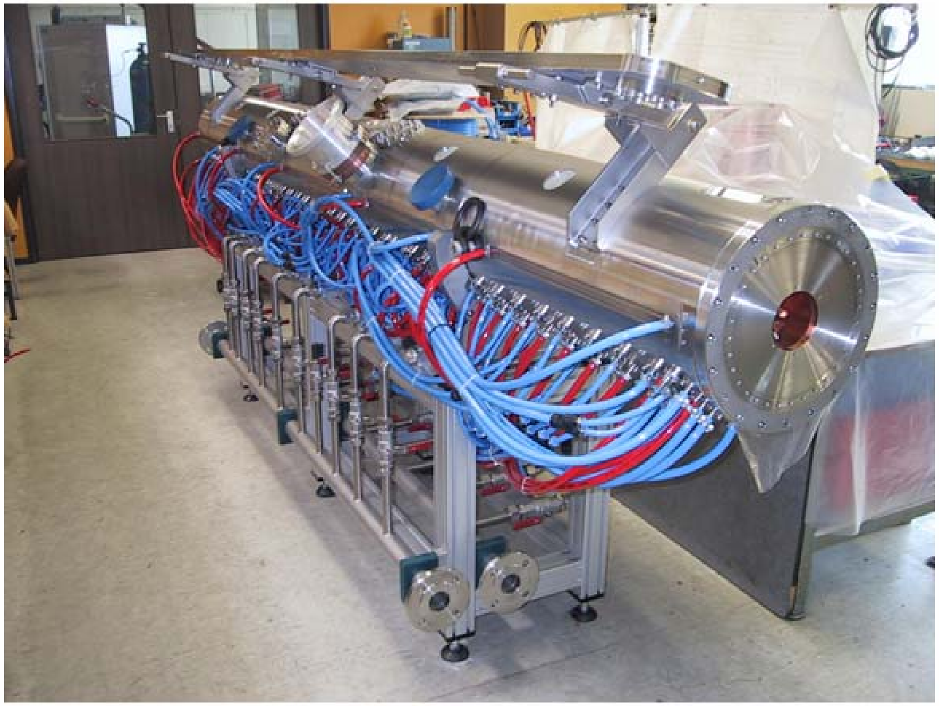


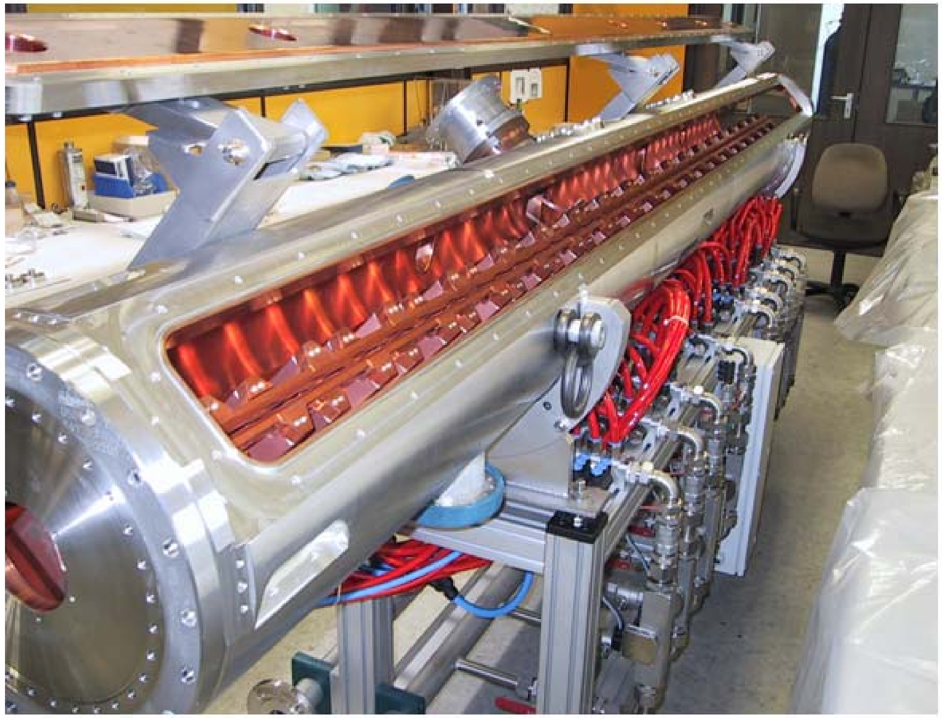
4-rod RFQs

- Simplest to build and the cheapest one
- Critical part is the cooling



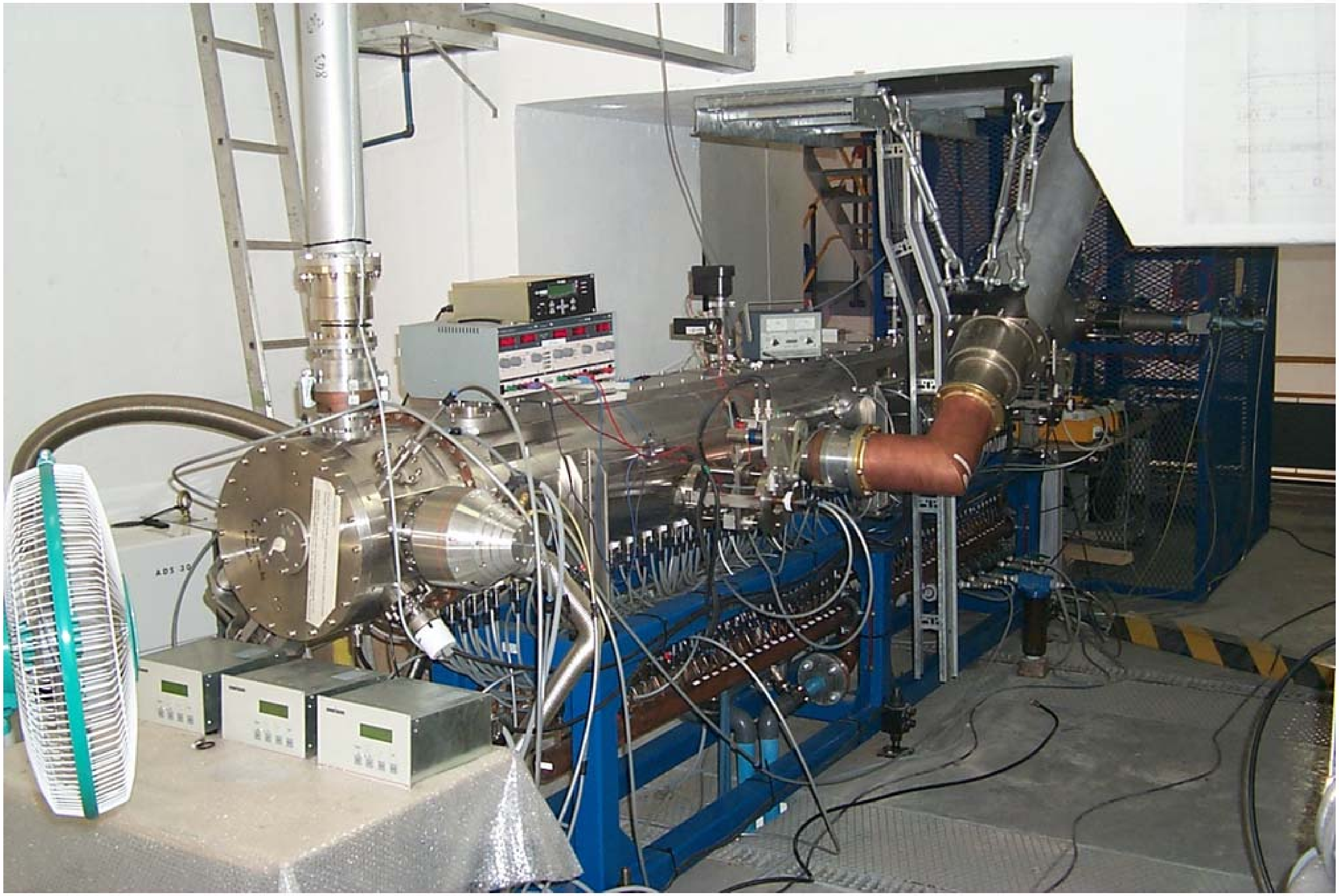
Recent results from A. Schempp's team





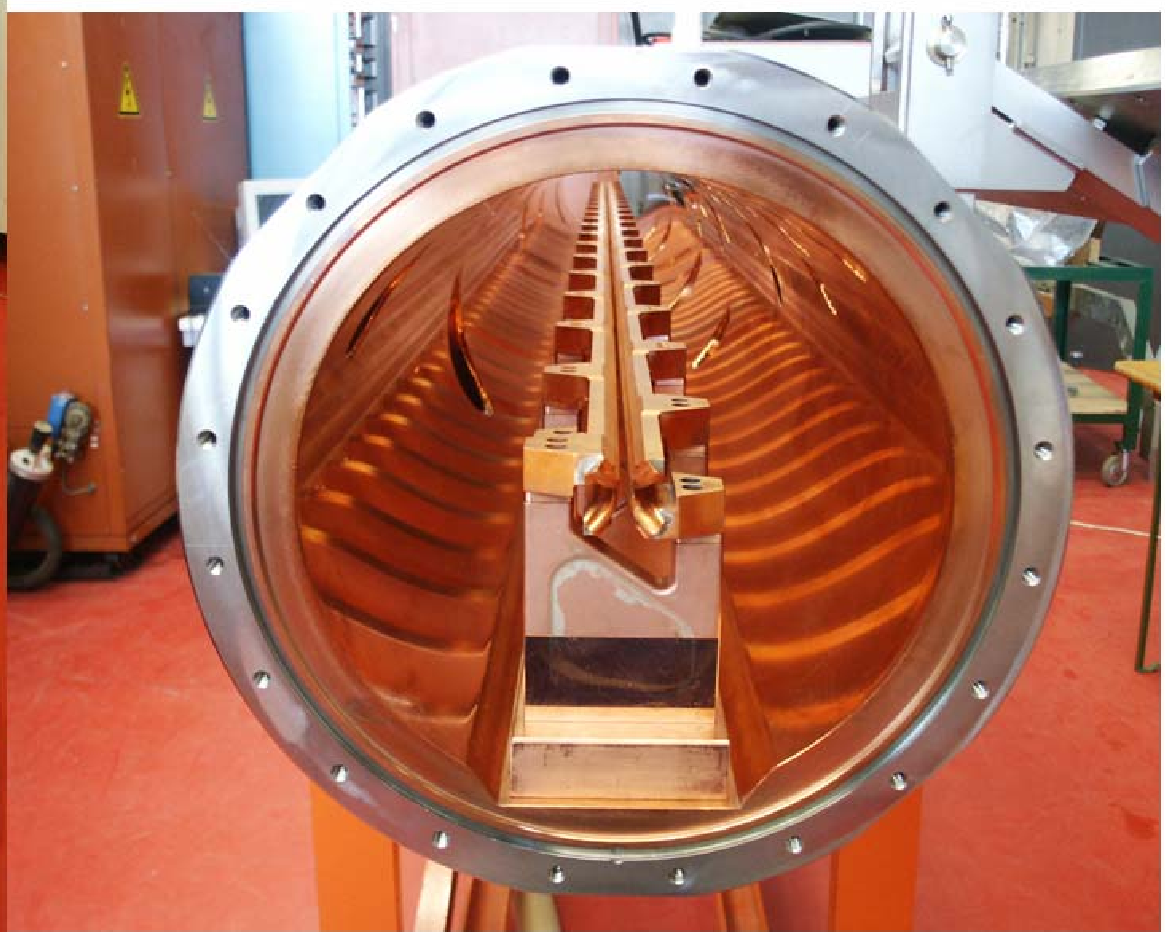
4-Rod RFQ (fixed frequency) / 176 MHz / 220 kW CW

4-Rod RFQ for industrial application



D+, 4/5MeV 20%df, 200MHz, 50/10mA

SARAF 4-Rod RFQ



3 MeV D^+, 175 MHz, CW

4-vanes RFQ

- Usually the less consuming one
- High intensity requires high vane voltage ➔ brazed 4-vanes RFQ still the reference HI CW solution
- Brazing process remains the complicated step of the fabrication, but is still a requirement
  - Nightmare in Europe (IPHI – TRASCO)
  - Asia and US seems OK (vertical brazing?)
- LEDA still the world leader : 110mA, CW, proton beam up to 6.7MeV at 350 MHz

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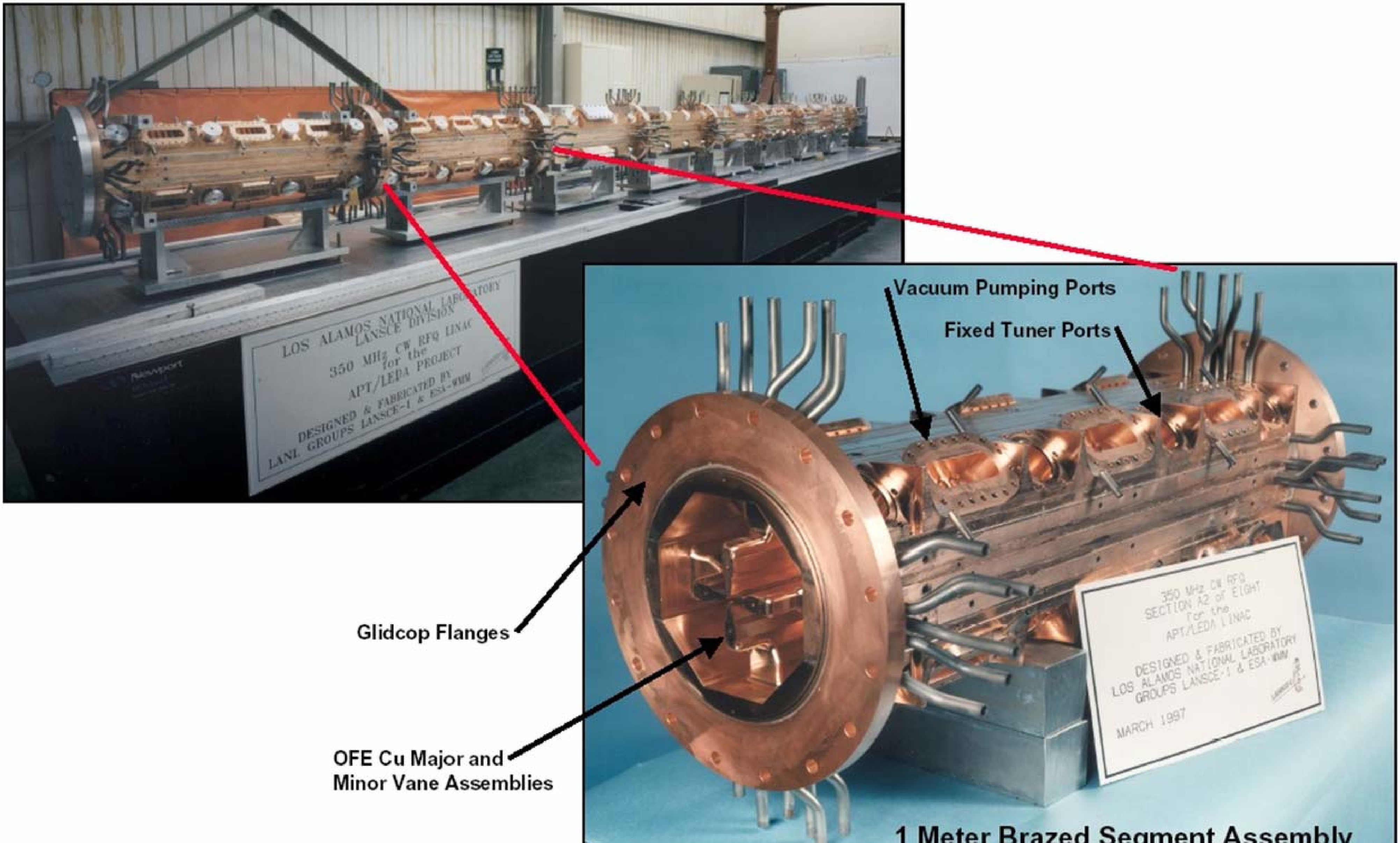

Photo Credit: Los Alamos National Laboratory

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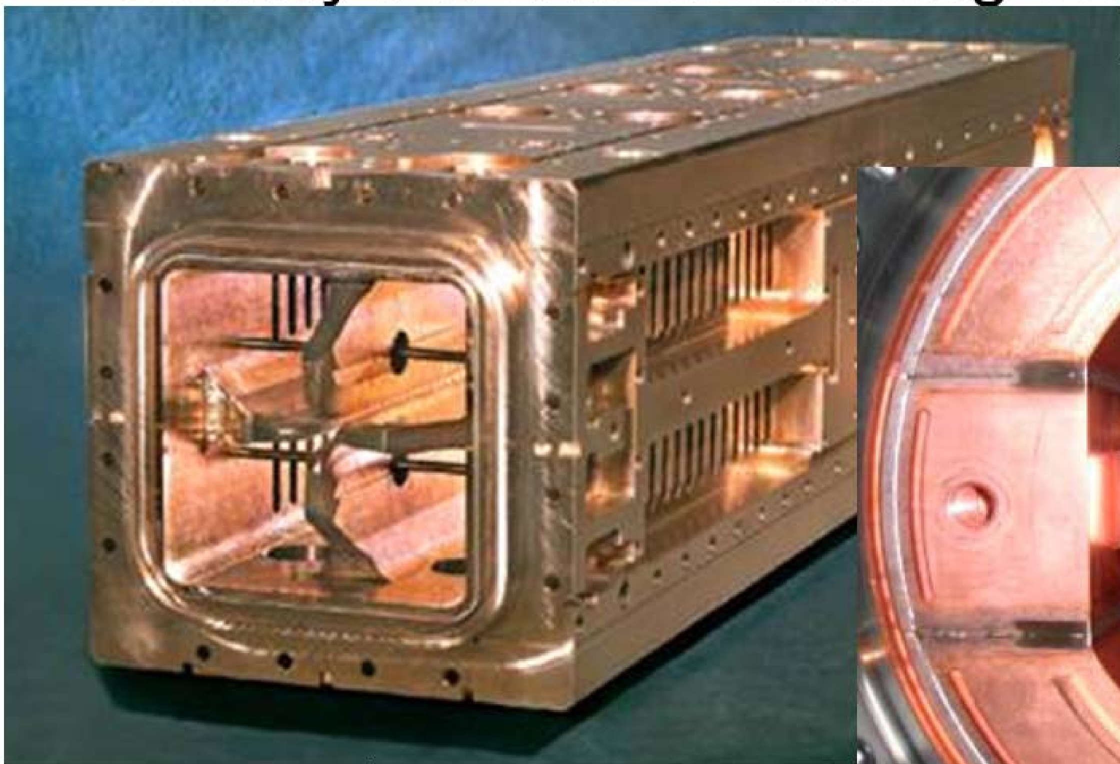

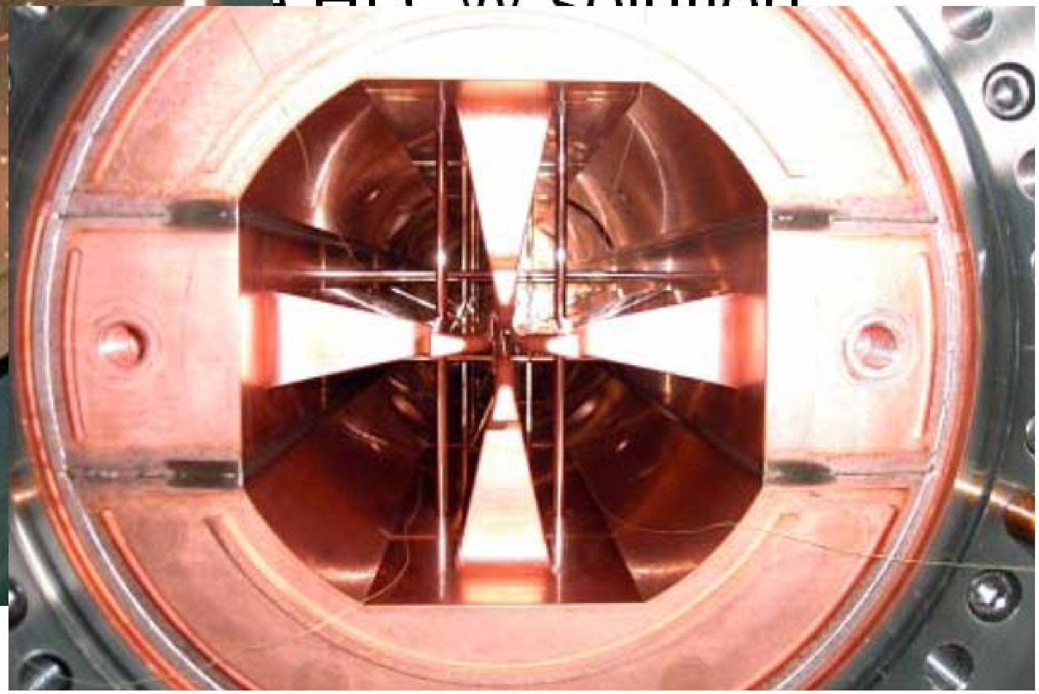

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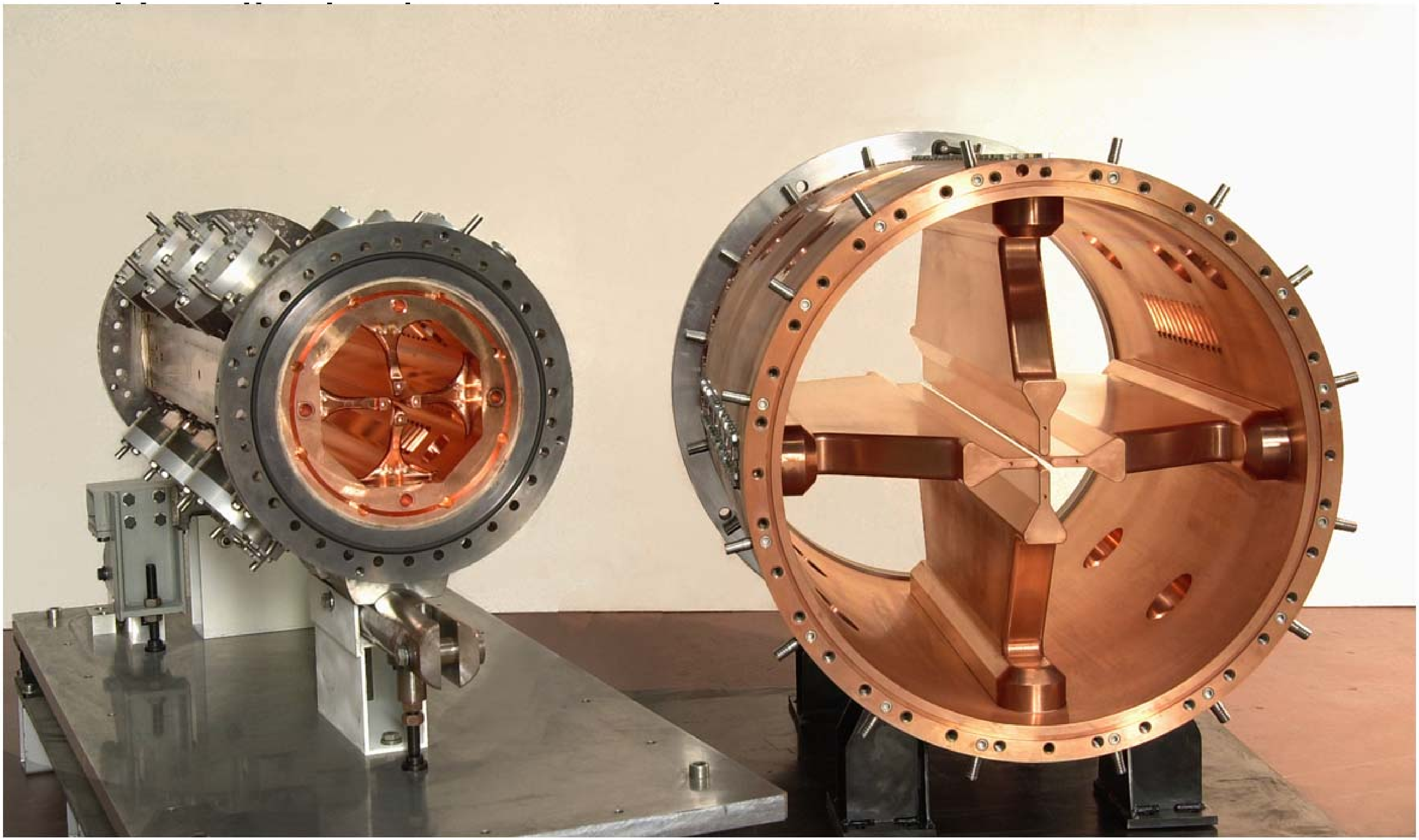
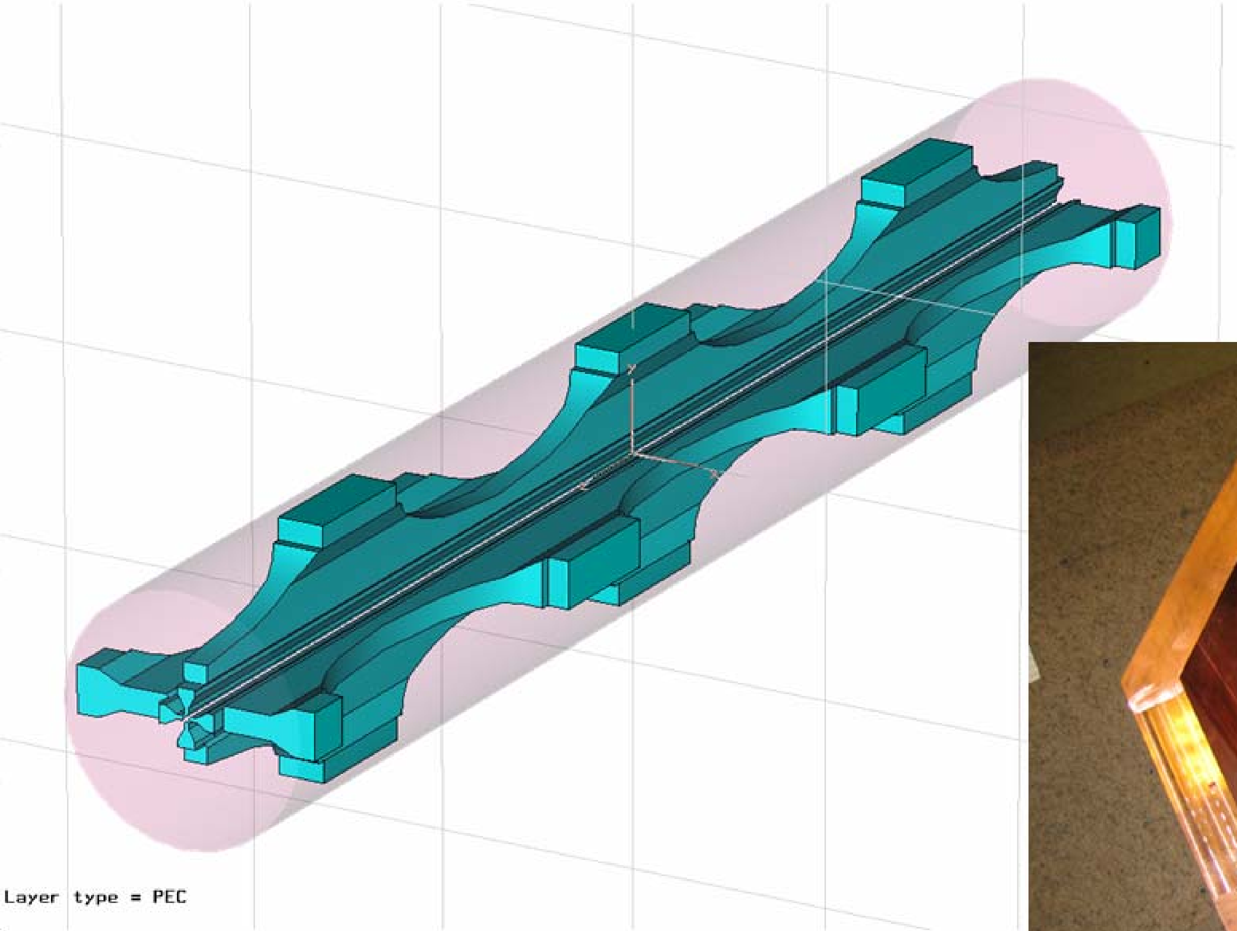


Other RFQ types

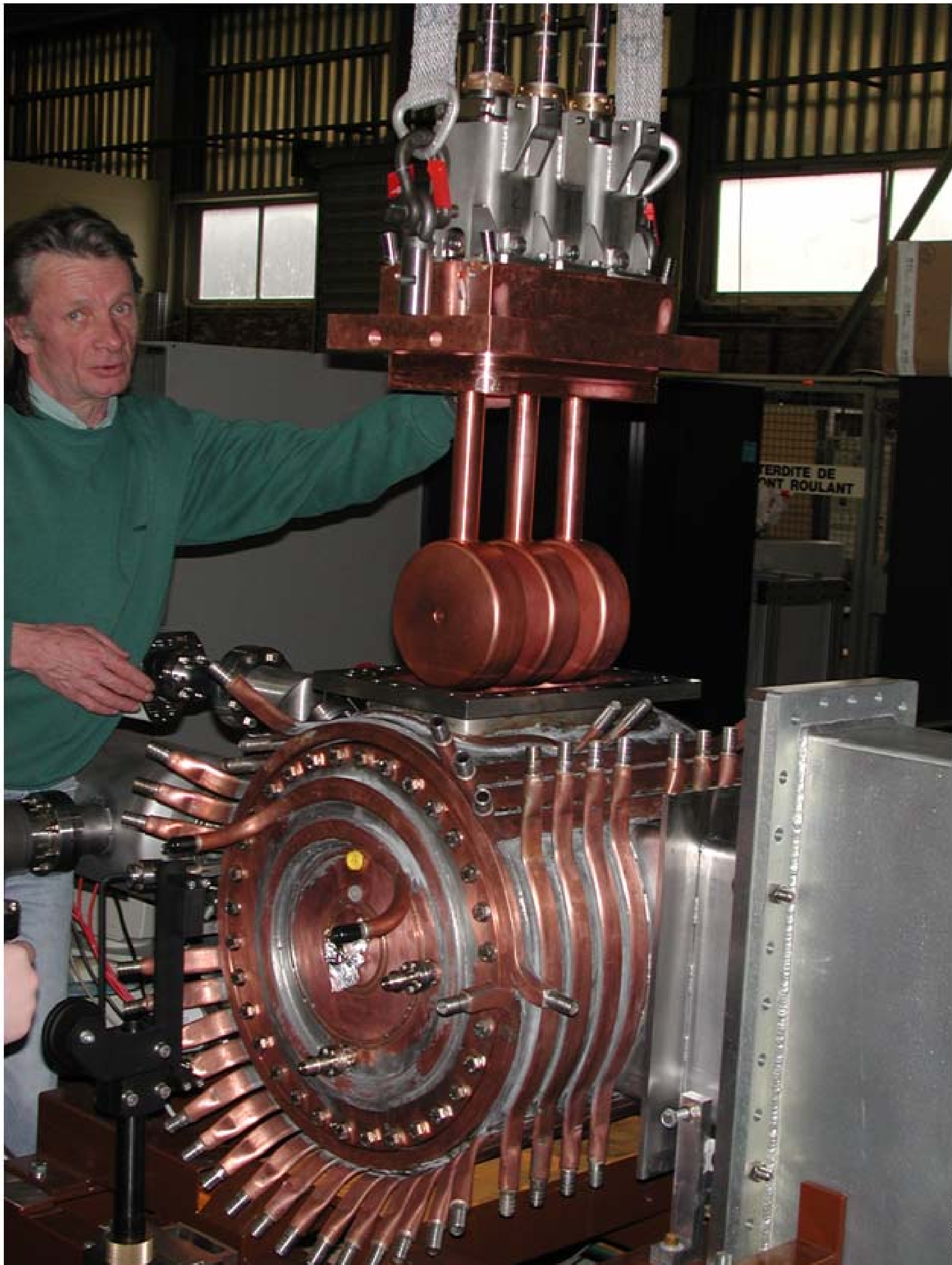
- RIA/AEBL split coaxial type looks promising



Intermediate energy cavities - DTL

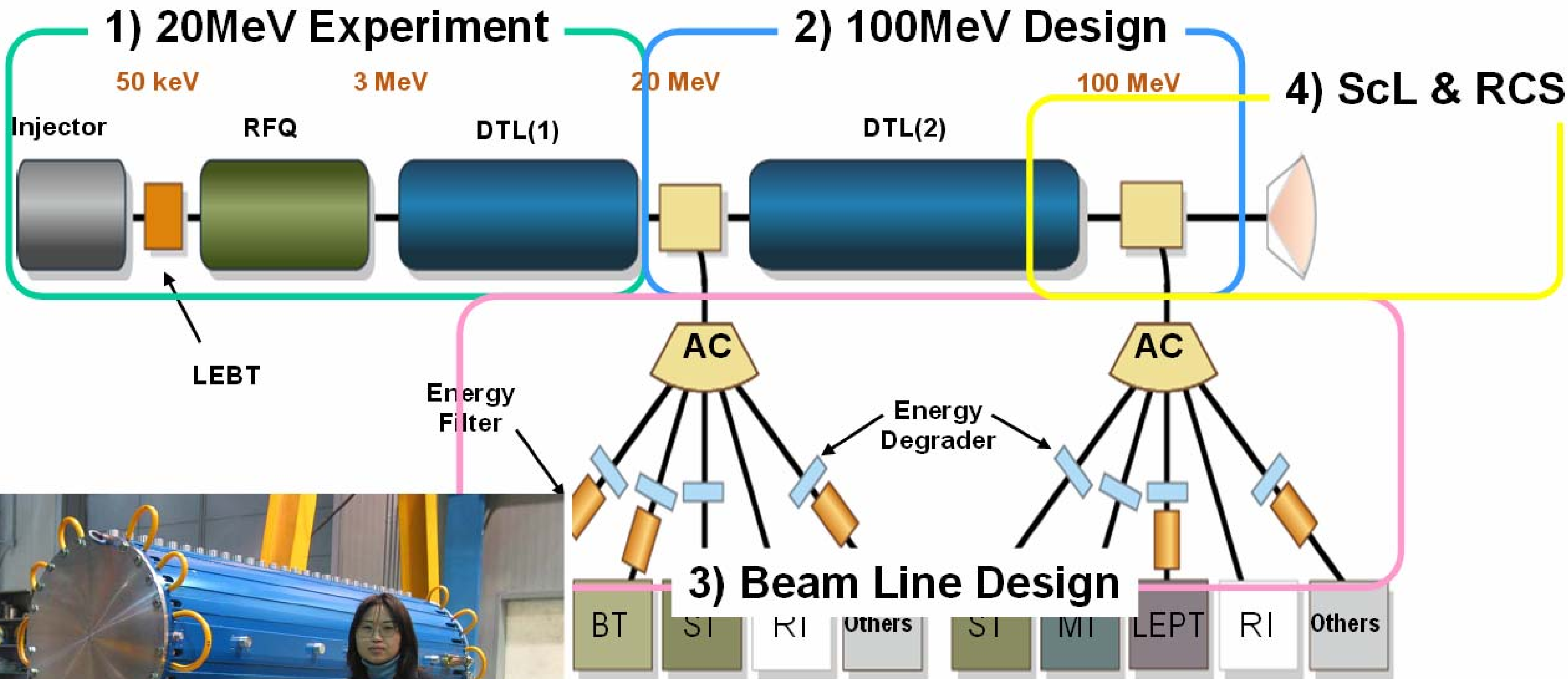
- DTL still the most common in use after RFQ
  - FODO lattice, match very well the RFQ output
  - Provide strong focusing
  - Acceptable shunt impedance
  - Design current independent
  - Well known
  - Only disadvantage is the insertion of the magnets
    - RFQ output energy depend on possibility to insert the devices
    - SNS : PMQs with a FF0DD0 lattice – lack of tuning knobs or reduction of tuning parameter with cost reduction?
    - PMQs allow for higher shunt impedance
    - classical electromagnet quadrupoles is demonstrated at 5MeV@350MHz CW (IPHI) and PMQ at 3MeV (SNS@400MHz 6.25%DF).

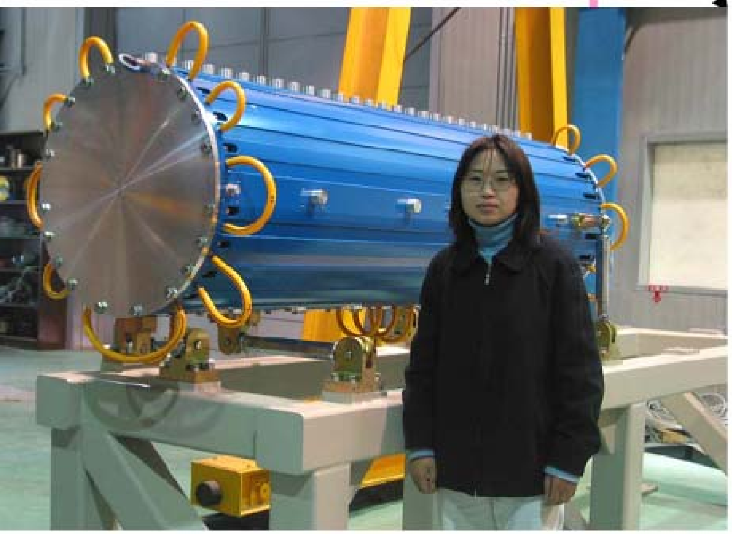
IPHI DTL



IPHI DTL

PEFP (KAERI) – same study





PEFP (KAERI) – same study

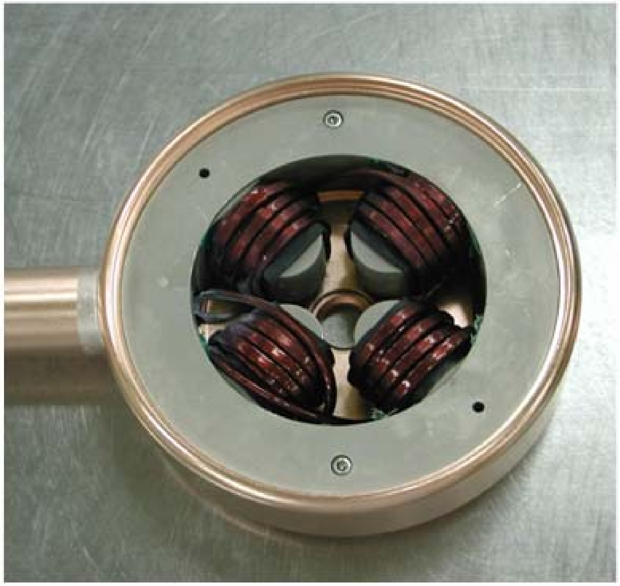
EQM in Drift Tube

PEFP Proton Engineering Frontier Project

Injector

RCS

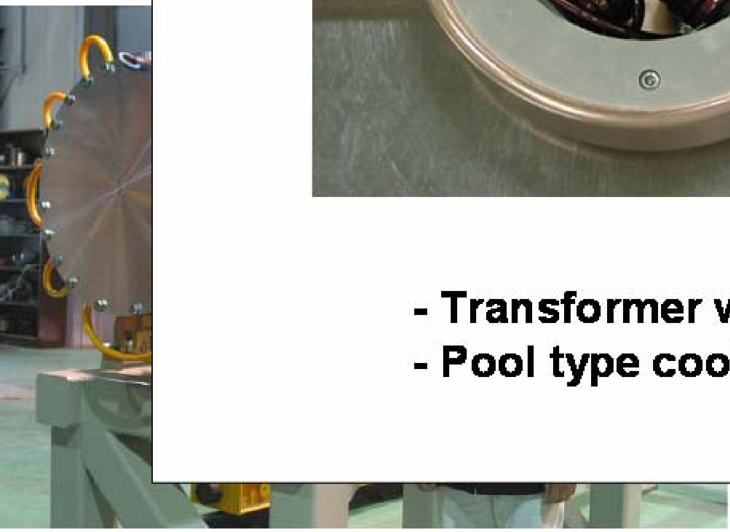
EQM for 20MeV DTL



- Transformer wire
- Pool type cooling

EQM for 20~100MeV DTL

- Hallow Conductor



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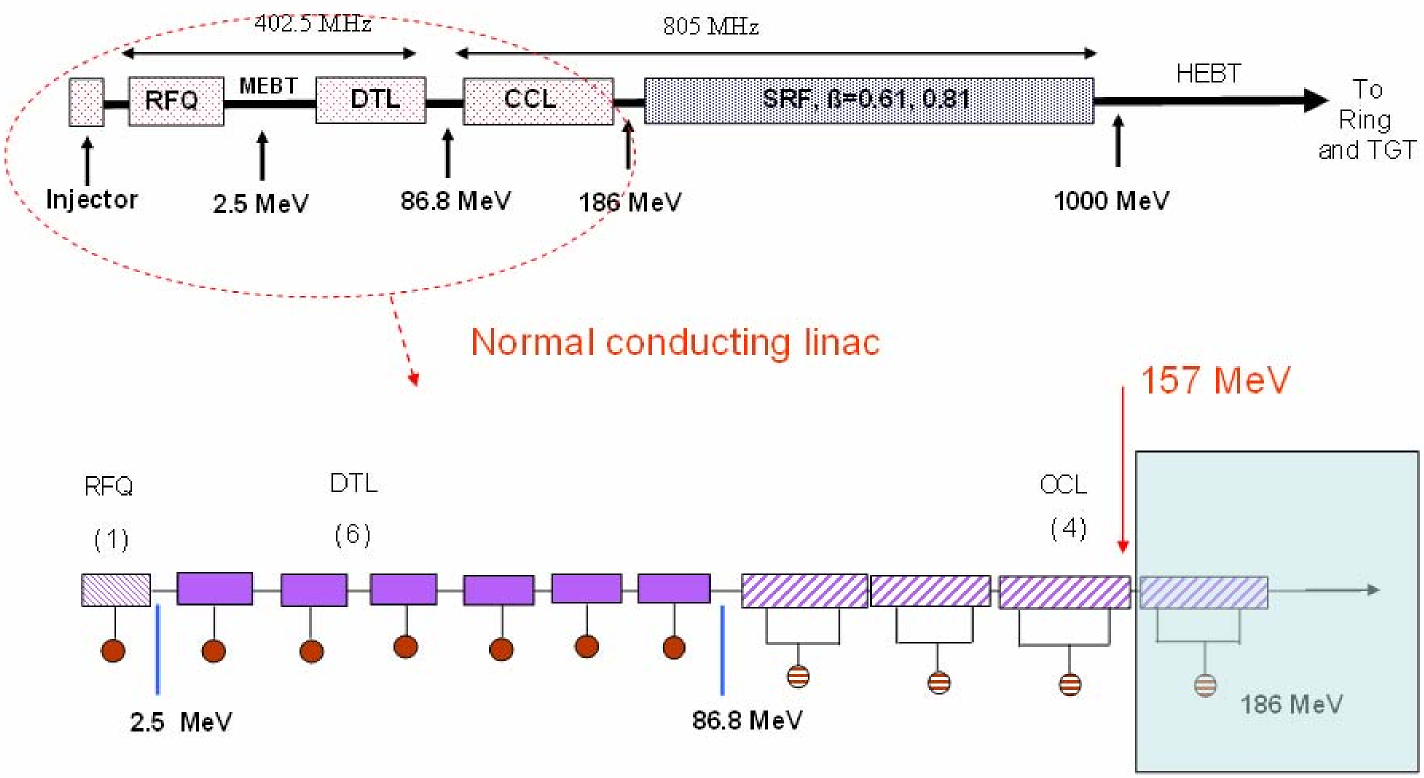
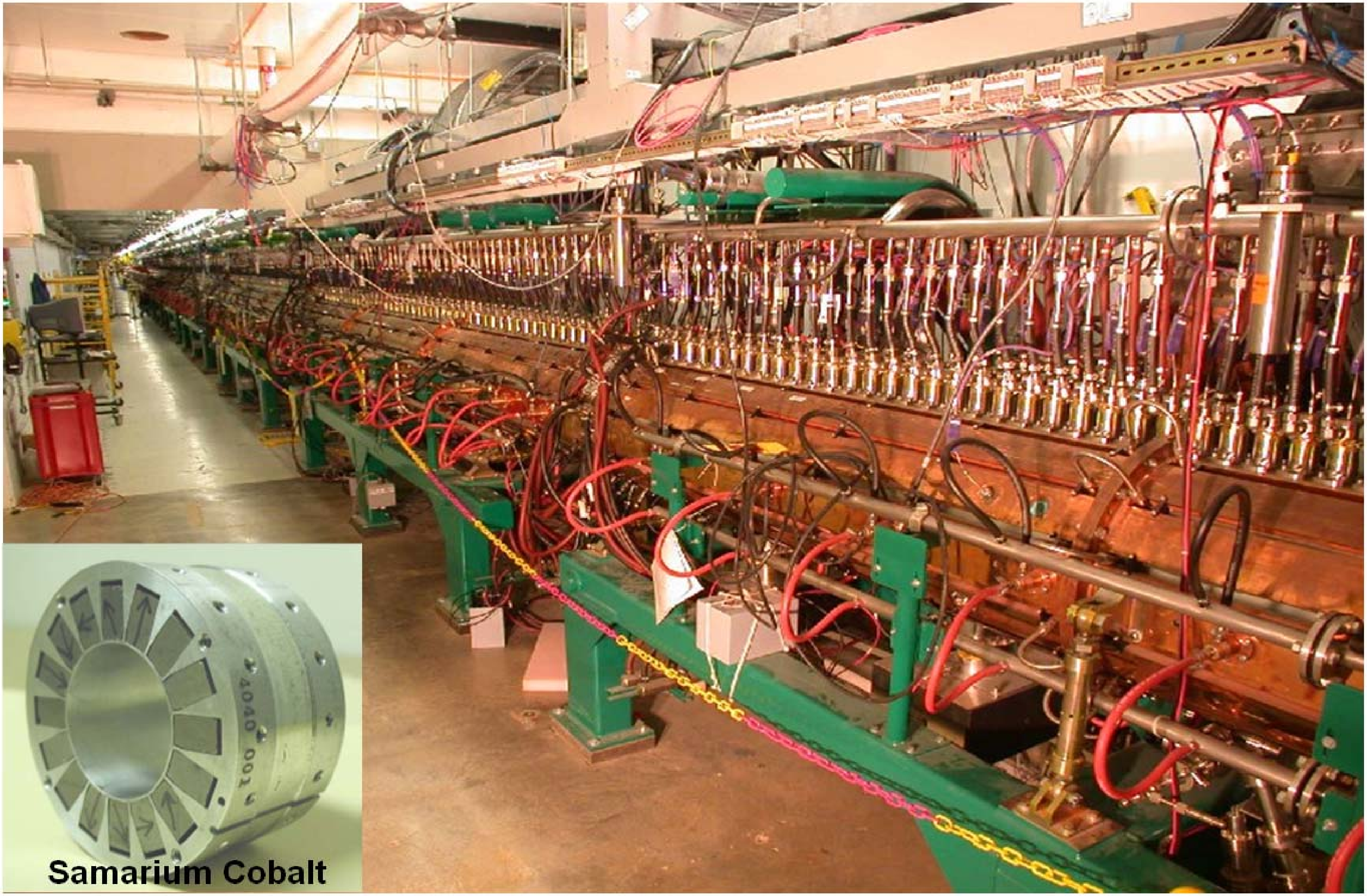
SNS

SNS Linac Layout



ICFA-HB 2004

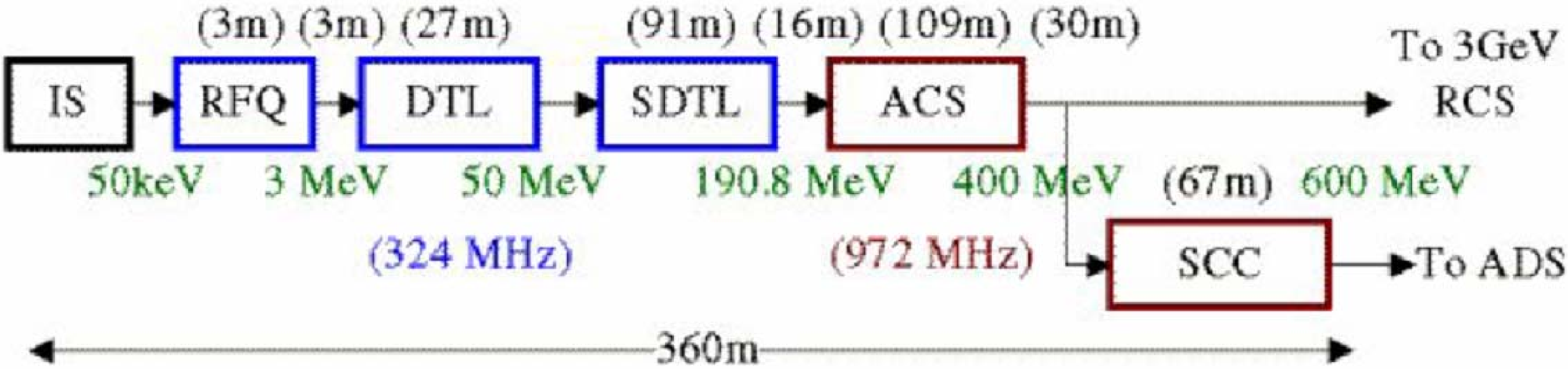
SNS



SDTL

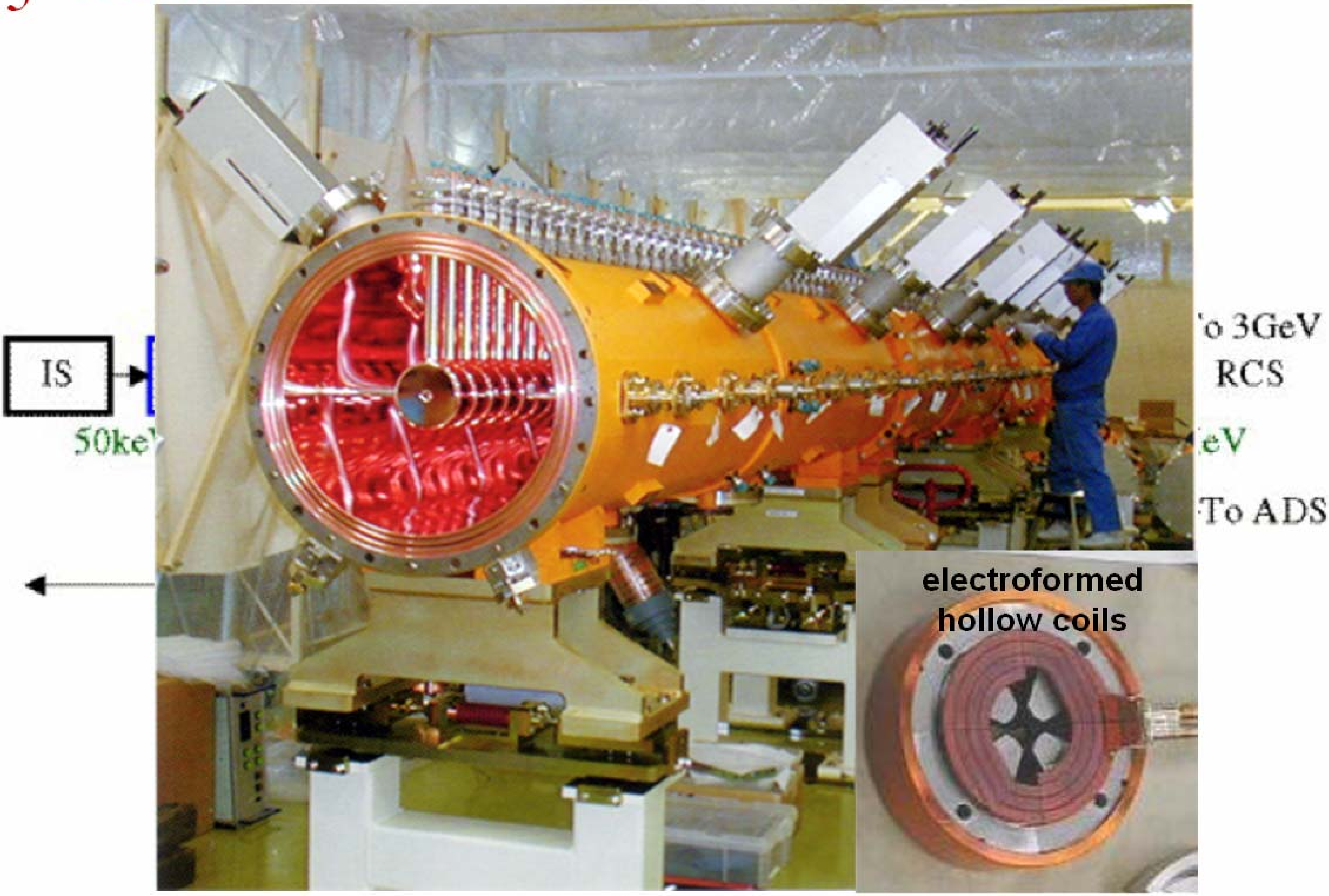
- The drift tube are empty
  - Easier manufacturing
  - Cheaper
  - Easier alignment (external magnets)
  - Better efficiency (small DT - small stems)
  - Bigger bunch size ➔ lower space charge
- Some drawback
  - Longer transverse focusing period ➔ larger bore aperture (for the same beam loss criteria)
  - Multiple of RF system, more wall losses
  - Choice made for ESS (20MeV)– J-Parc (50MeV)
  - Typically difficult at the RFQ exit
  - Complementary to DTL more than concurrent

J-Parc



(3m) (3m) (27m)
(91m) (16m) (109m) (30m)
IS
RFQ
DTL
SDTL
ACS
To 3GeV RCS
50keV
3 MeV
50 MeV
190.8 MeV
400 MeV
(67m)
600 MeV
(324 MHz)
(972 MHz)
SCC
To ADS
360m

J-Parc

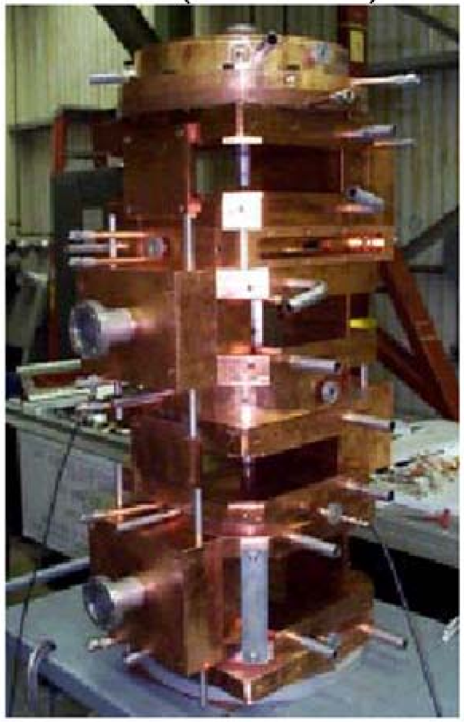


J-Parc

CCDTL

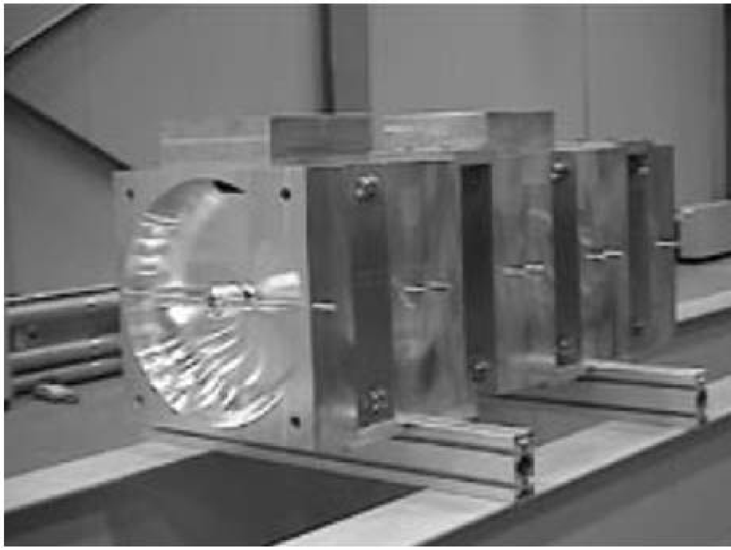
- Good compromise between size, maximum gradient, efficiency and focalization.
- DTL/CCDT: Easier access and cooling, easier machining and alignment
- Removed from the SNS design to minimize the number of developing teams

APT (6.7MeV)



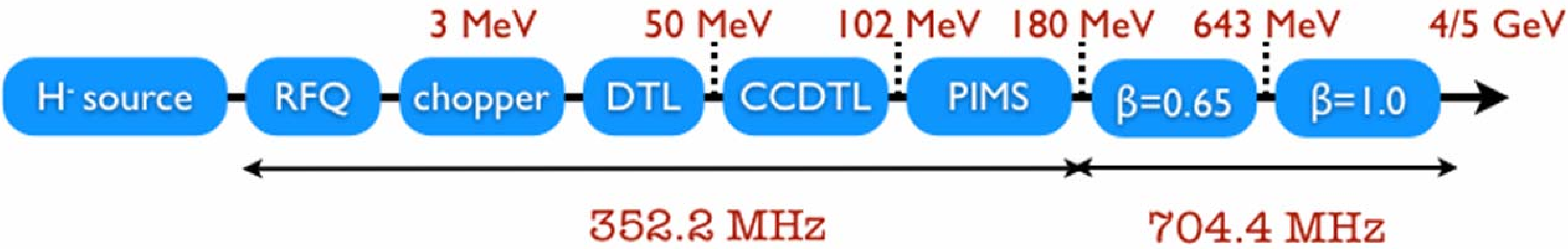
SPL (50-102MeV)

KOMAC (3MeV and 20MeV)



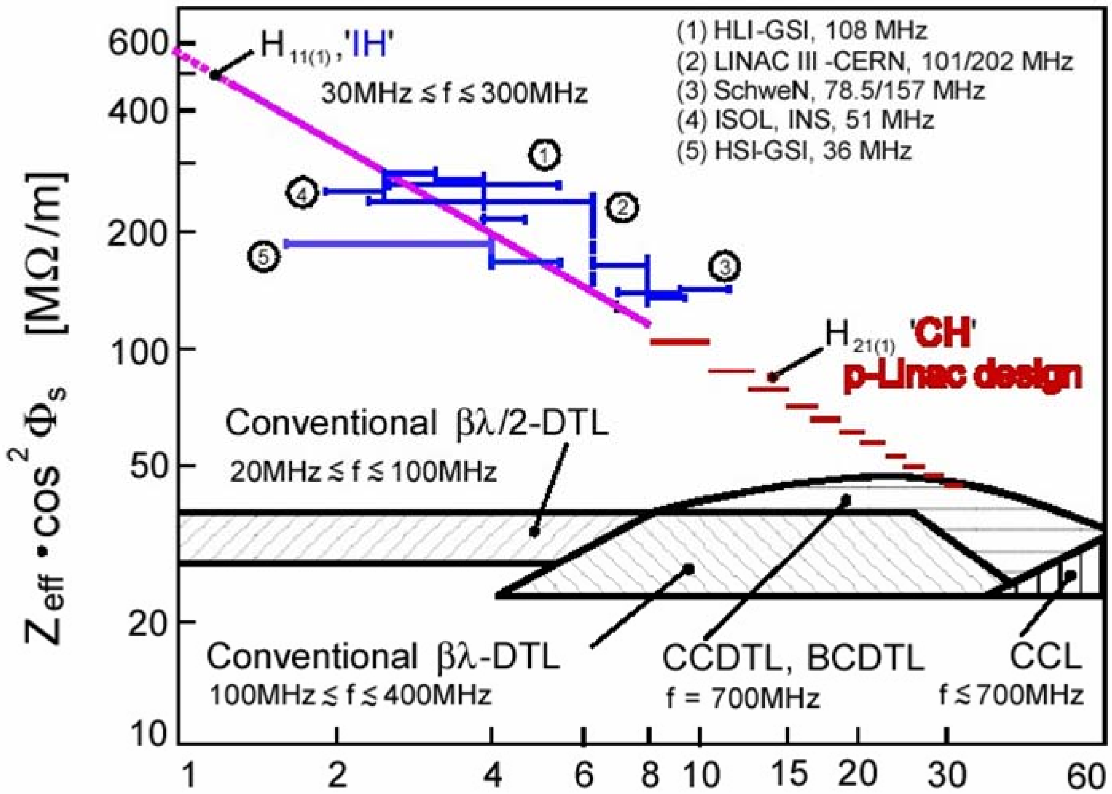
LINAC 4 - SPL

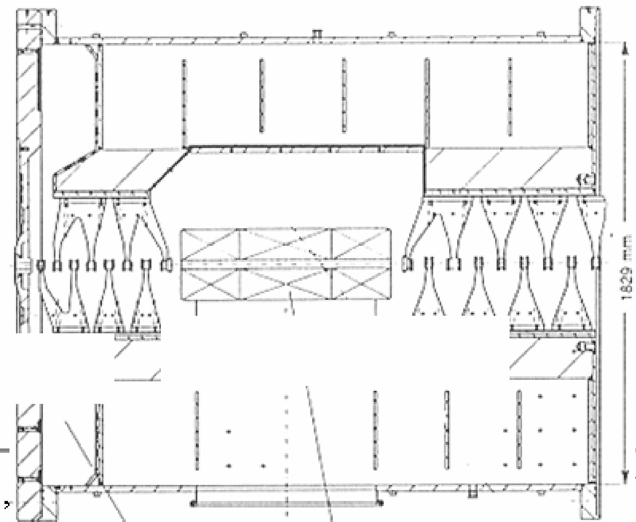
- Linac4 is proposed to replace the existing proton linac
- 40 mA 5%DF
- 3 DTL tanks with PMQs



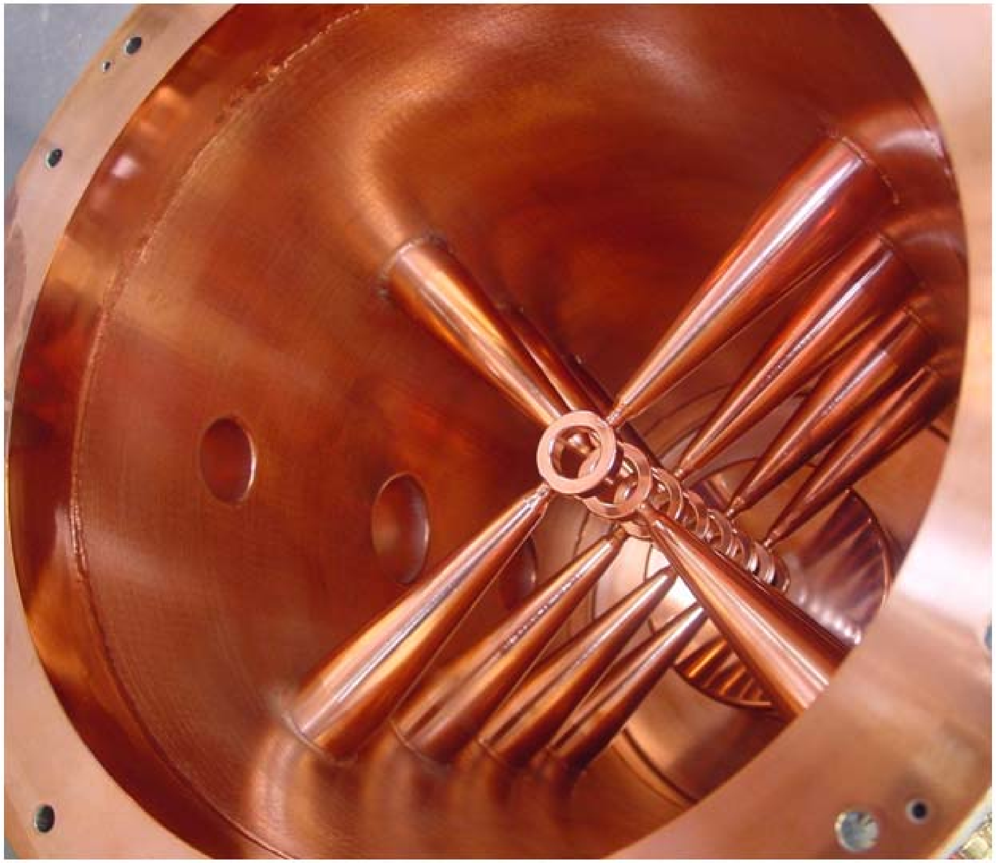
CH-DTL / IH-DTL

- Growing interest in such cavity types
- H-Type/DTL:
  - higher voltage gain
  - Lower number of elements
  - Improvement on focusing element
- Acceleration using TE_{111} (no TM_{010})
- Proposed for
  - IFMIF (RT CH-DTL then SC CH-DTL)
  - EURISOL
  - EUROTRANS
  - …



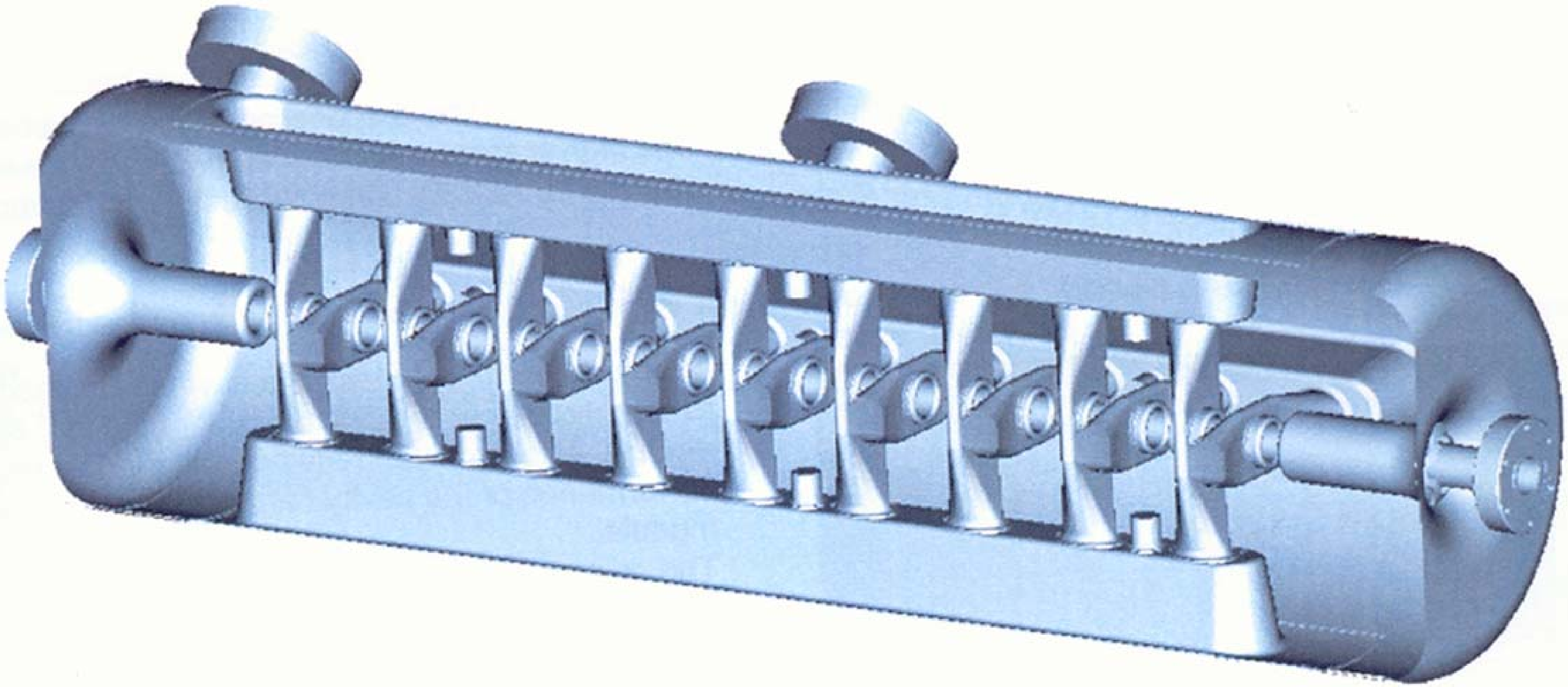


Hot-model of a rt. CH-Prototype

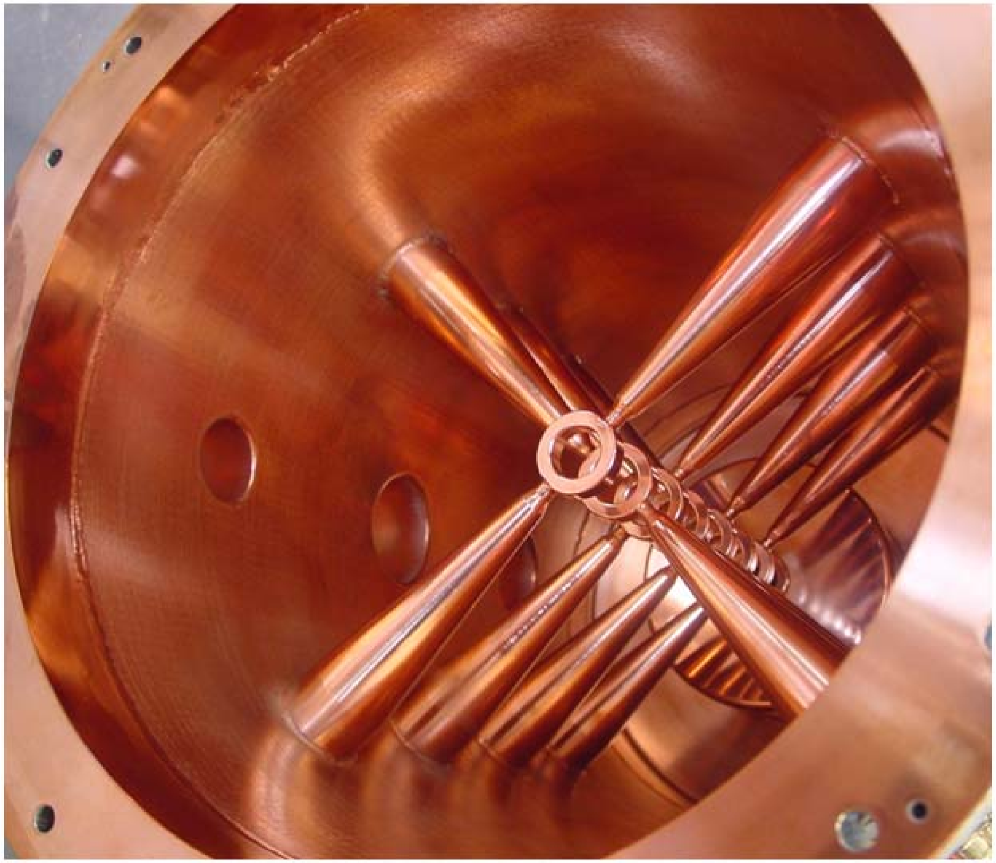


sc. CH-Prototype

Hot-model of a rt. CH-Prototype



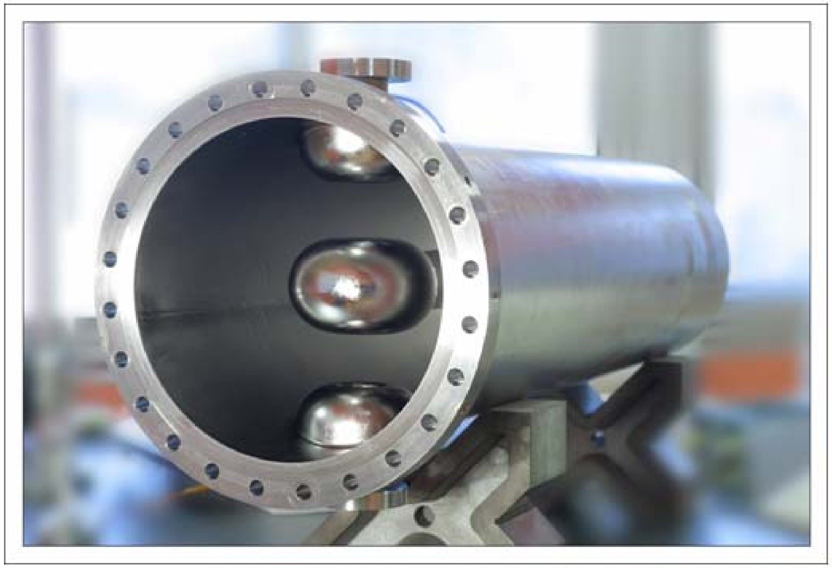
Hot-model of a rt. CH-Prototype

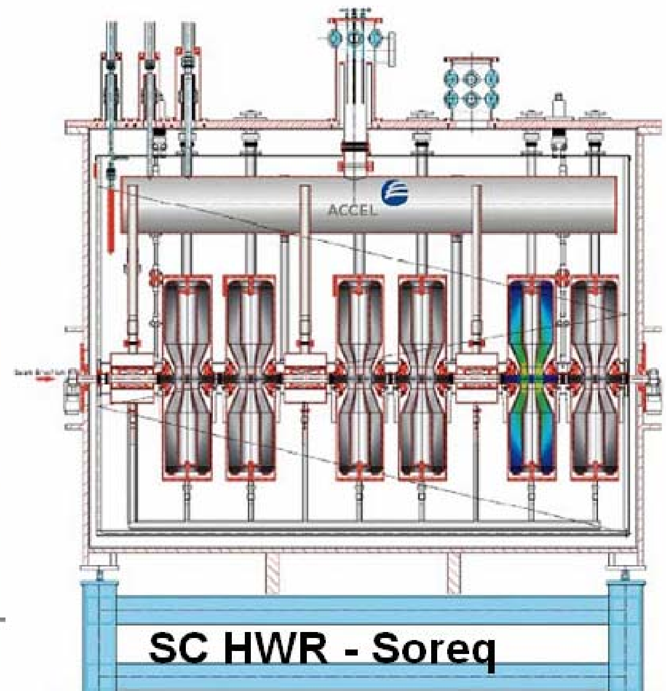


sc. CH-Prototype

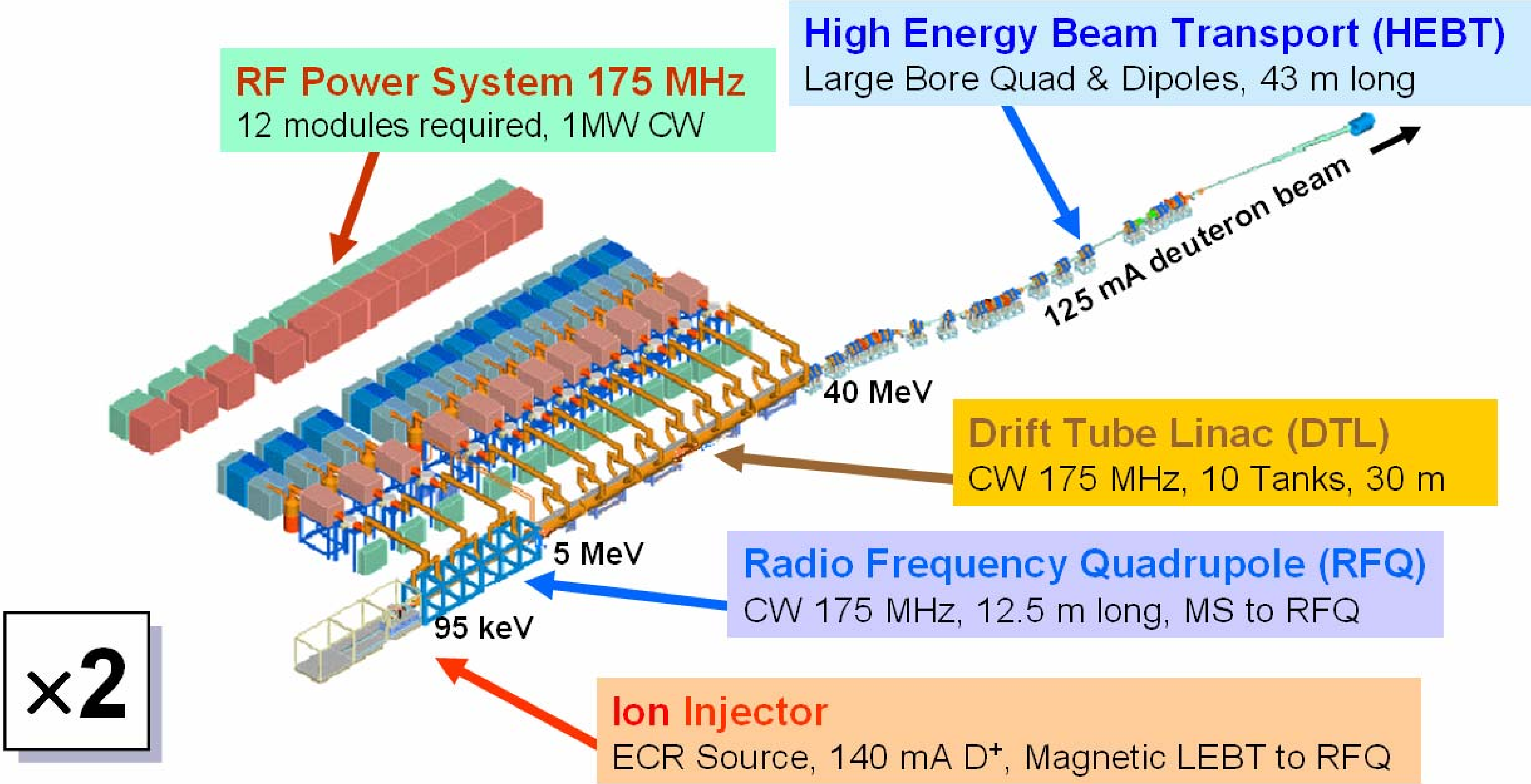
SC cavities

- Reentrant, QWR (SPIRAL2-AEBL), HWR (SARAF-EURISOL-AEBL), spoke cavities (EURISOL, EUROTRANS, AEBL)





IFMIF – a very good example

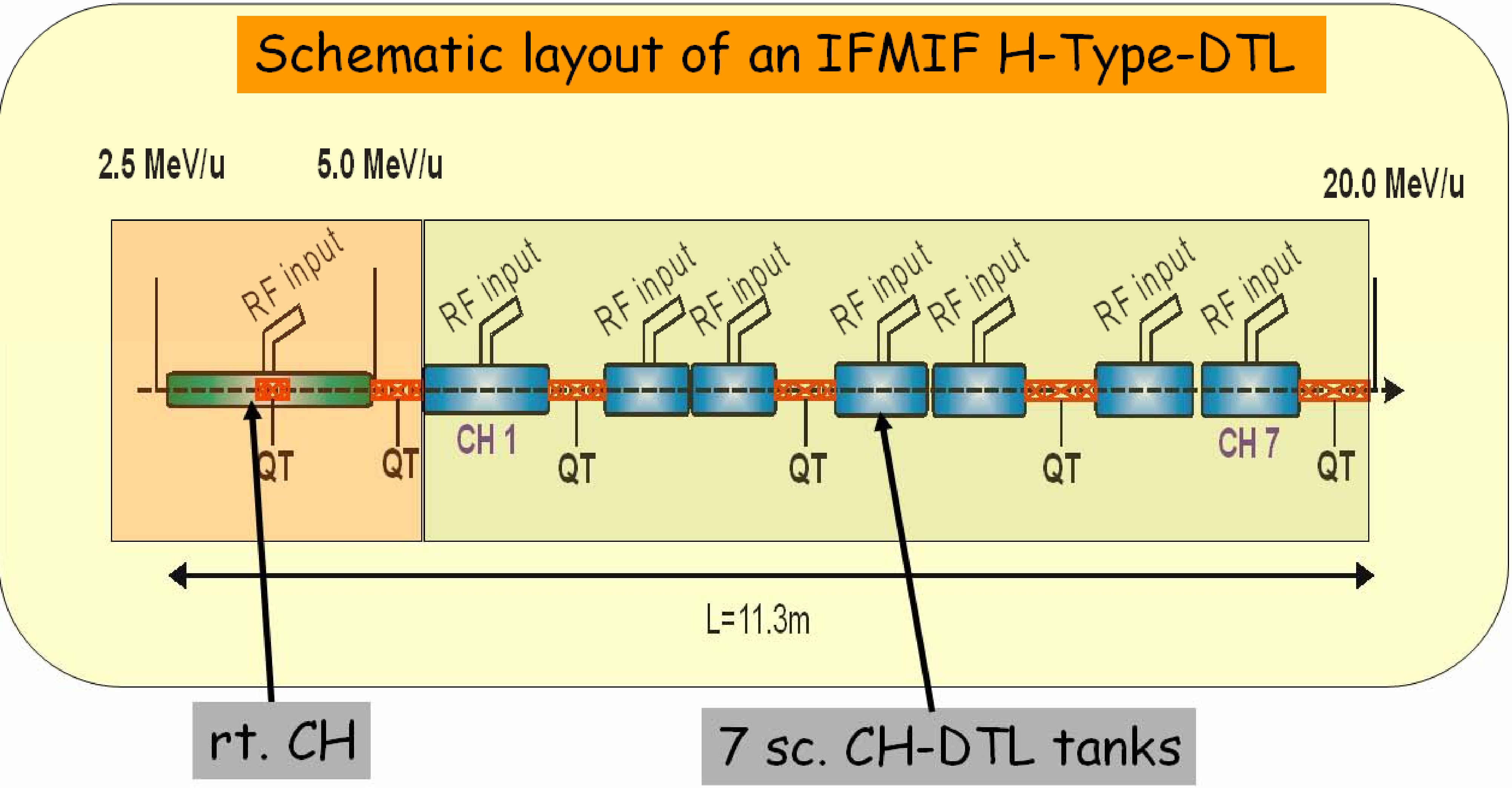


IFMIF uses 2 continuous-wave 175 MHz linear accelerators, each providing a 125 mA, 40 MeV deuteron beam (5MW each)

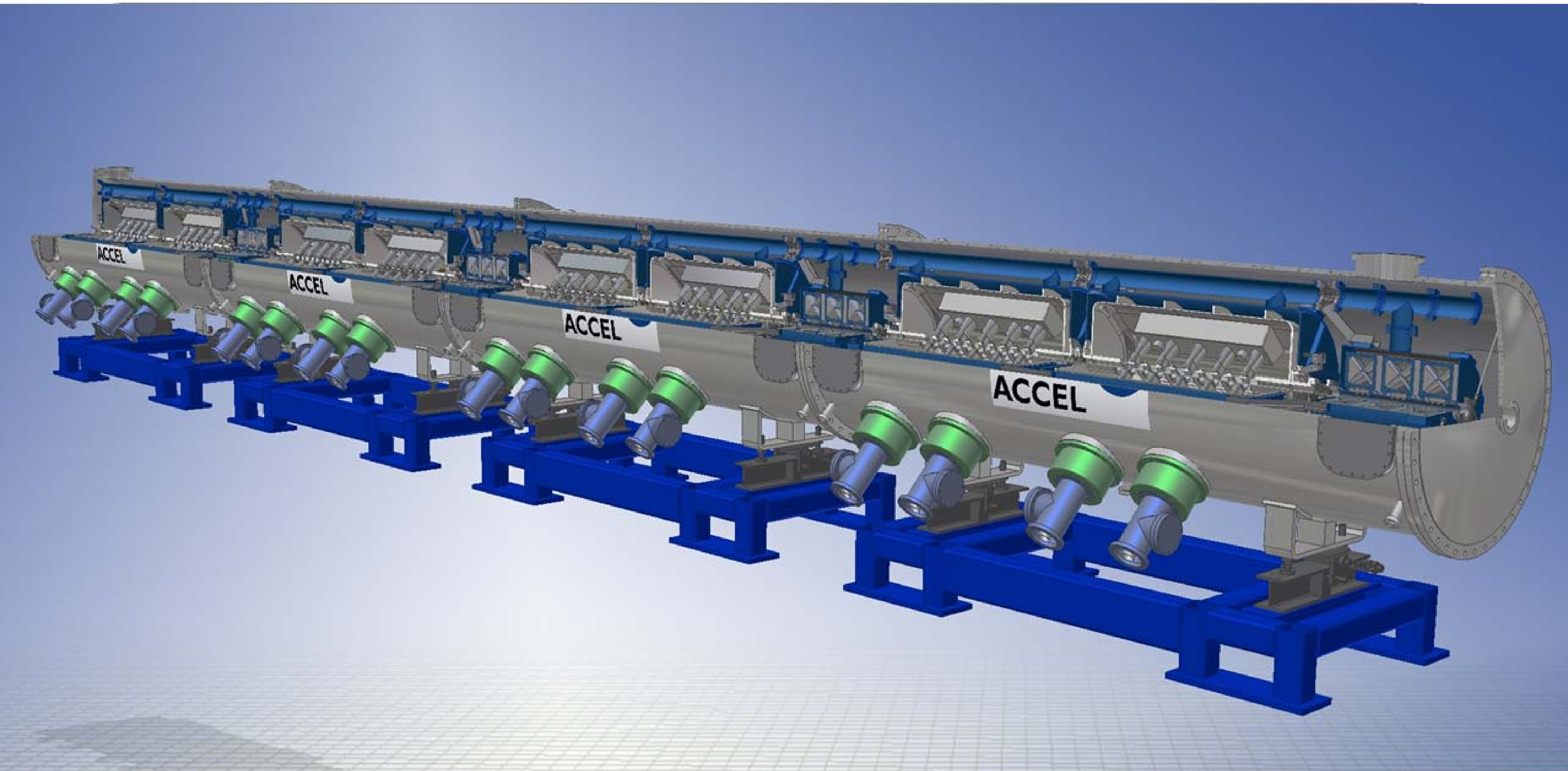
IFMIF

- First CW DTL
- Design was chosen for the sake of reliability and for the focusing scheme in accordance with strong space charge
- There is confidence that the tolerance objectives could be reach (+/- 50µm)
- Diagnostics are essentials
- Superconducting option allow to save 7MW but requires R&D

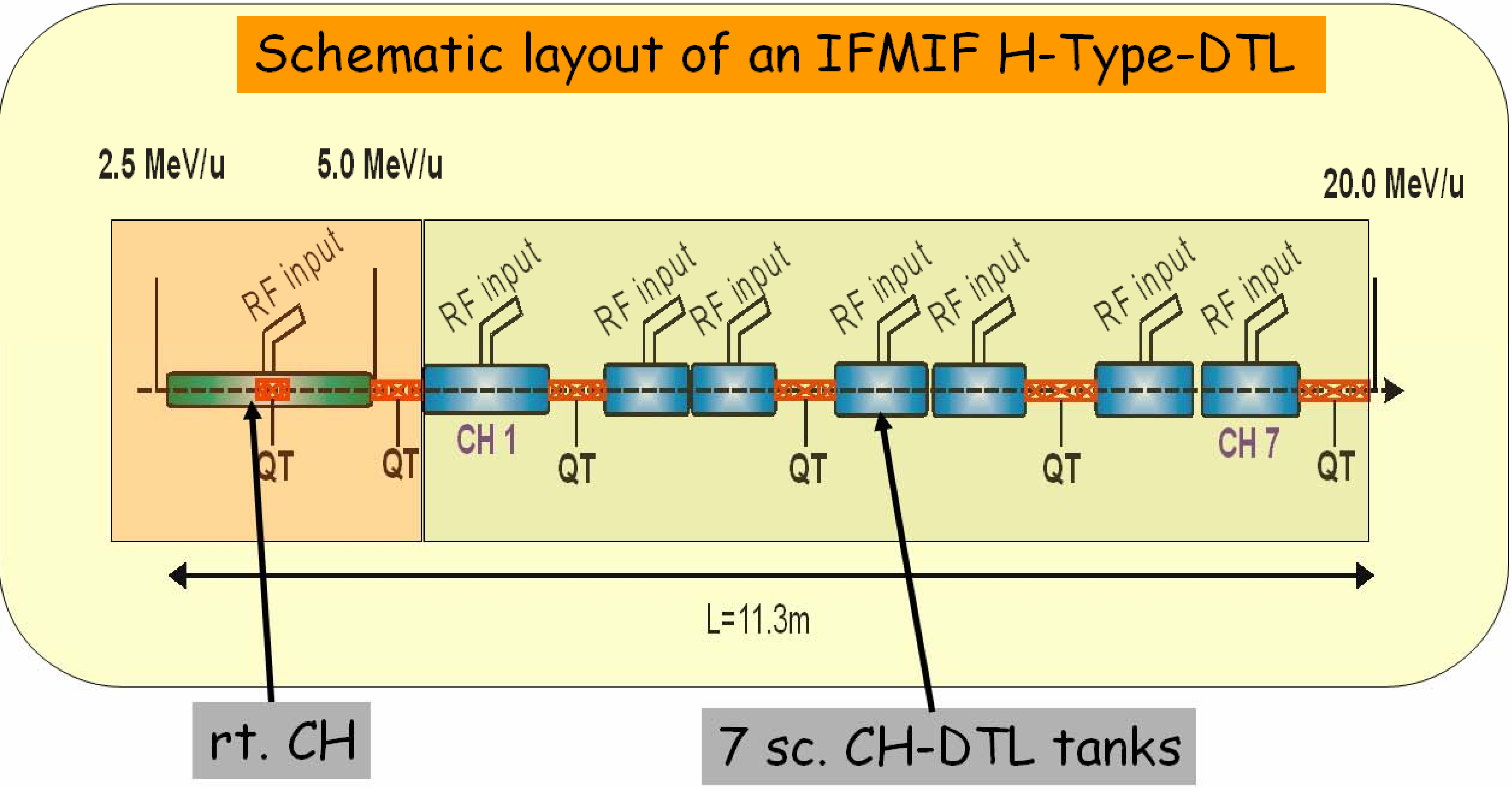
IFMIF superconducting option



IFMIF superconducting option



IFMIF superconducting option



Thank you for your attention

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