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LABORATORI NAZIONALI DEL SUD

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# THE DEVELOPMENTS OF THE RF SYSTEM RELATED TO THE K-800 SUPERCONDUCTING CYCLOTRON UPGRADE

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# Talking points

- Overview of the superconducting cyclotron and RF system
- Main reasons to operate the superconducting cyclotron upgrade
- Upgrade as opportunity to refurbish/redesign/change obsolete parts
- RF main modifications according to the cyclotron upgrade
- Conclusions

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# The Superconducting Cyclotron

| | |
|---|---|
| Bending limit | K=800 |
| Focusing limit | Kfoc=200 |
| Pole radius | 90 cm |
| Yoke outer radius | 190.3 cm |
| Yoke full height | 286 cm |
| Total weight | 176 tons |
| Min-Max field | 2.2-4.8 Tesla |
| Main coil A/turn | 6.5 $10^6$ |
| Sectors | 3 |
| Min. hill gap 8.6 cm | |
| Max valley gap | 91.6 cm |
| Trim coils | 20 |
| **Dees** | **3** |
| **RF range** | **15-48 MHz** |
| **Oper. Harmonics** | 1,**2**,3,4 |
| **Peak dee voltage** | **100 KV** |


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In **the initial configuration**, the cyclotron was a booster of the 16 MV Tandem. The injection was radial and the **Tandem and Cyclotron** operated together as **a coupled accelerator system**.

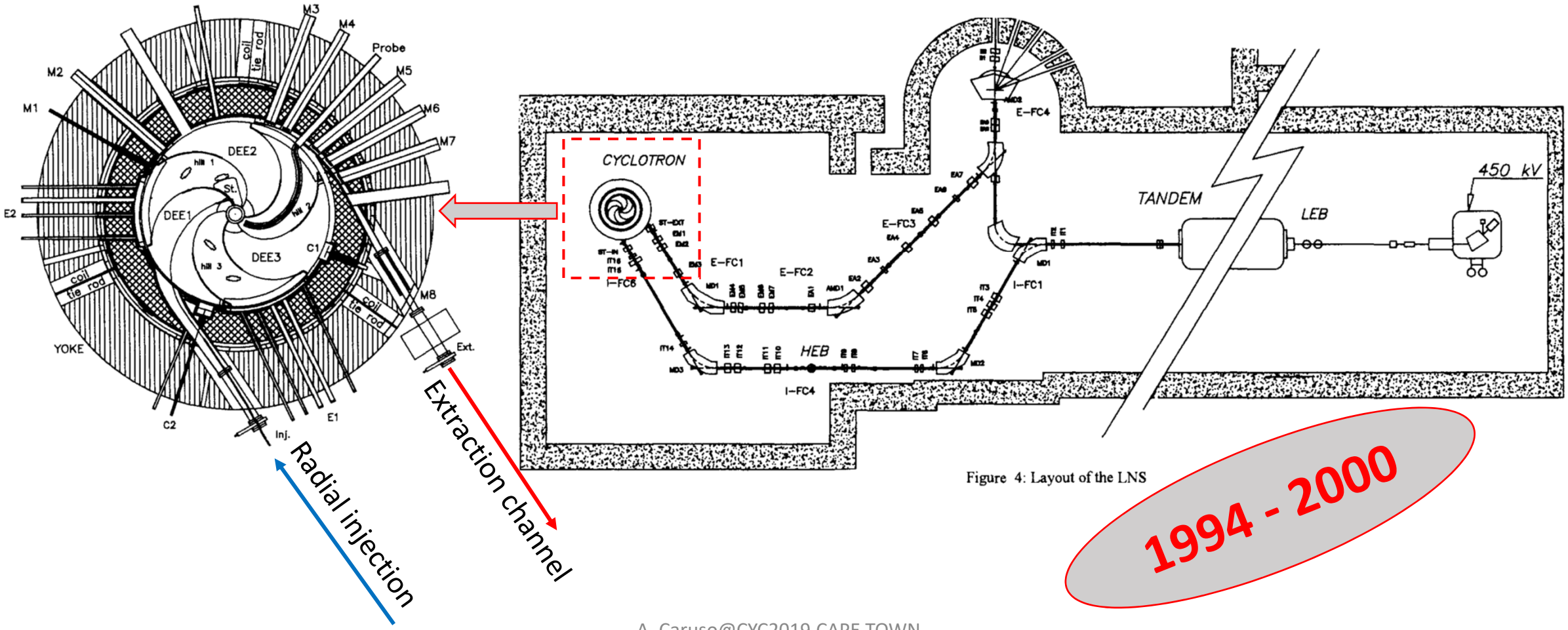
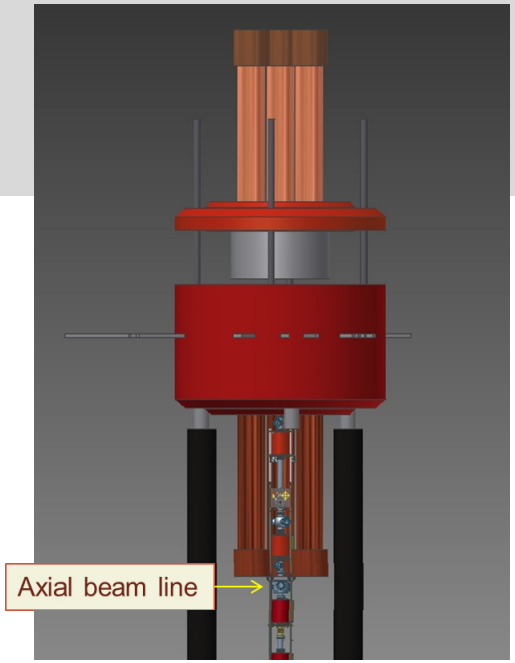
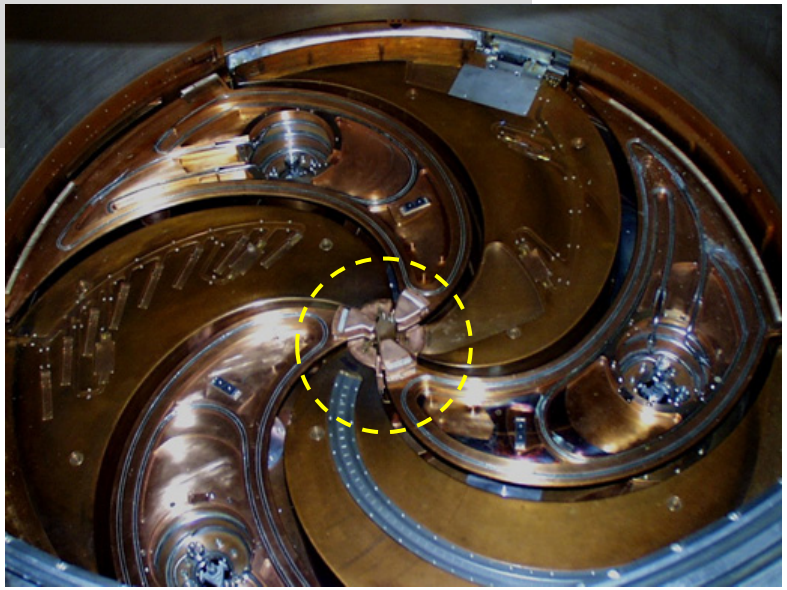



Figure 4: Layout of the LNS

1994 - 2000

The introduction of the **axial injection and the redesign of the central region** means the **cyclotron has been a stand-alone accelerator since 2000**. The two accelerators, **Tandem and Cyclotron, have been operating independently** for the last 19 years



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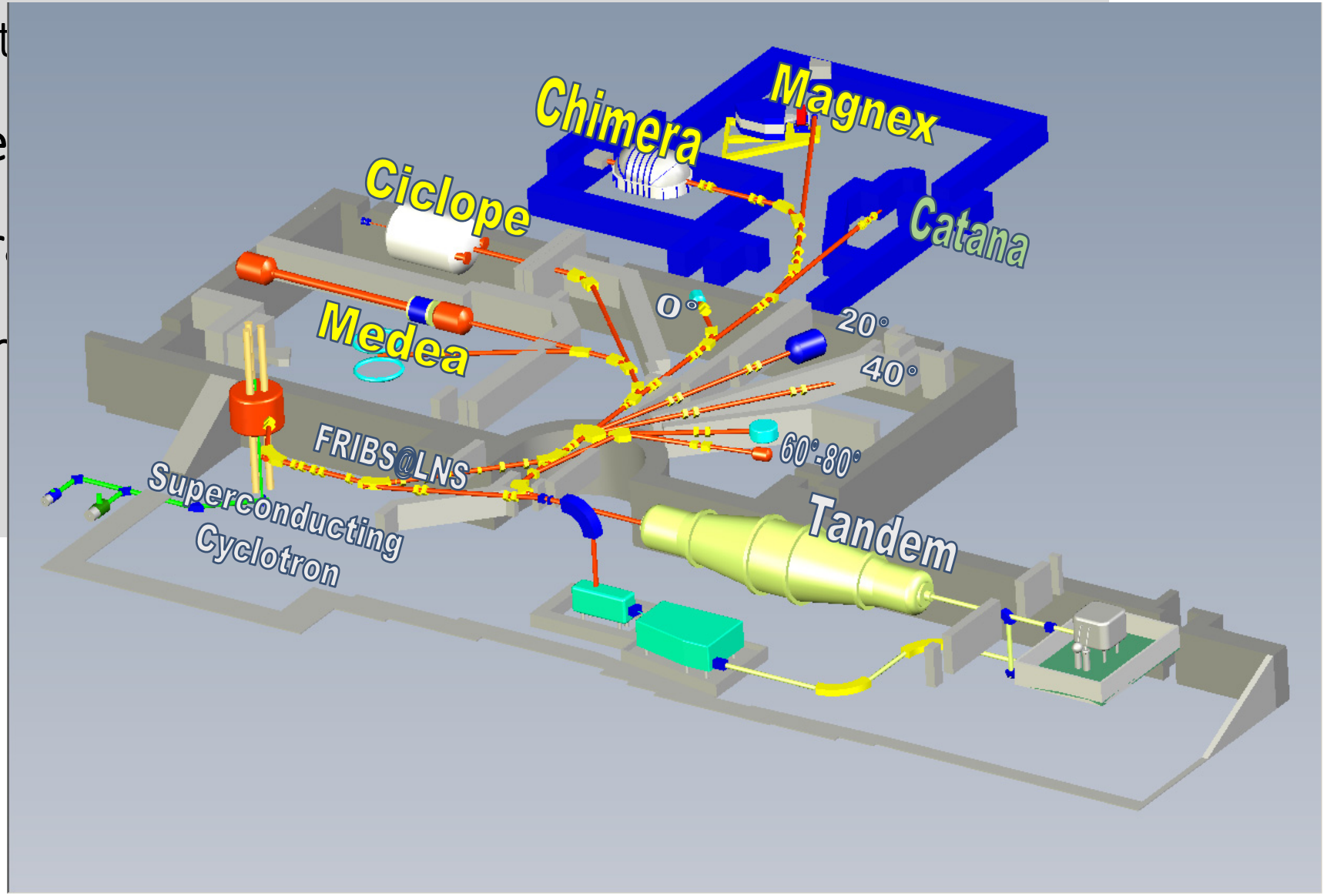
The introduct

the central re

alone acceler

and Cyclotron

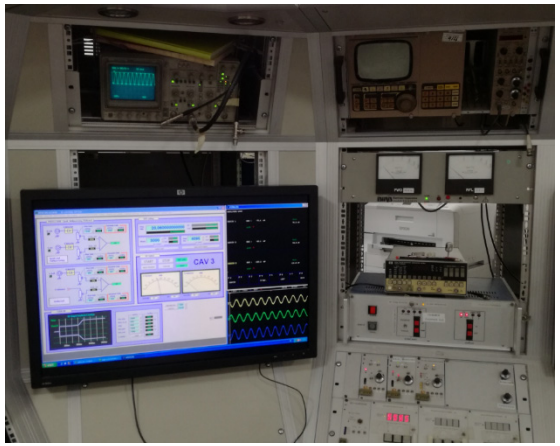
- *Superconducting Cyclotron and Tandem MP*
- *Nine experimental halls, four big experimental permanent set-up*
- *A proton therapy and irradiation line*
- *Fragment Recoil Separator*



*a continuous working in progress…resumed in 3 parts*

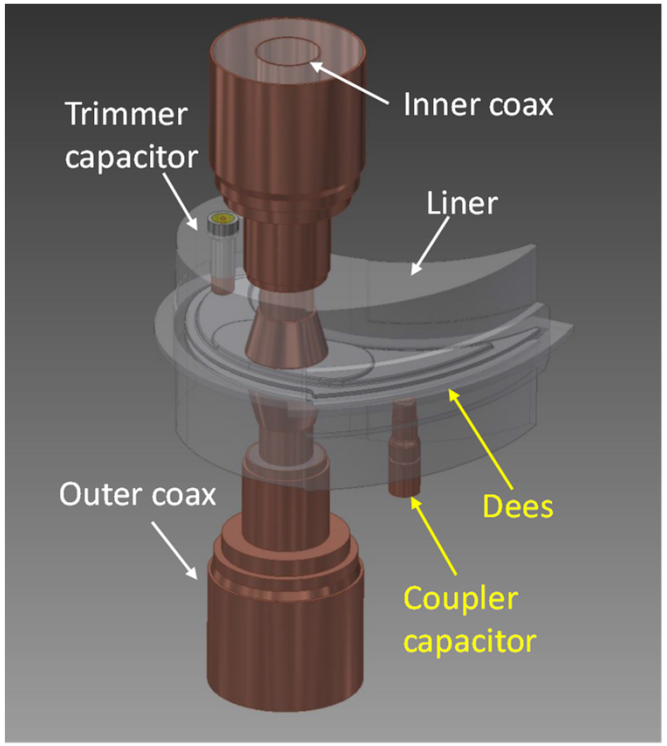
if **The K-800 superconducting cyclotron** has been **subjected to continuous upgrades and modifications since 1994**, a continuous working in progress has been involved the radiofrequency system too: **the RF couplers** have been **redesigned**, the **new dees** have been changed **from aluminium to copper**, as has the **new central region** from radial to **axial injection** of the beam, the **hybrid configuration solid state - tube of the power amplifiers, the digital LLRF**, etc.

*We are used to change, evolving the systems…*

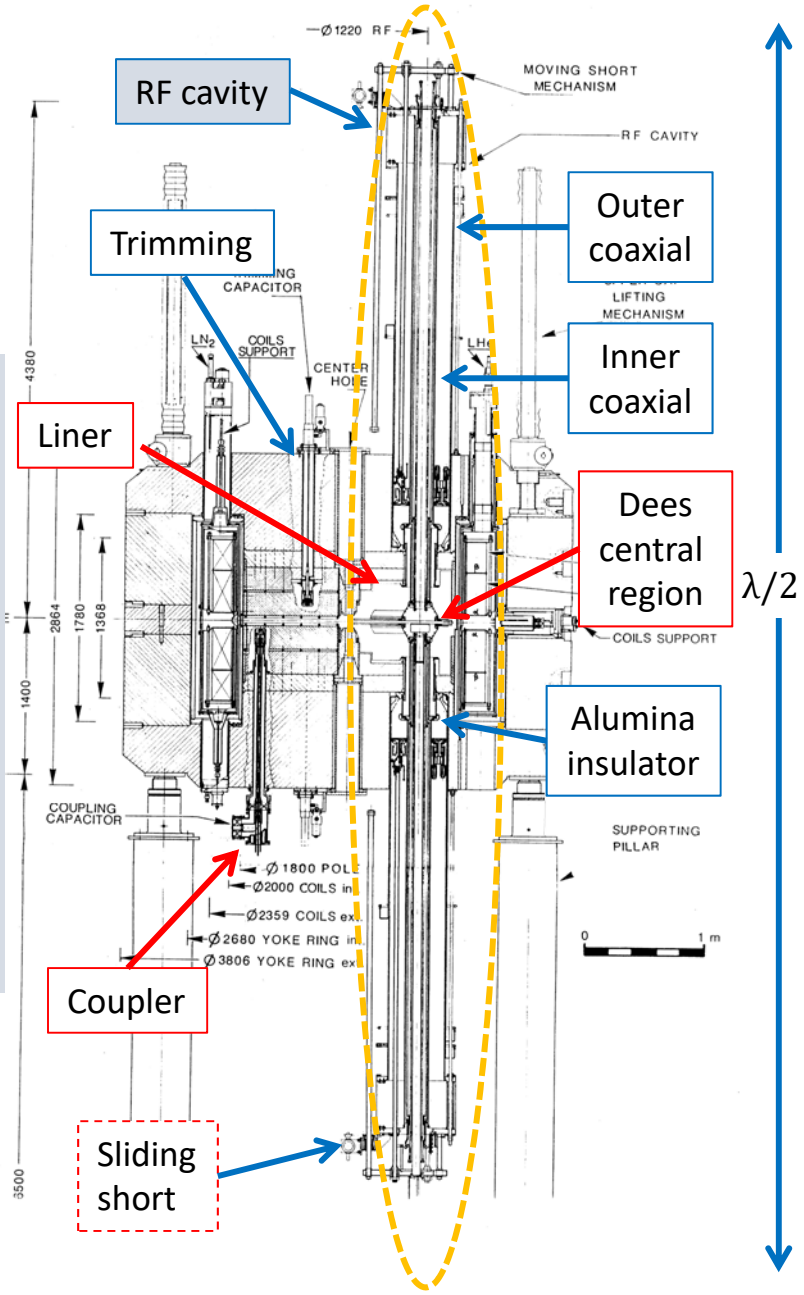


Analog to Digital LLRF

SSA – Tube amplifier



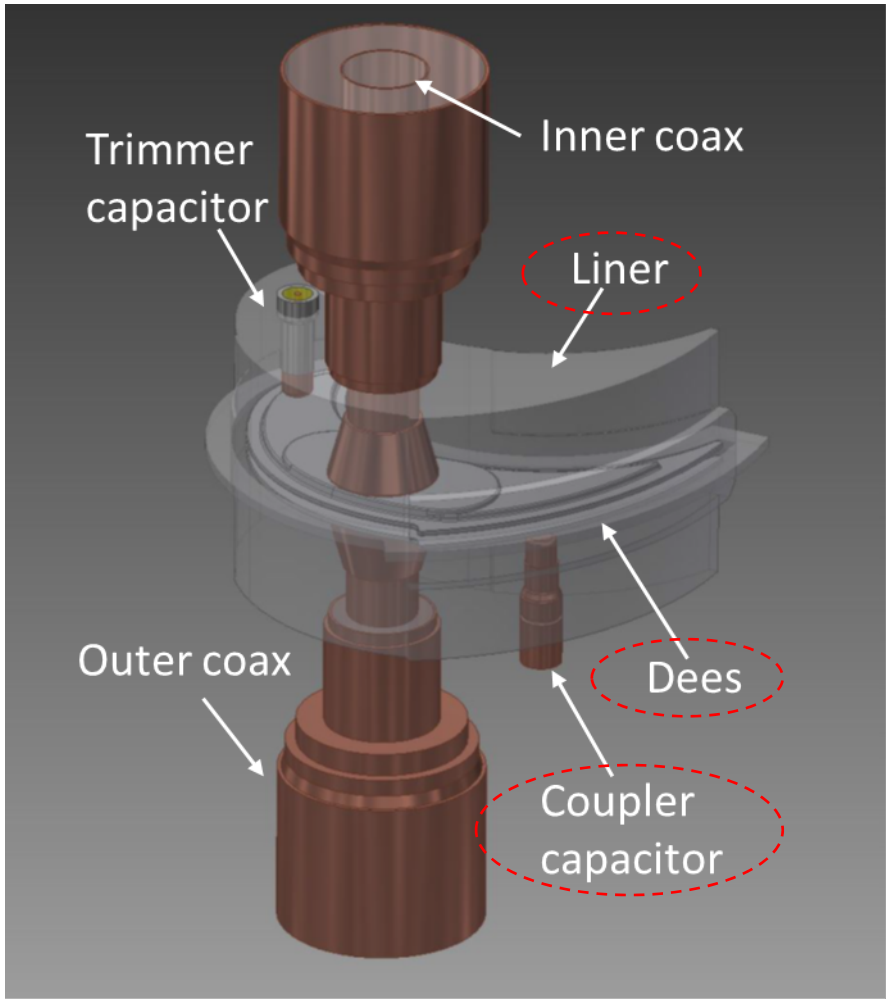
R F - C A V I T Y



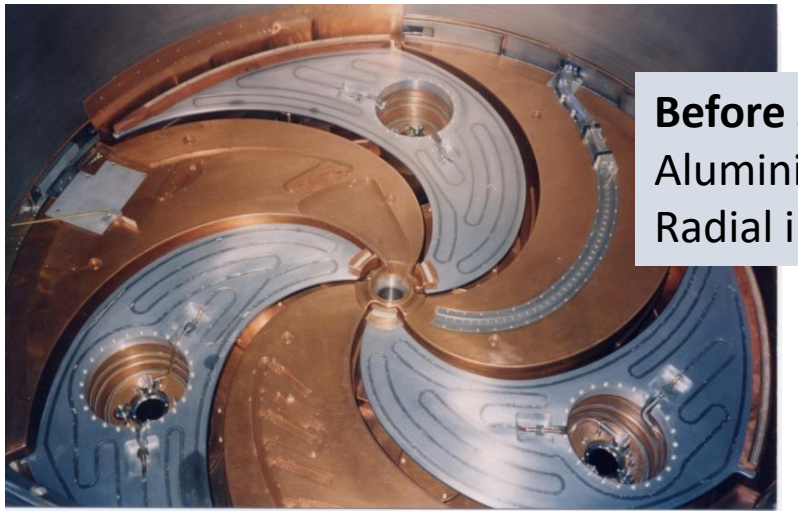

VERTICAL CROSS SECTION OF THE RF CAVITY

The RF system consists of three symmetrical coaxial resonators. Each resonator is two vertical

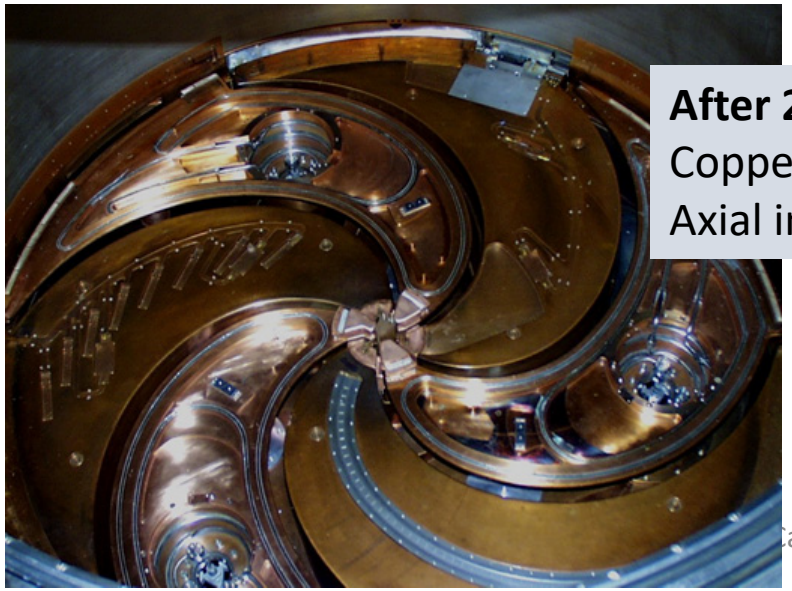
¼ λ cylindrical cavities connected at the centre by Dees placed in valleys.



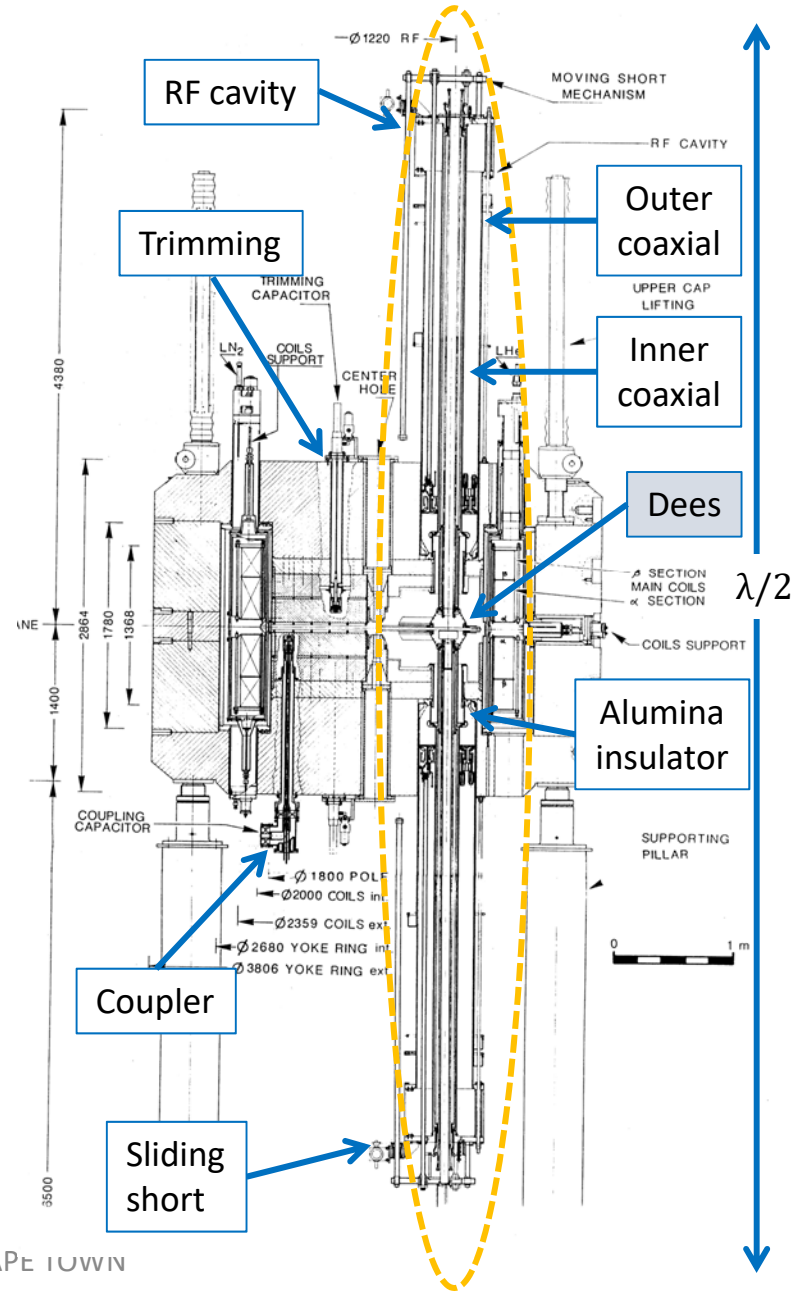
# The DEES



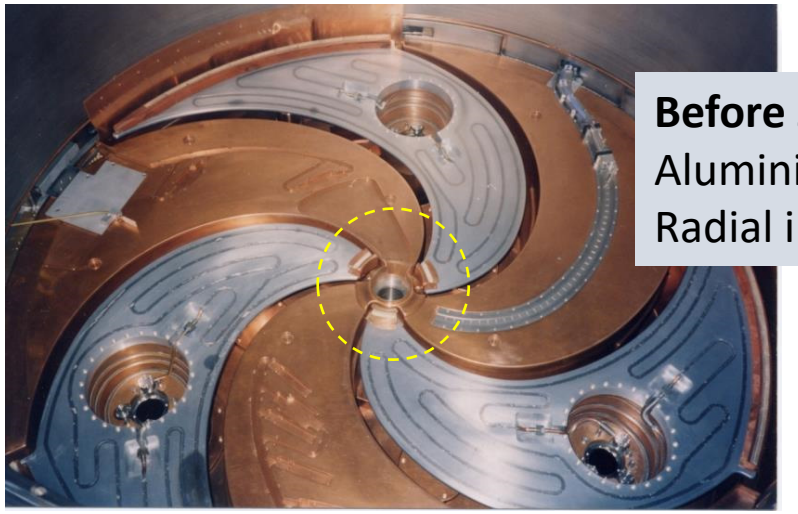
**Before 2000**
Aluminium Dees
Radial injection



**After 2000**
Copper Dees
Axial injection



# The DEES



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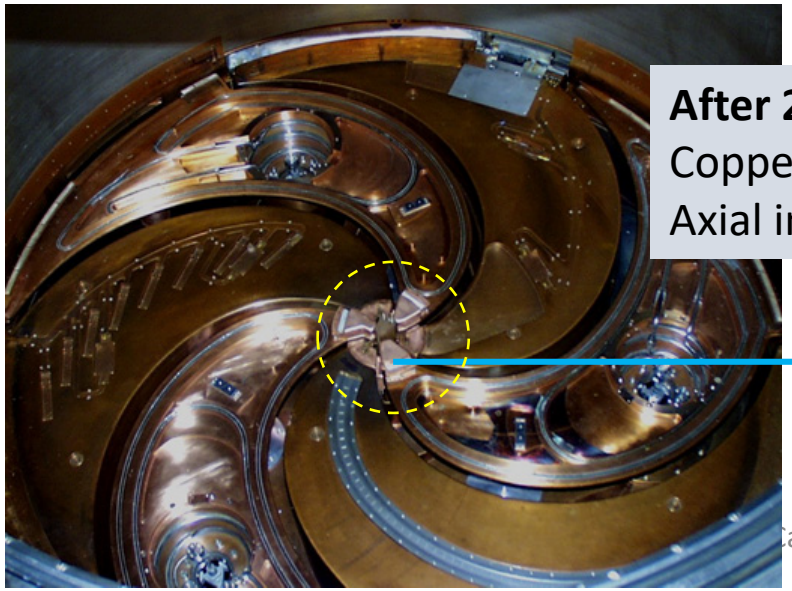
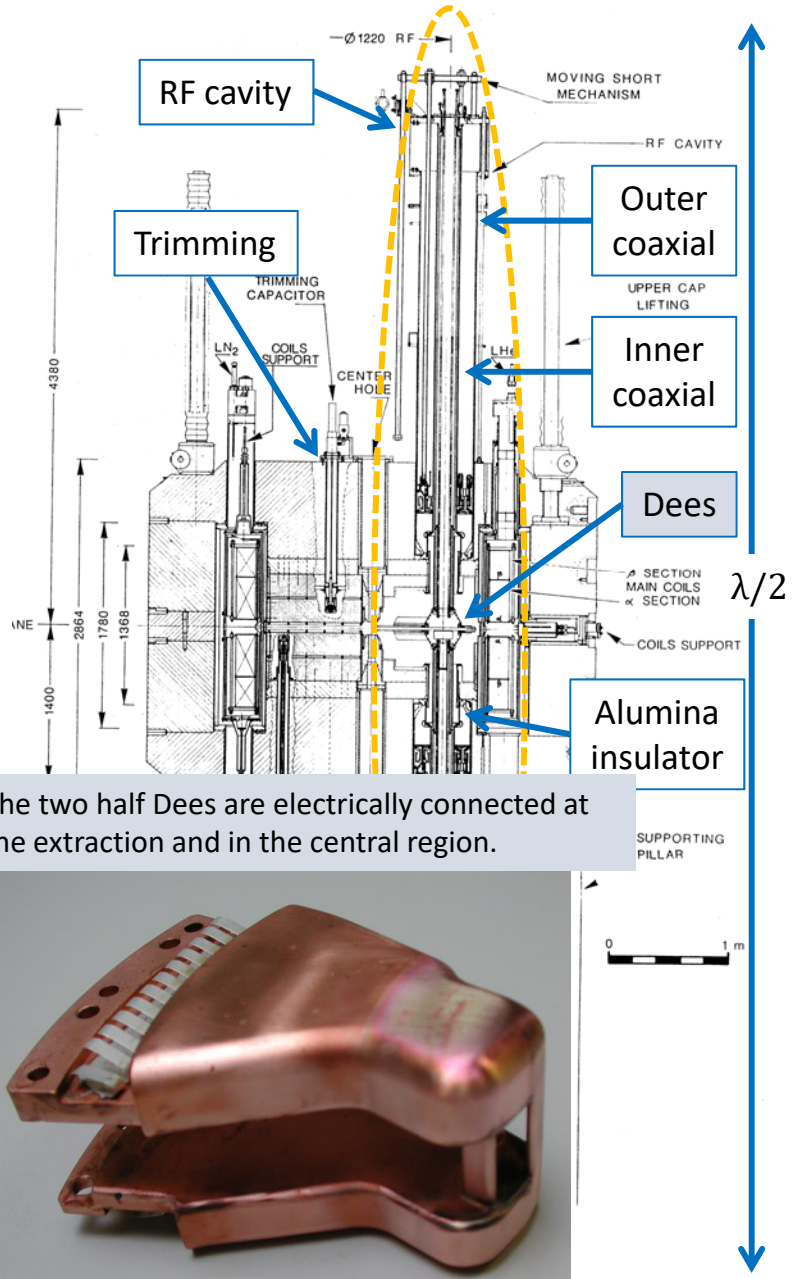
Radial injection

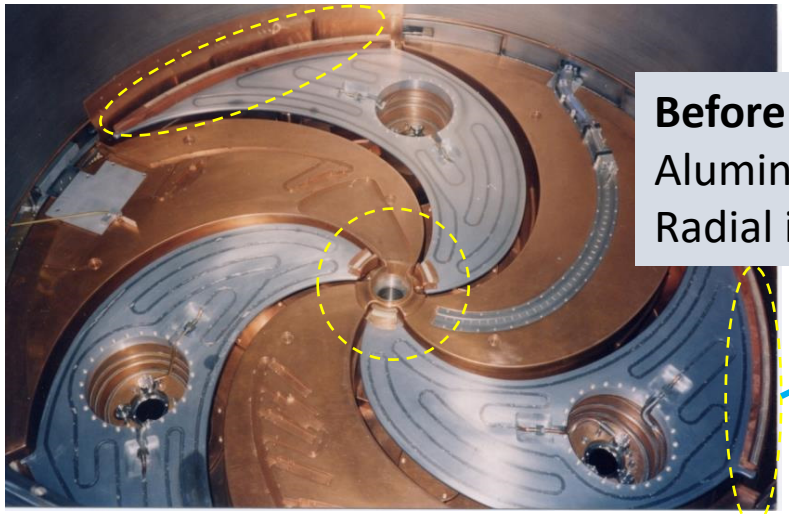


**After 2000**
Copper Dees
Axial injection

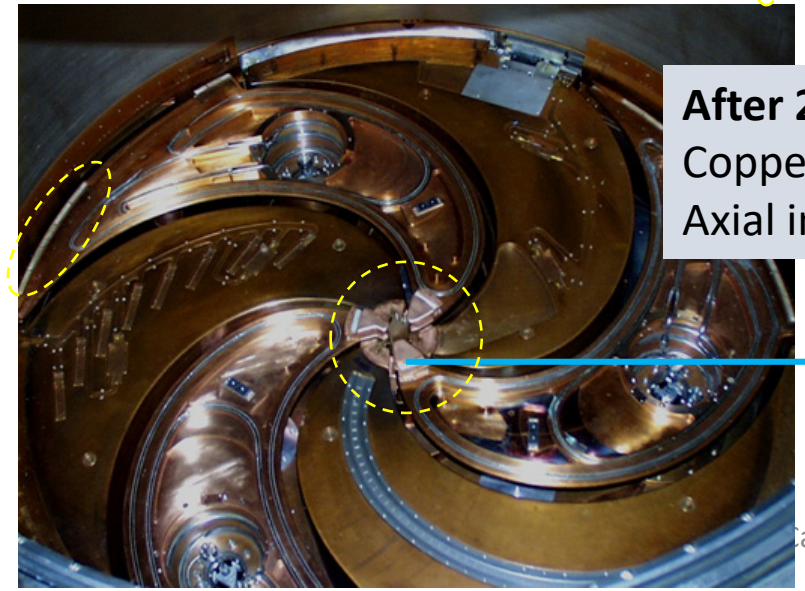



The two half Dees are electrically connected at the extraction and in the central region.

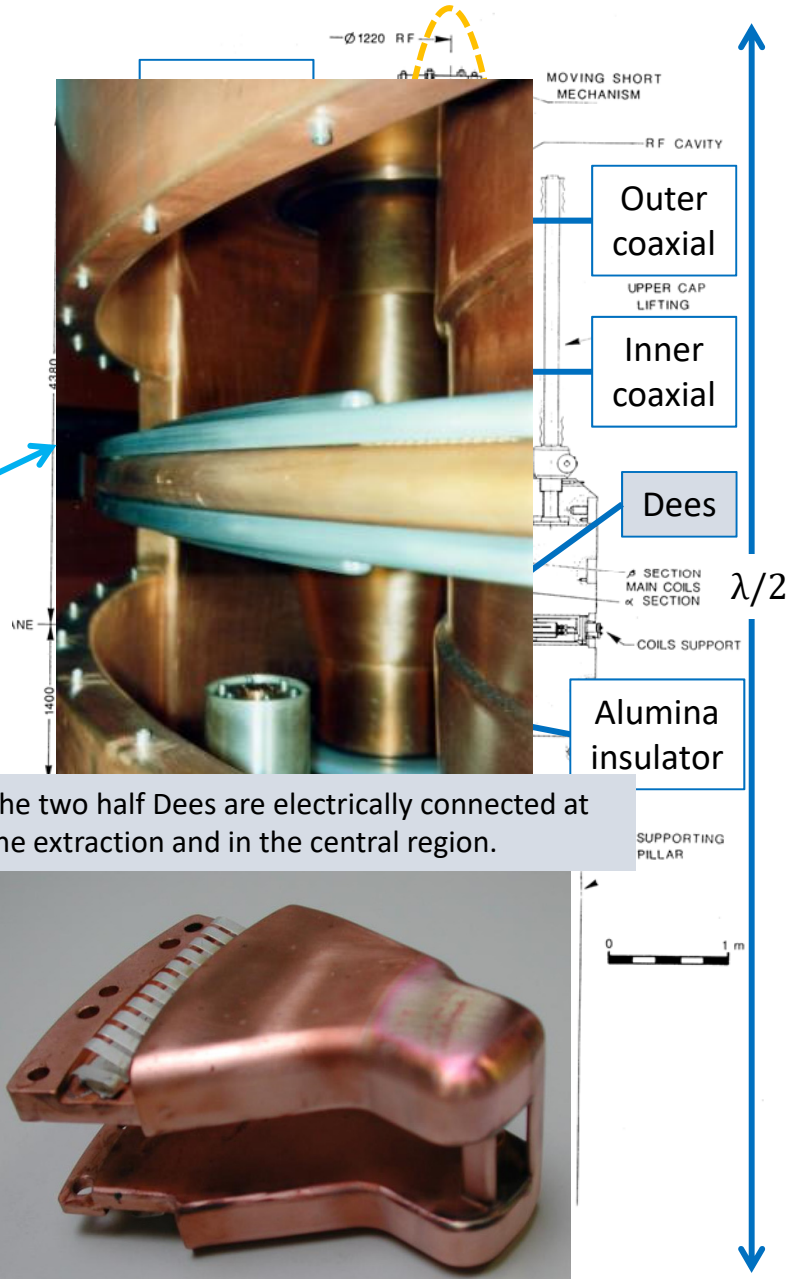
# The DEES



**Before 2000**
Aluminium Dees
Radial injection



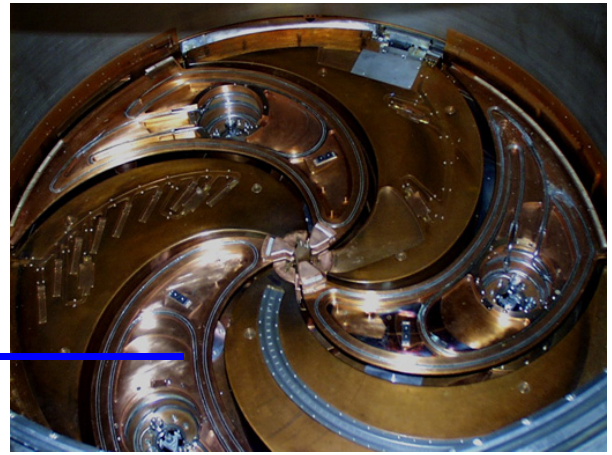
**After 2000**
Copper Dees
Axial injection




The two half Dees are electrically connected at the extraction and in the central region.

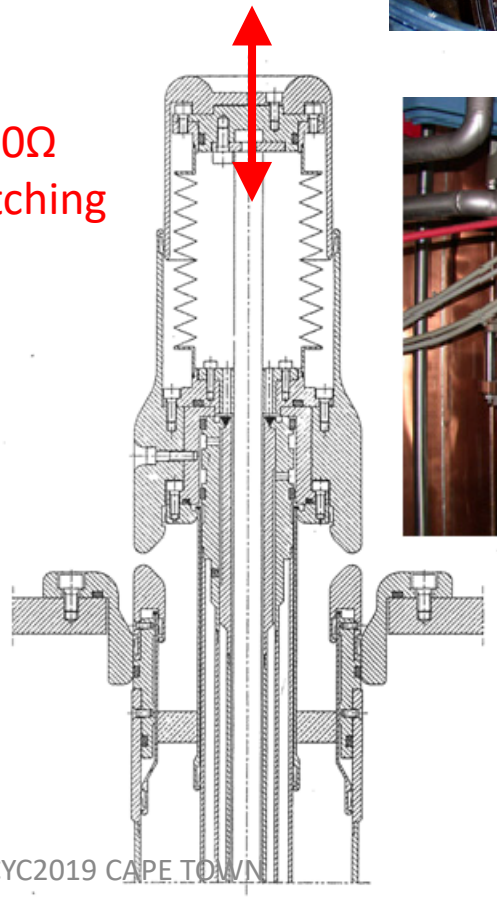
# Coupling Capacitor after 1995

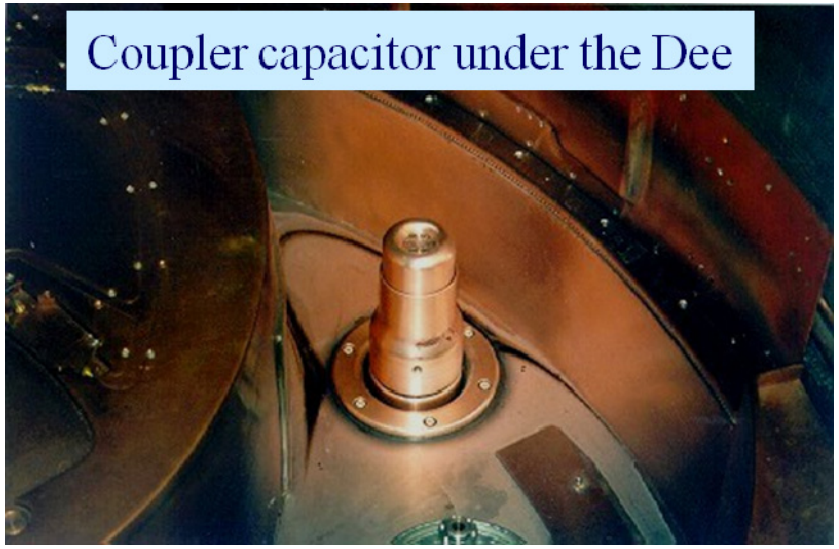
- simple mechanics
- also applicable for tuning control
- high voltage
  - insulator
  - discharge



Dee

50Ω
matching

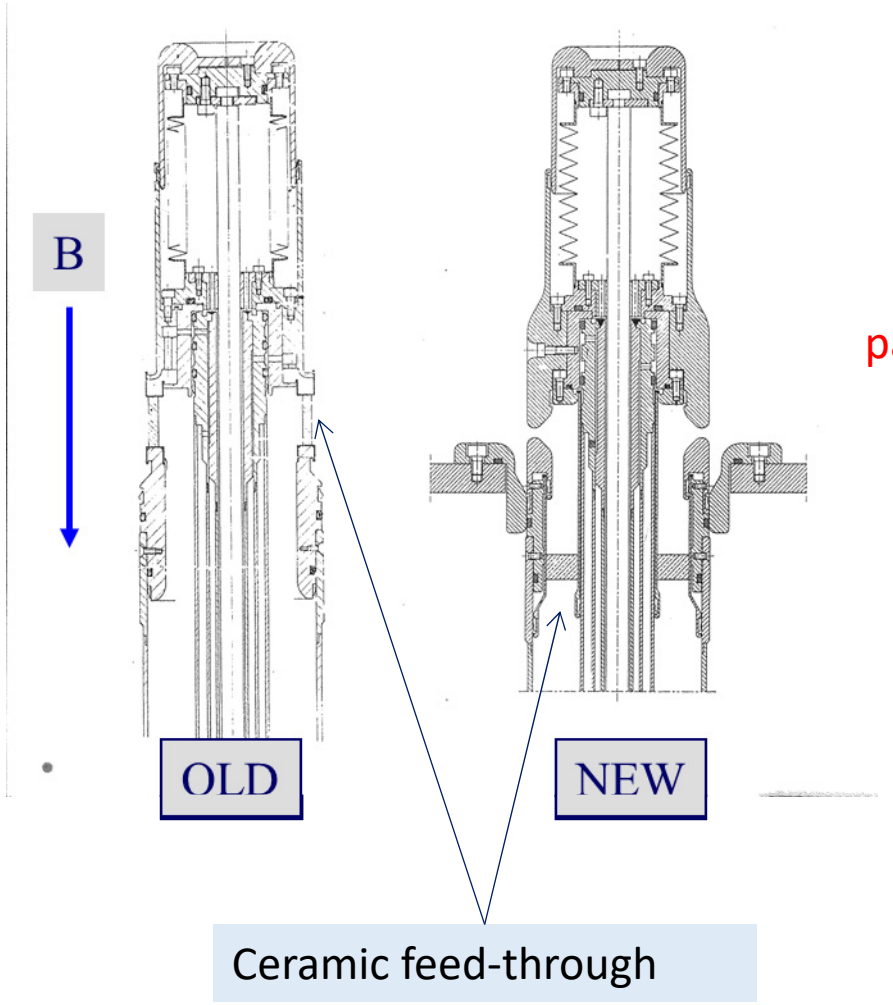





INFN-LNS, Catania

Standard
6”1/8 coaxial rigid
transmission line,
Directional coupler
just before the coupler

# Something to strongly avoid




avoid ceramic insulator
parallel to magnetic field


# cyclotron beams up to now

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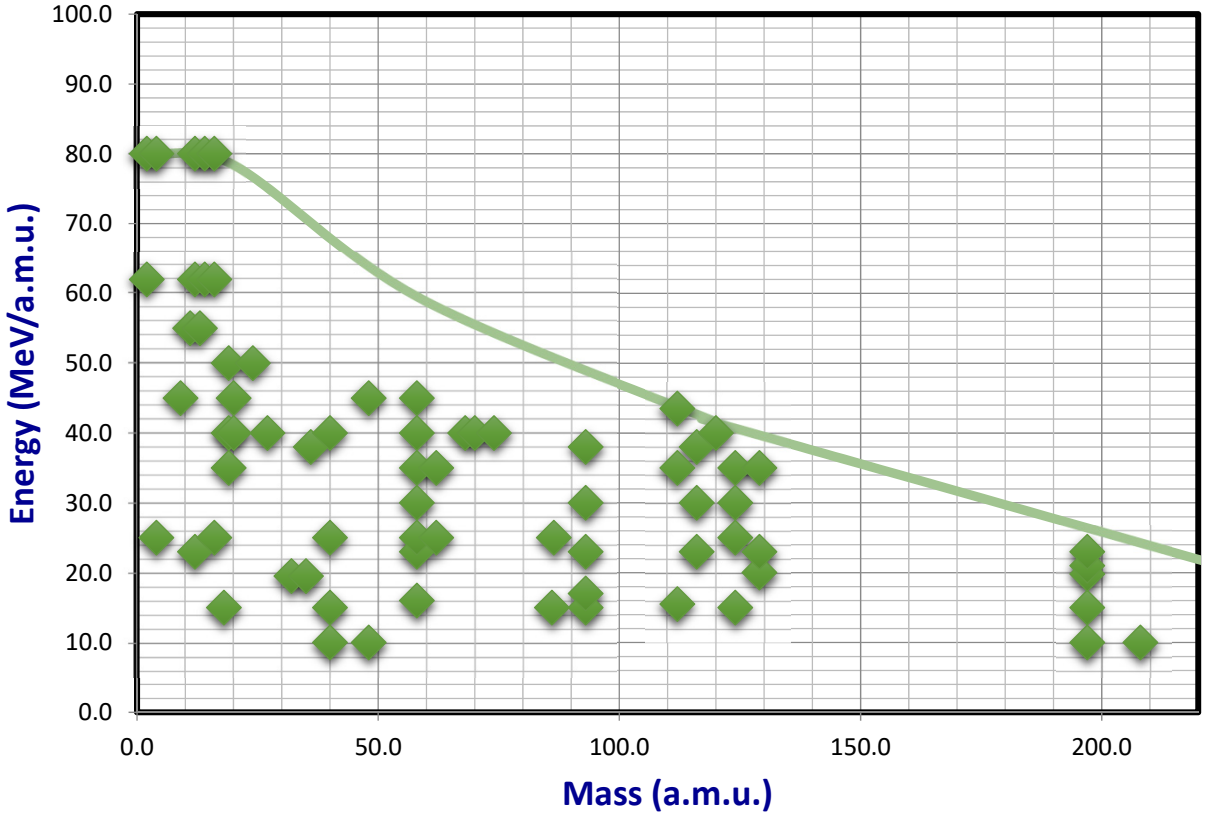
the cyclotron's good results with the axial injection were a sort of flywheel to develop, through the EXCYT project, the production of radioactive ion beams on a thick target with the ISOL technique, few years ago [1]




| $^{A}X$ | E (AMeV) |
|---|---|
| $H_2^+$ | 62,80 |
| $H_3^+$ | 30,35,45 |
| $^{2}D^+$ | 35,62,80 |
| $^{4}He$ | 25,62,80 |
| He-H | 10, 21 |
| $^{9}Be$ | 45 |
| $^{11}B$ | 55 |
| $^{12}C$ | 23,62,80 |
| $^{13}C$ | 45,55 |
| $^{14}N$ | 62,80 |
| $^{16}O$ | 21,25,55,62,80 |
| $^{18}O$ | 15,55 |
| $^{19}F$ | 35,40,50 |
| $^{20}Ne$ | 20,40,45,62 |
| $^{24}Mg$ | 50 |
| $^{27}Al$ | 40 |
| $^{36}Ar$ | 16,38 |
| $^{40}Ar$ | 15,20,40 |
| $^{40}Ca$ | 10,25,40,45 |
| $^{42,48}Ca$ | 10,45 |
| $^{58}Ni$ | 16,23,25,30,35,40,45 |
| $^{62,64}Ni$ | 25,35 |
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| $^{74}Ge$ | 40 |
| $^{78,86}Kr$ | 10 |
| $^{84}Kr$ | 10,15,20,25 |
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| $^{107}Ag$ | 40 |
| $^{112}Sn$ | 15.5,35,43.5 |
| $^{116}Sn$ | 23,30,38 |
| $^{124}Sn$ | 15,25,30,35 |
| $^{129}Xe$ | 20,21,23,35 |
| $^{197}Au$ | 10,15,20,21,23 |
| $^{208}Pb$ | 10 |

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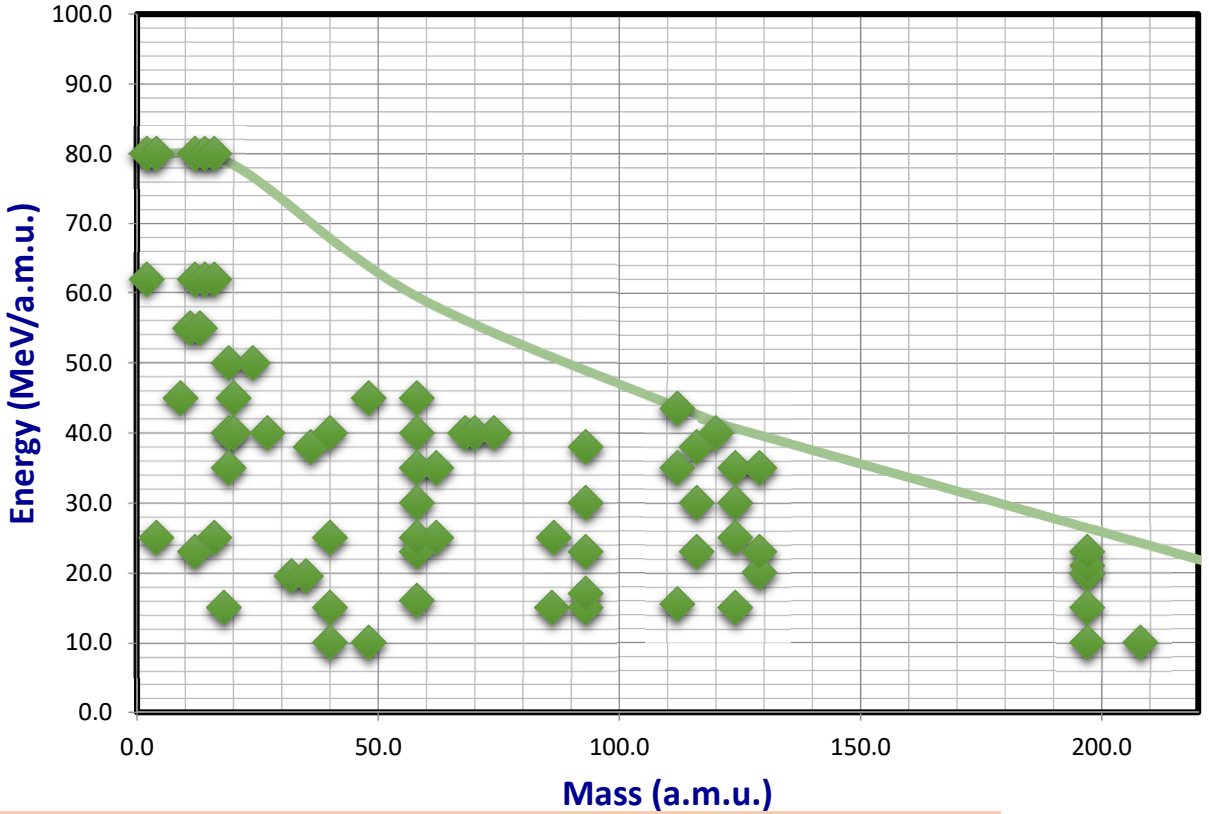


However, the **limitation, in terms of maximum output power (<150 Watts) of our extraction system** due to some intrinsic constraints and efficiency around 50-60% of the electrostatic deflector (ED), became quite clear

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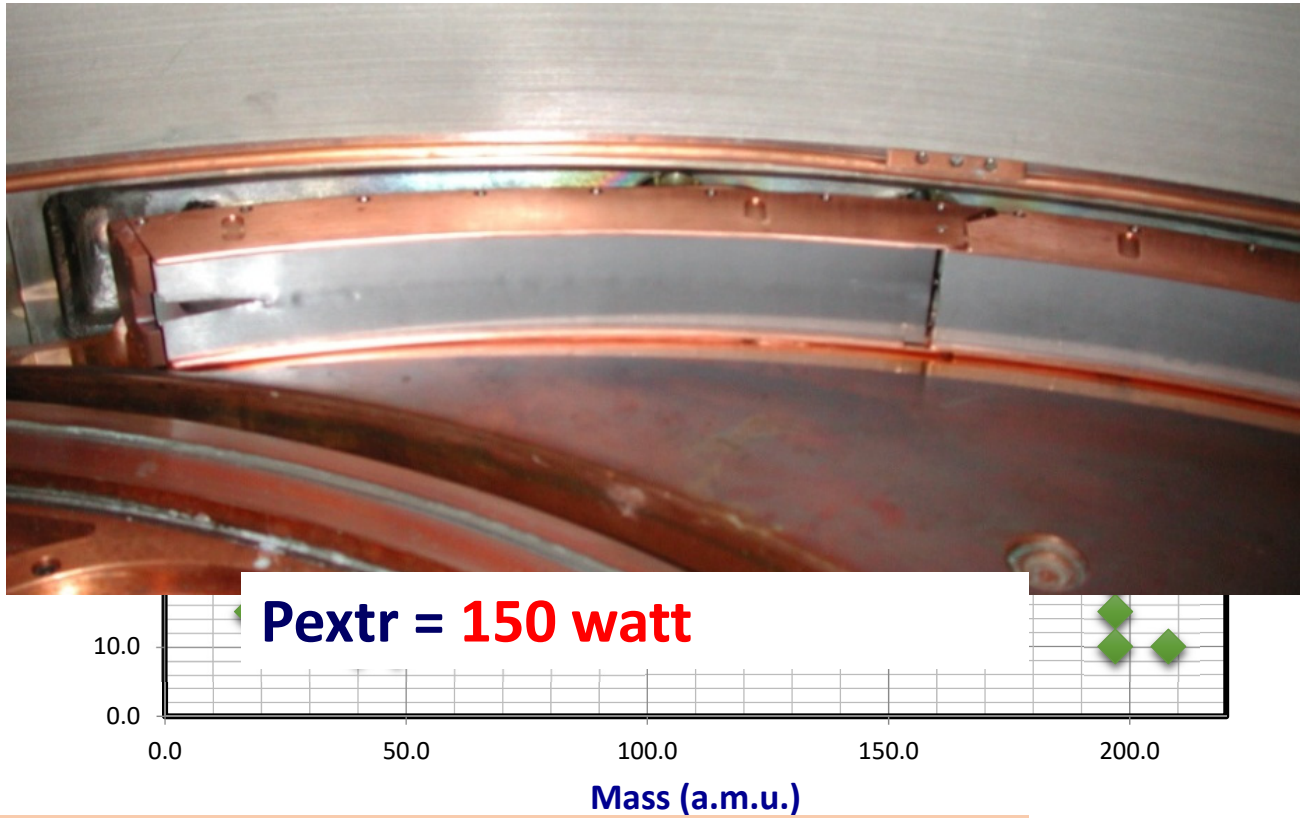


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| $^{197}Au$ | 10,15,20,21,23 |
| $^{208}Pb$ | 10 |

# So, why an upgrade of the cyclotron in terms of increasing output power of 10-100 times, up to 10 kW?

## Because the strong interest, in terms of demand, for high intensive beams is still valid

1

A new important project, in fact, has requested this kind of beam. The project, called **NUMEN (NUclear Matrix Elements for Neutrinoless double beta decay**), proposes an innovative technique to measure the nuclear matrix that is of relevant interest for the double β decay without neutrino emission [2].

This ambitious technique needs beams of $^{12}C^{4+}$ $^{18}O^{6+}$ $^{20}Ne^{4+}$ mainly, with a maximum beam current intensity of $10^{14}$ pps, which means a **cyclotron beam power between 1 and 10 kW**. This is more or less 10-100 times the present maximum beam power of 100 W

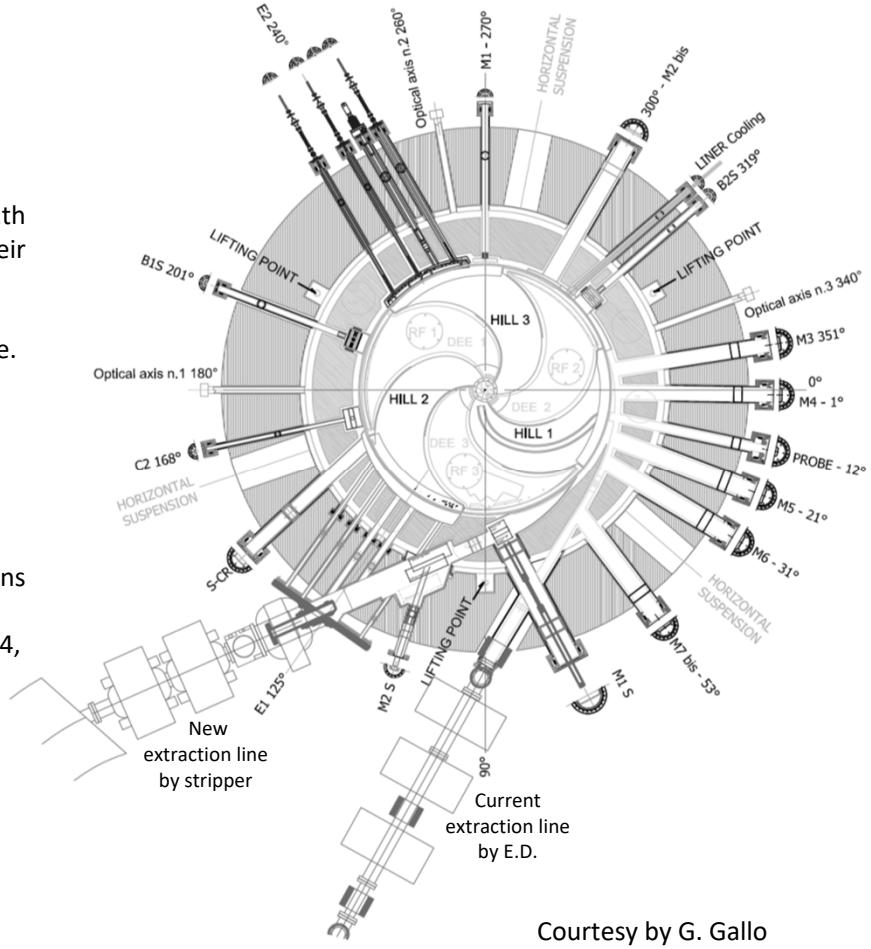
2

Another facility, strongly interested in high intensive beams, using the inflight technique to produce RIBs is **FRIBs@LNS (in Flight Radioactive Ion BeamS at LNS)**, already installed at LNS, allows one to carry out nuclear physics experiments investigating the properties of short-lived nuclear species [3].

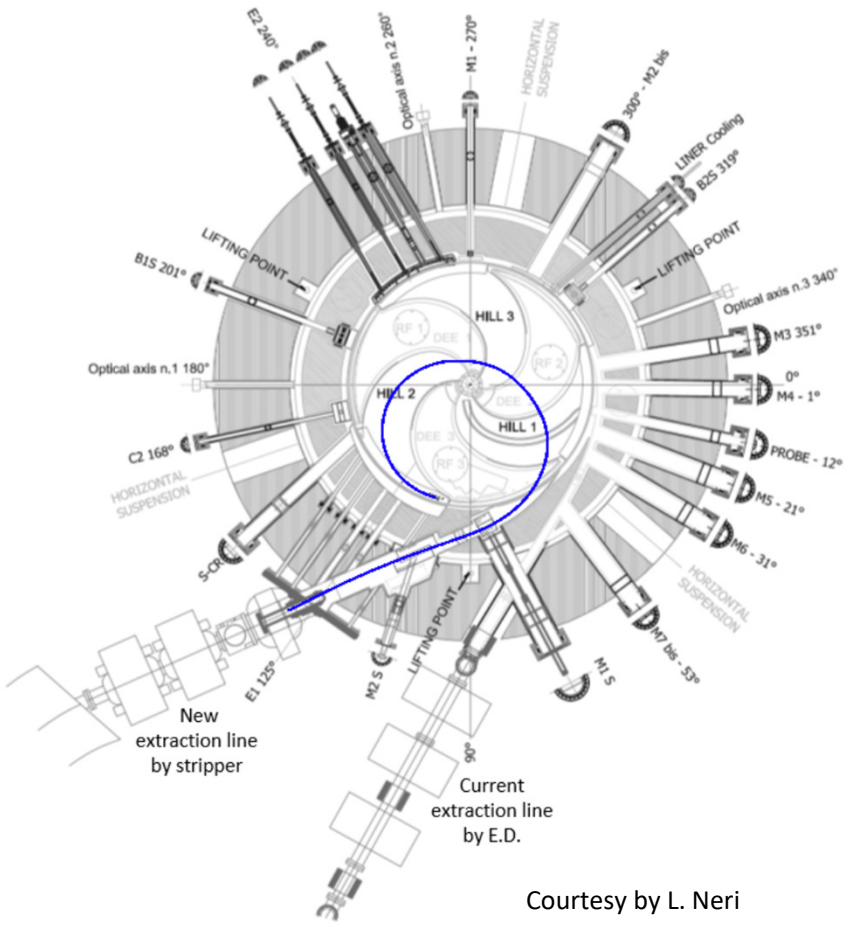
The main difference between the present configuration of the cyclotron and the future upgraded one, is the **introduction of a second extraction technique by stripping**. In this way **the extraction efficiency (>99%) is enough to achieve the high intensity requests.**

G. Gallo *et al.*, "Mechanical modifications of the median plane for the superconducting cyclotron upgrade", in Proc. 22th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'19), Cape Town, South Africa, Sep. 2019, MOP013, this conference.

L. Neri, *et al.*, Magnetic optimization of the new extraction channel for the LNS superconducting cyclotron, in Proc. 22th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'19), Cape Town, South Africa, Sep. 2019, MOP04, this conference.

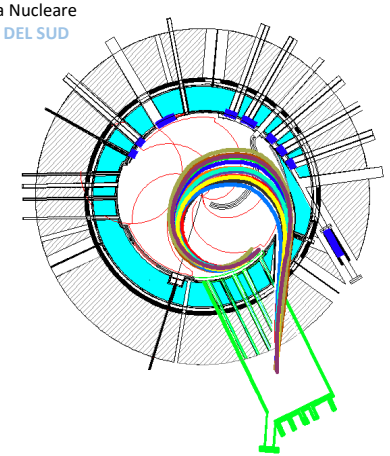



Courtesy by G. Gallo




Courtesy by L. Neri

# Beam extraction by stripping: **Efficiency >99%**

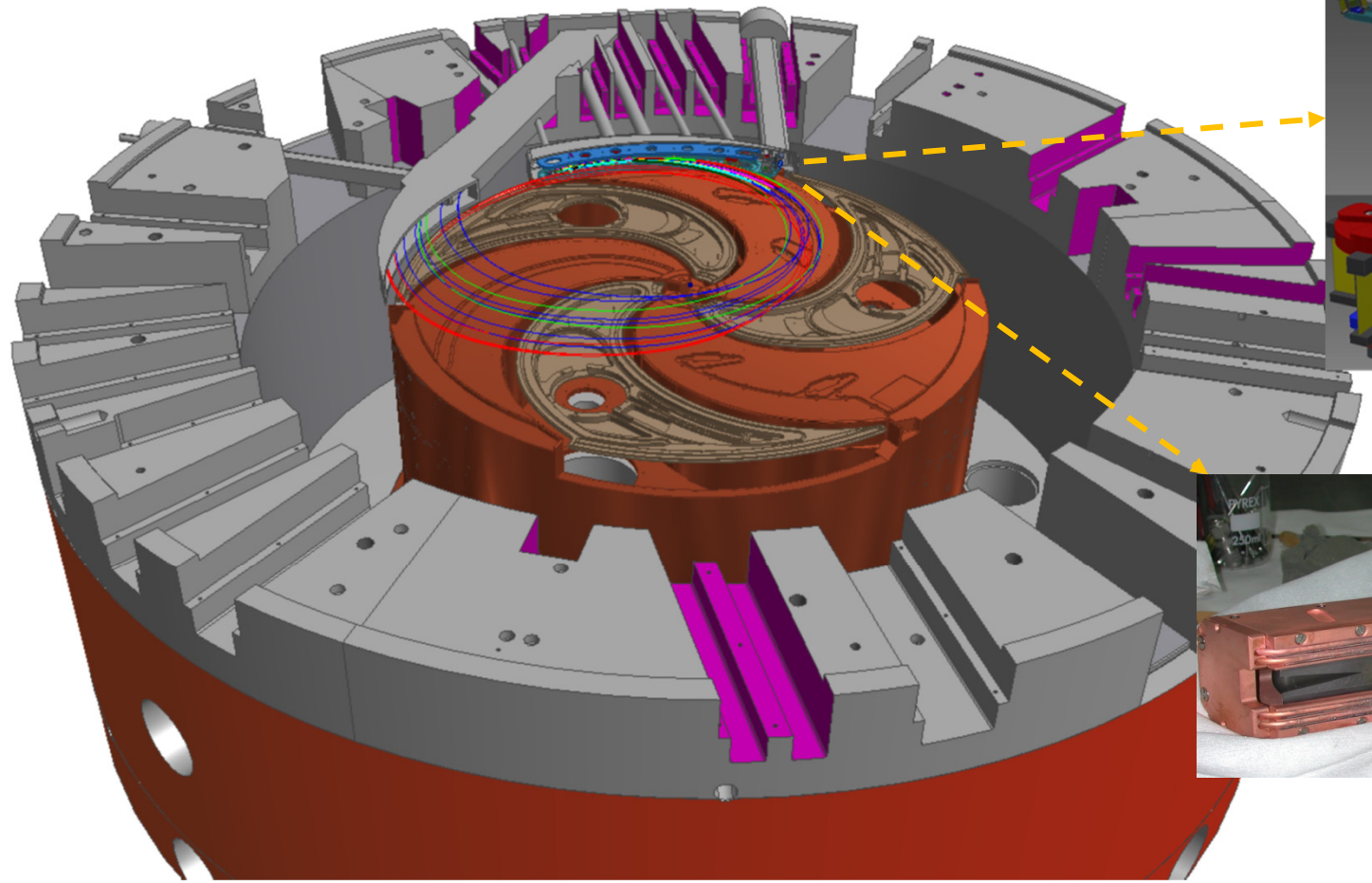


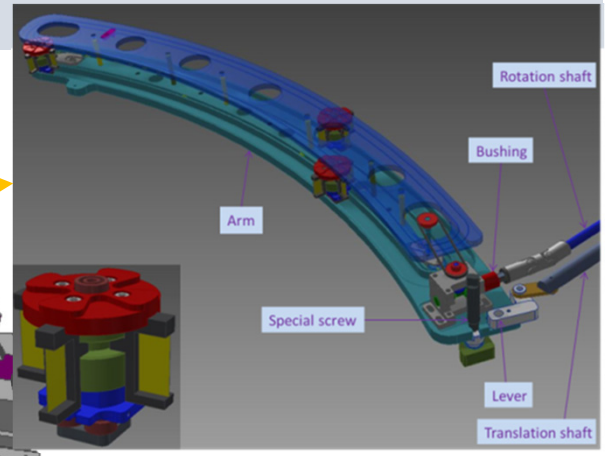
Extraction by stripping is based on the instantaneous change of the magnetic rigidity of the accelerated ion, when its charge state is suddenly increased crossing a thin carbon foil

| Ion | Energy | Isource | Iacc | Iextr | Iextr | Pextr |
|---|---|---|---|---|---|---|
| | MeV/u | eμA | eμA | eμA | pps | watt |
| $^{12}$C q=5+ | 30 | 200 | 30 (4+) | 45 (6+) | $4.7 \cdot 10^{13}$ | 2700 |
| $^{12}$C q=4+ | 45 | 400 | 60 (4+) | 90 (6+) | $9.4 \cdot 10^{13}$ | 8100 |
| $^{12}$C q=4+ | 60 | 400 | 60 (4+) | 90 (6+) | $9.4 \cdot 10^{13}$ | 10800 |
| $^{18}$O q=6+ | 20 | 400 | 60 (6+) | 80 (8+) | $6.2 \cdot 10^{13}$ | 3600 |
| $^{18}$O q=6+ | 29 | 400 | 60 (6+) | 80 (8+) | $6.2 \cdot 10^{13}$ | 5220 |
| $^{18}$O q=6+ | 45 | 400 | 60 (6+) | 80 (8+) | $6.2 \cdot 10^{13}$ | 8100 |
| $^{18}$O q=6+ | 60 | 400 | 60 (6+) | 80 (8+) | $6.2 \cdot 10^{13}$ | 10800 |
| $^{18}$O q=7+ | 70 | 200 | 30 (7+) | 34.3 (8+) | $2.7 \cdot 10^{13}$ | 5400 |
| $^{20}$Ne q=7+ | 28 | 400 | 60 (7+) | 85.7 (10+) | $5.3 \cdot 10^{13}$ | 4800 |
| $^{20}$Ne q=7+ | 70 | 400 | 60 (7+) | 85.7 (10+) | $5.3 \cdot 10^{13}$ | 10280 |
| $^{40}$Ar q=14+ | 60 | 400 | 60 (14+) | 77.1 (18+) | $2.7 \cdot 10^{13}$ | 10280 |

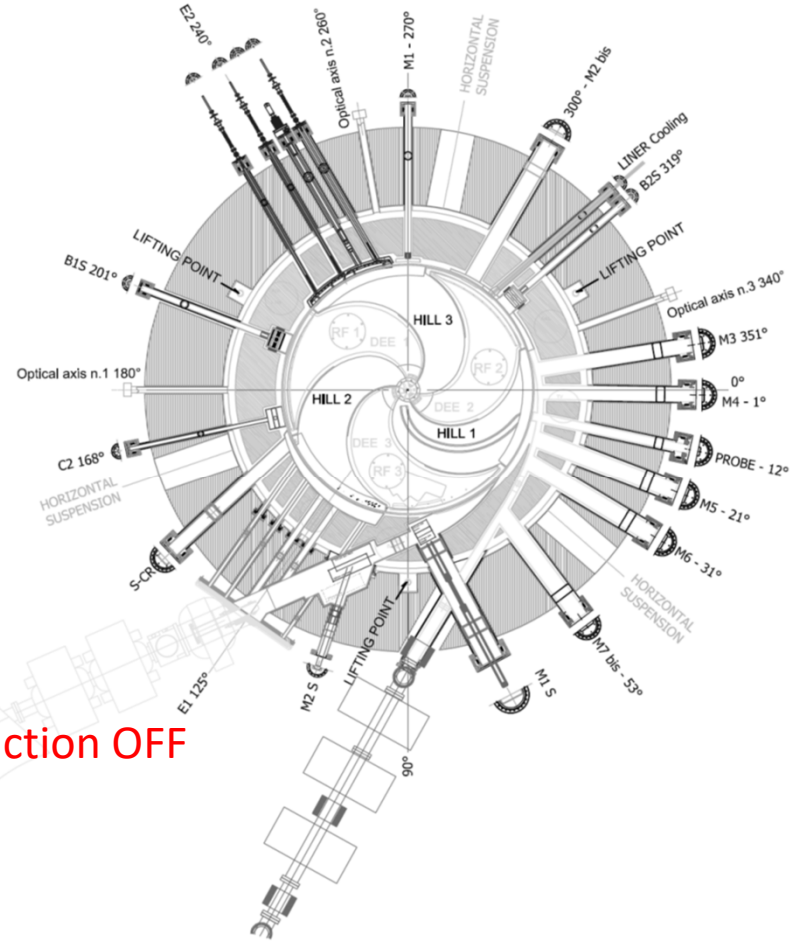
Courtesy by G. Cosentino, D. Rifuggiato

A detailed beam dynamic study **has optimized the extraction trajectory of the stripped beams with the extraction trajectory by E.D**. This perfect overlap trajectory allows for the interchanging of the two systems in the present ED position [4]. To reduce the interchanging phases, **two sessions have been scheduled during the year: one for high intensive beams and the other for the beam extracted by E.D.** [5]





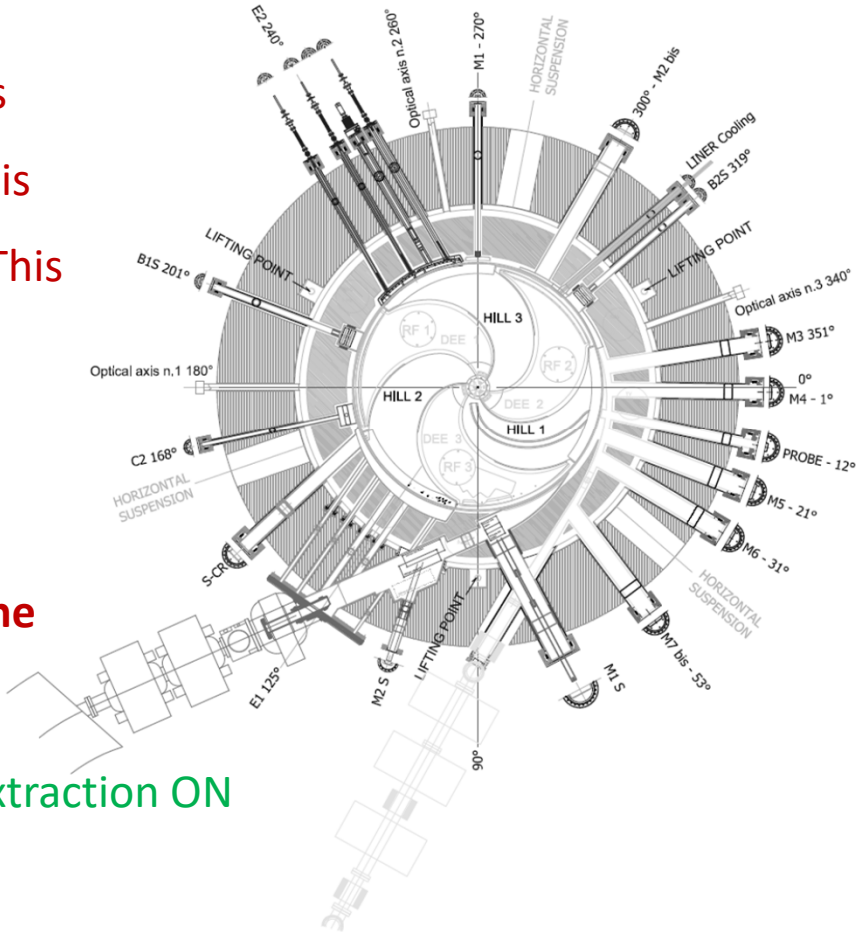

# Two different operation mode: stripper and ED




Stripper extraction OFF

ED extraction ON

A new hole/penetration along the median plane is necessary to introduce this new extraction channel. This means **redesigning the magnet, cryostat and** making some other modifications including **the RF system.**




Stripper extraction ON

ED extraction OFF

The most important reasons for **changing something in the RF system are mostly related to the power and size of the stripped beam** during the acceleration phase, inside the median plane and subsequently in the extraction channel.

related to the new geometry of the median plane

related to the final dissipated power.

*Mechanic modifications*

*Electronic modifications (LLRF-HLRF)*

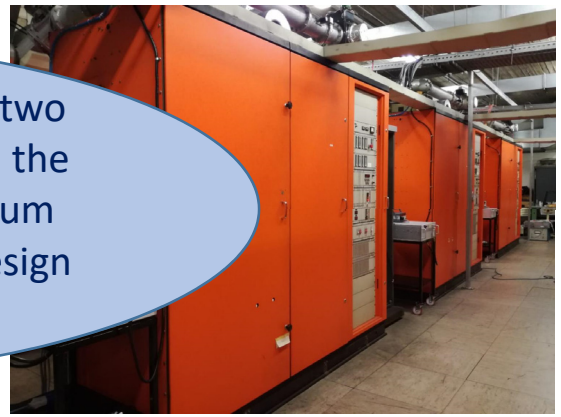
The most important reasons for **changing something in the RF system are mostly related to the power and size of the stripped beam** during the acceleration phase, inside the median plane and subsequently in the extraction channel.

related to the new geometry of the median plane

related to the final dissipated power.

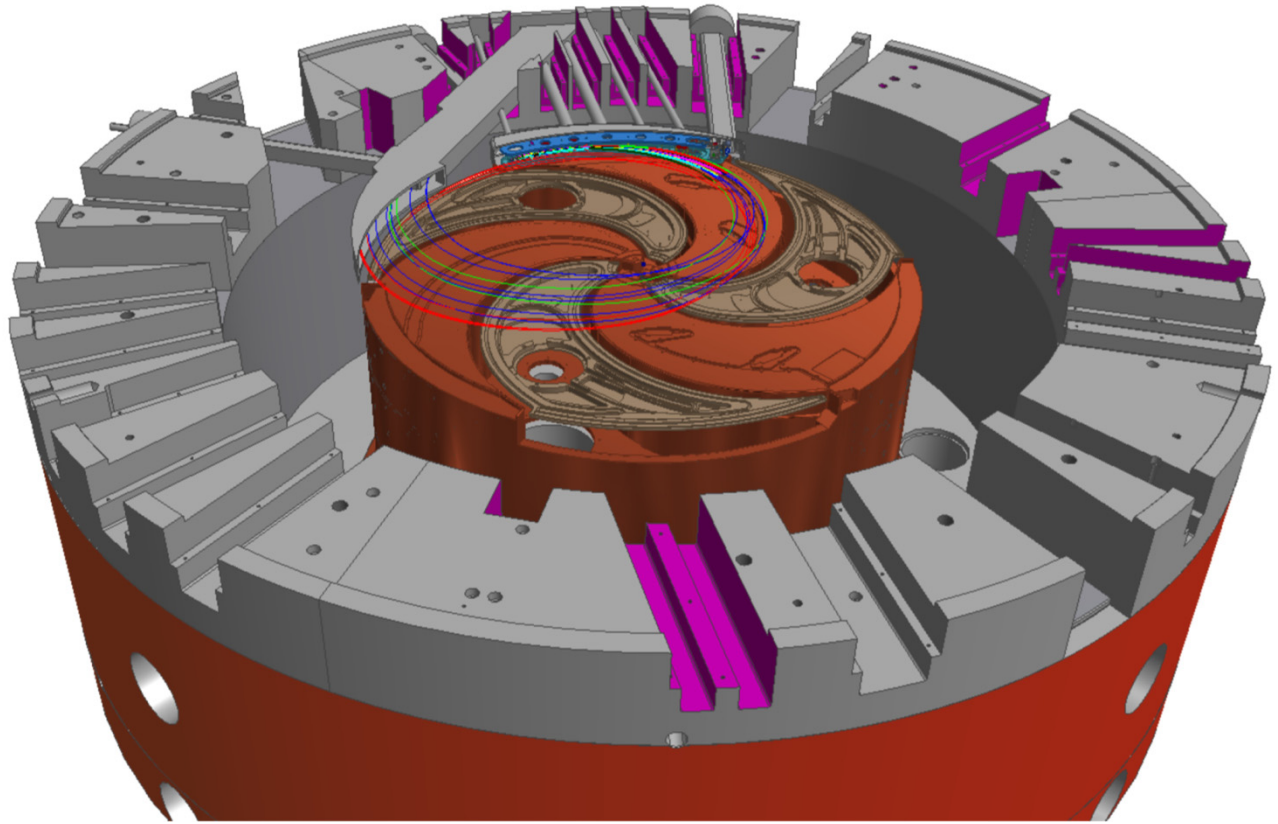
*Mechanic modifications*

These **two** reasons can also be seen as two **opportunities** to improve and refurbish the RF system in terms of mechanics, vacuum quality improvement, with new liner design and high/low level electronic



*Electronic modifications (LLRF-HLRF)*

The **present vertical distance** between the upper and lower dees and inside the liner **is 24 mm**, not enough for all the future beams extracted with the stripper technique. An **extra space of ± 3 mm** in the vertical gap **should be enough** to allow for the acceleration of the high intensive beams and to also minimize the beam loss inside the acceleration chamber.



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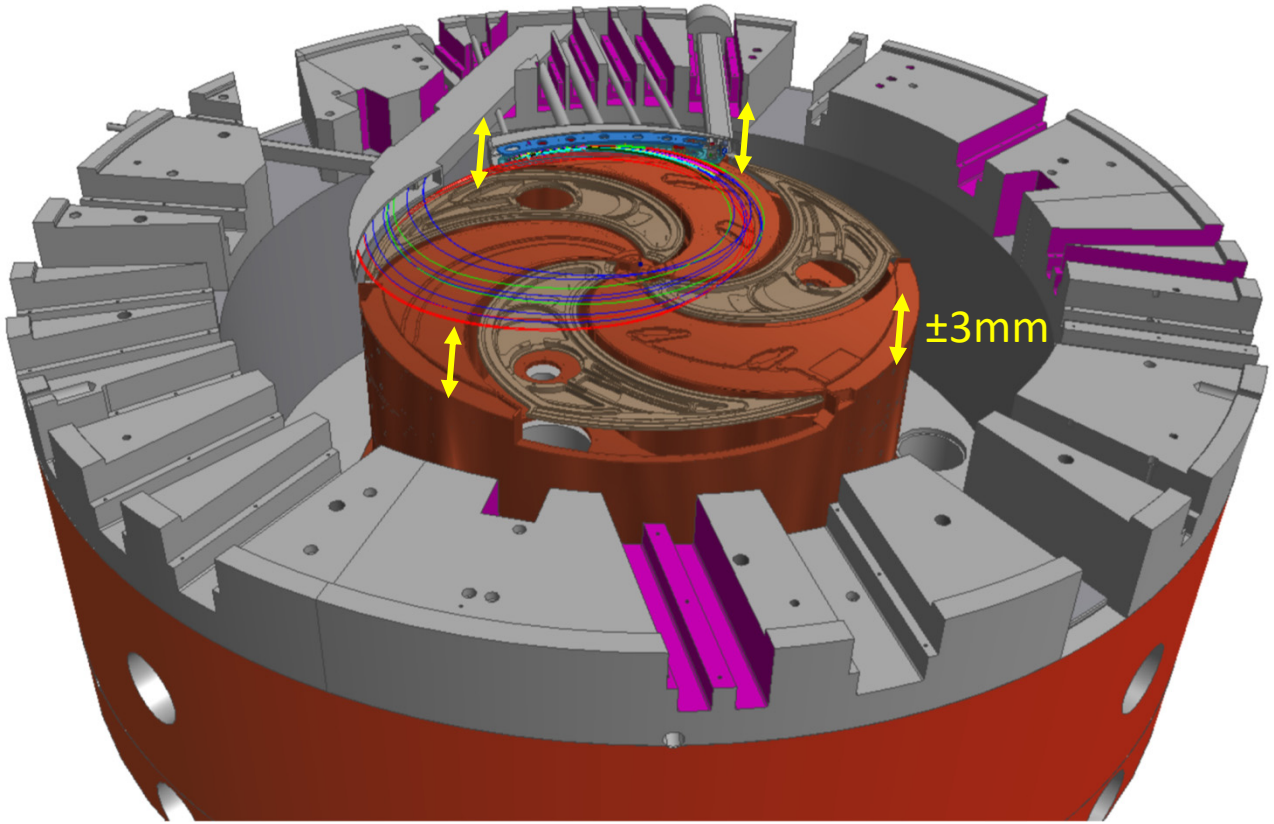
How to increase/decrease?



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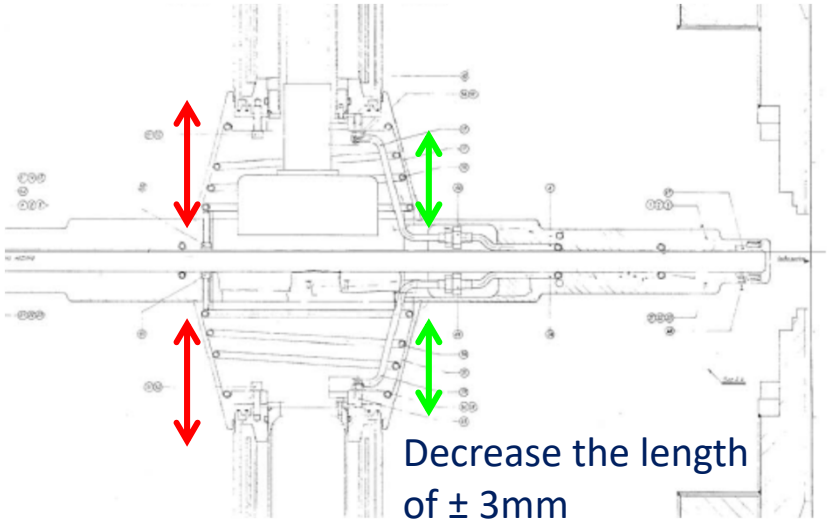
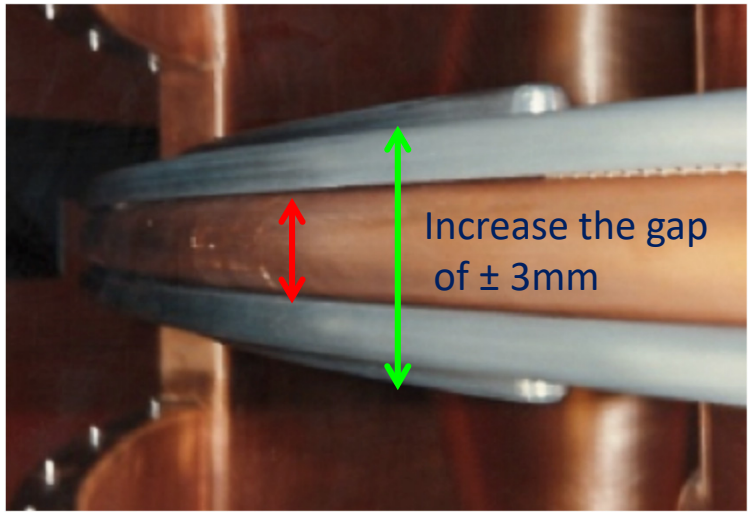
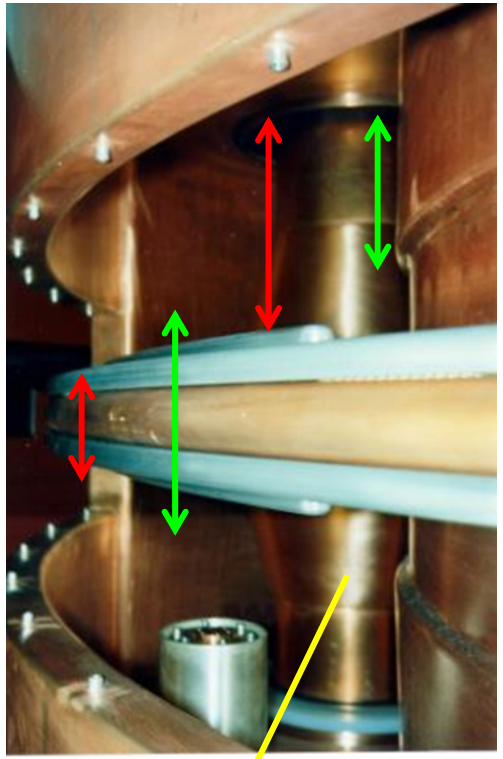
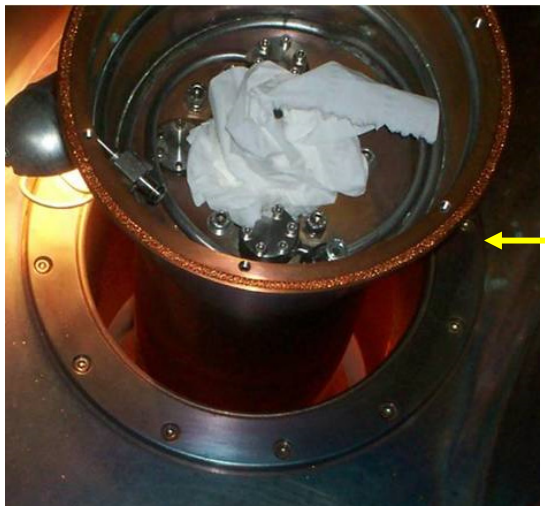
How to increase/decrease?

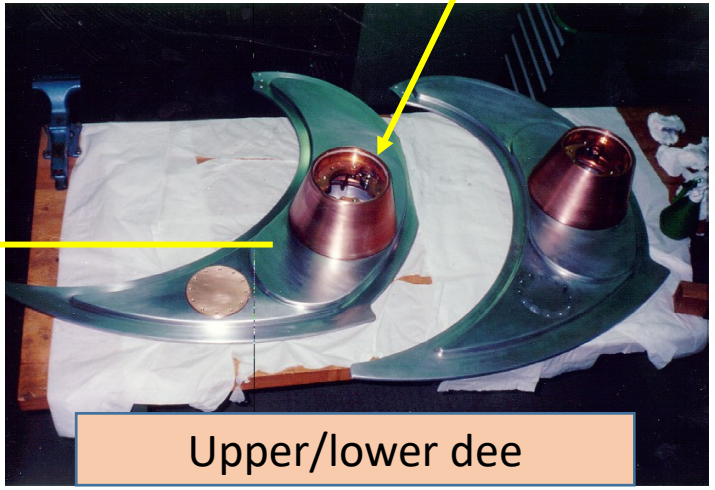
To increase the distance between the acceleration electrodes, from 24 to 30 mm, a reduction of the upper and lower conical connection length between the dees and the inner coaxial of ±3 mm has to be made.



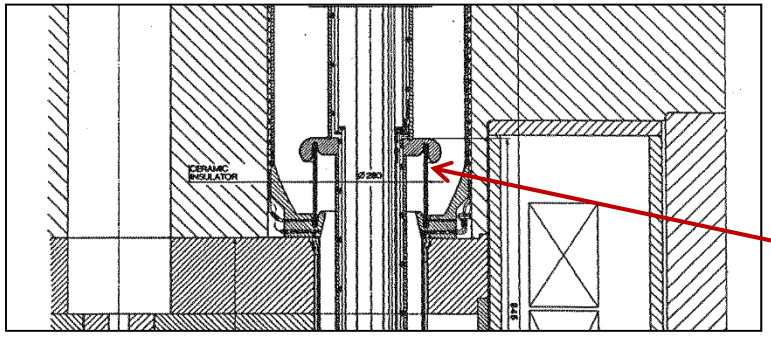



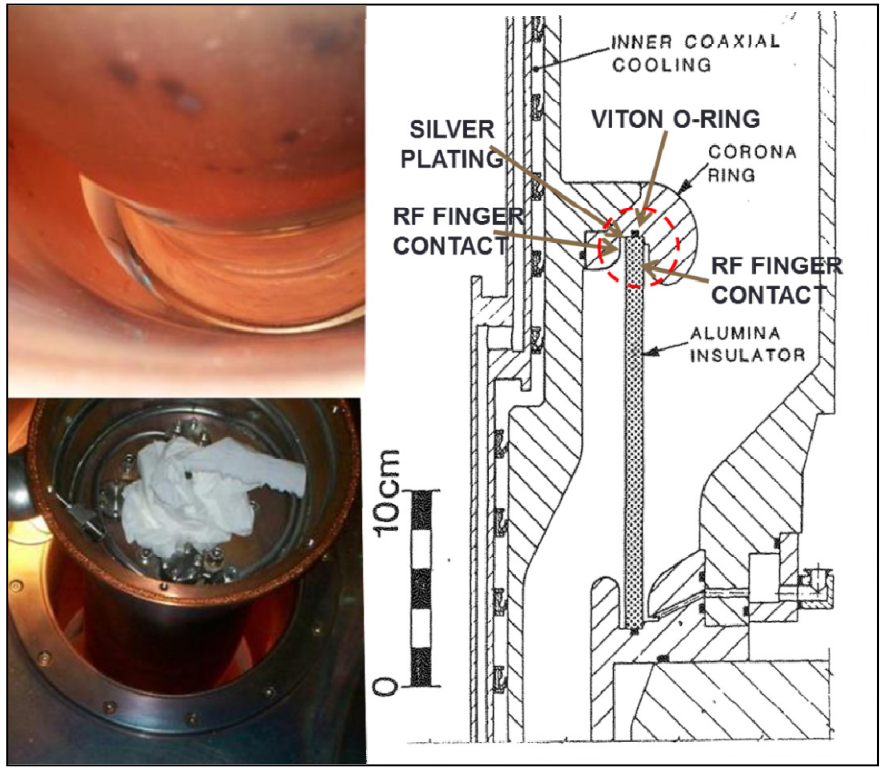



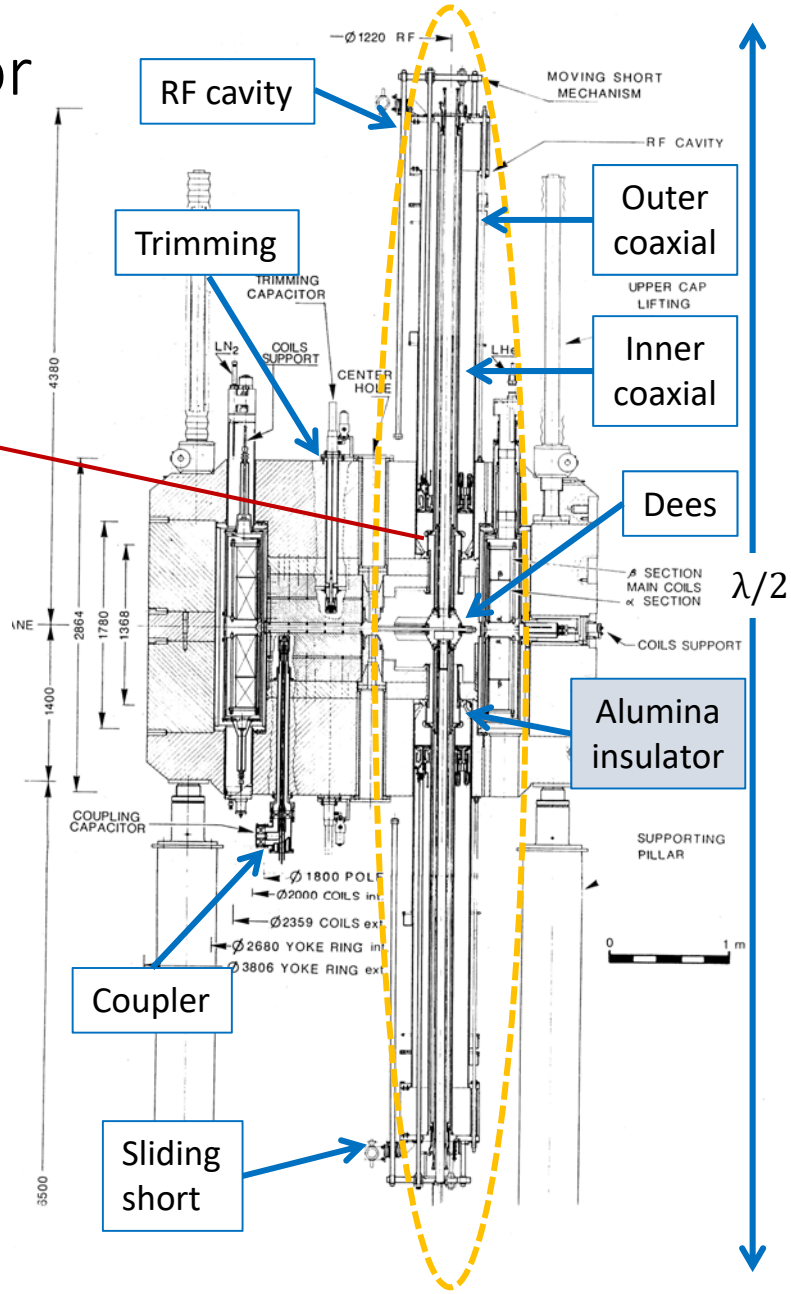




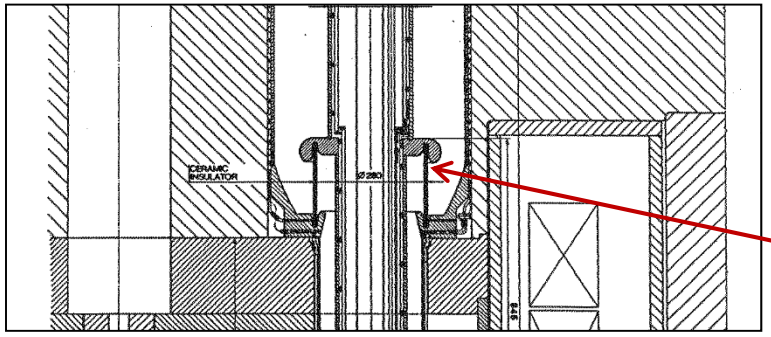
# The high voltage ceramic insulator

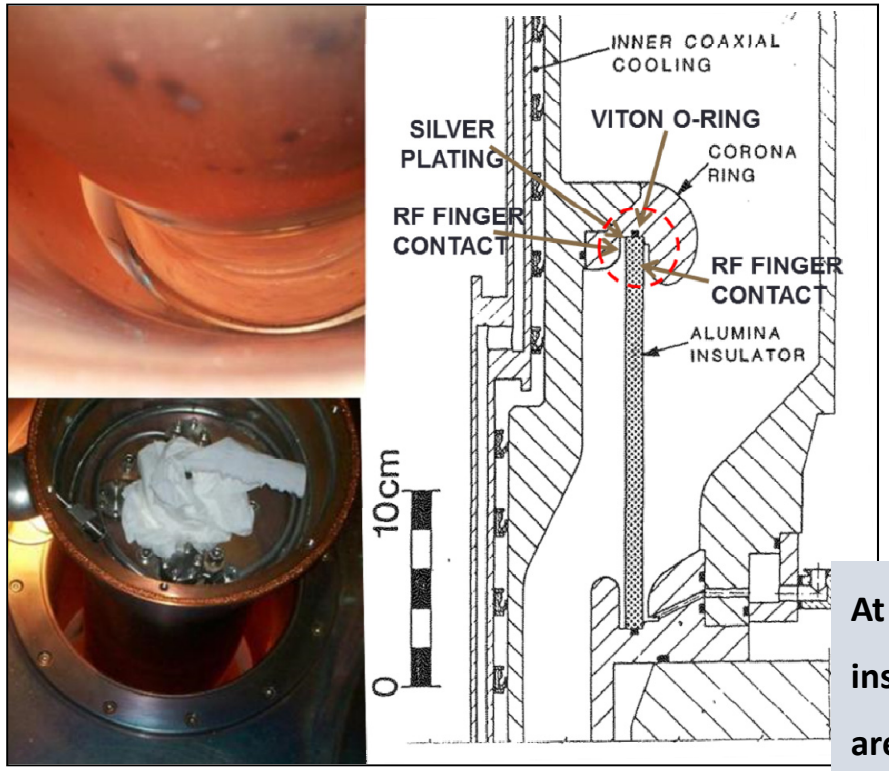


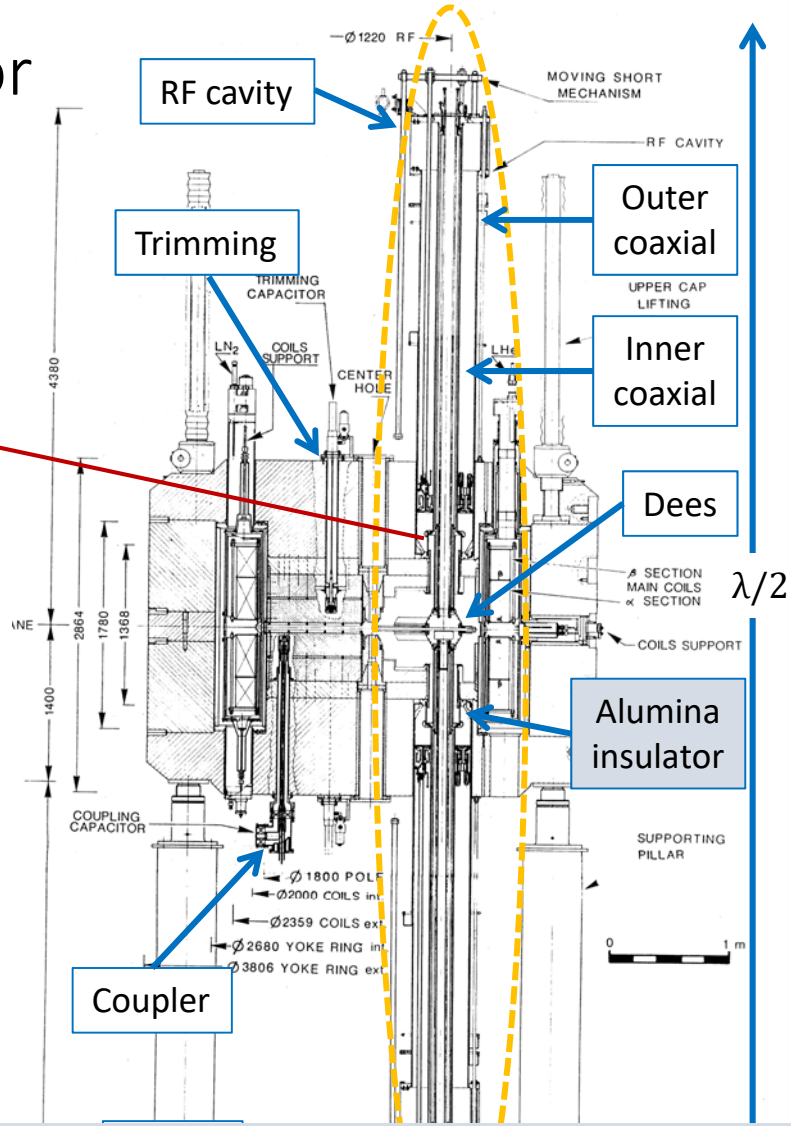



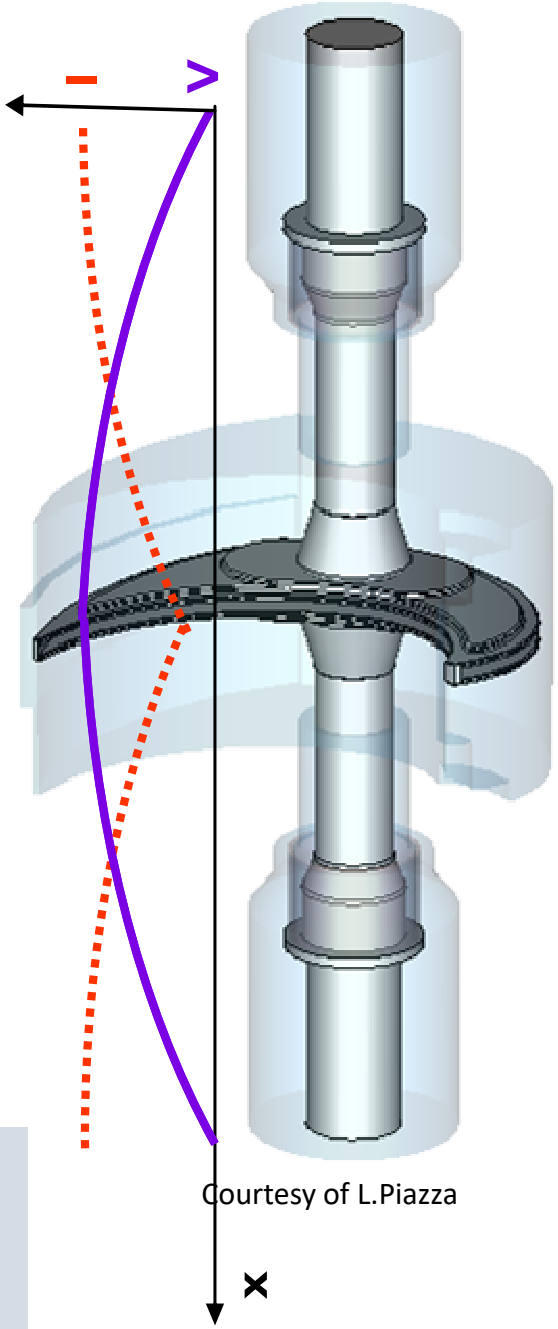



# The high voltage ceramic insulator



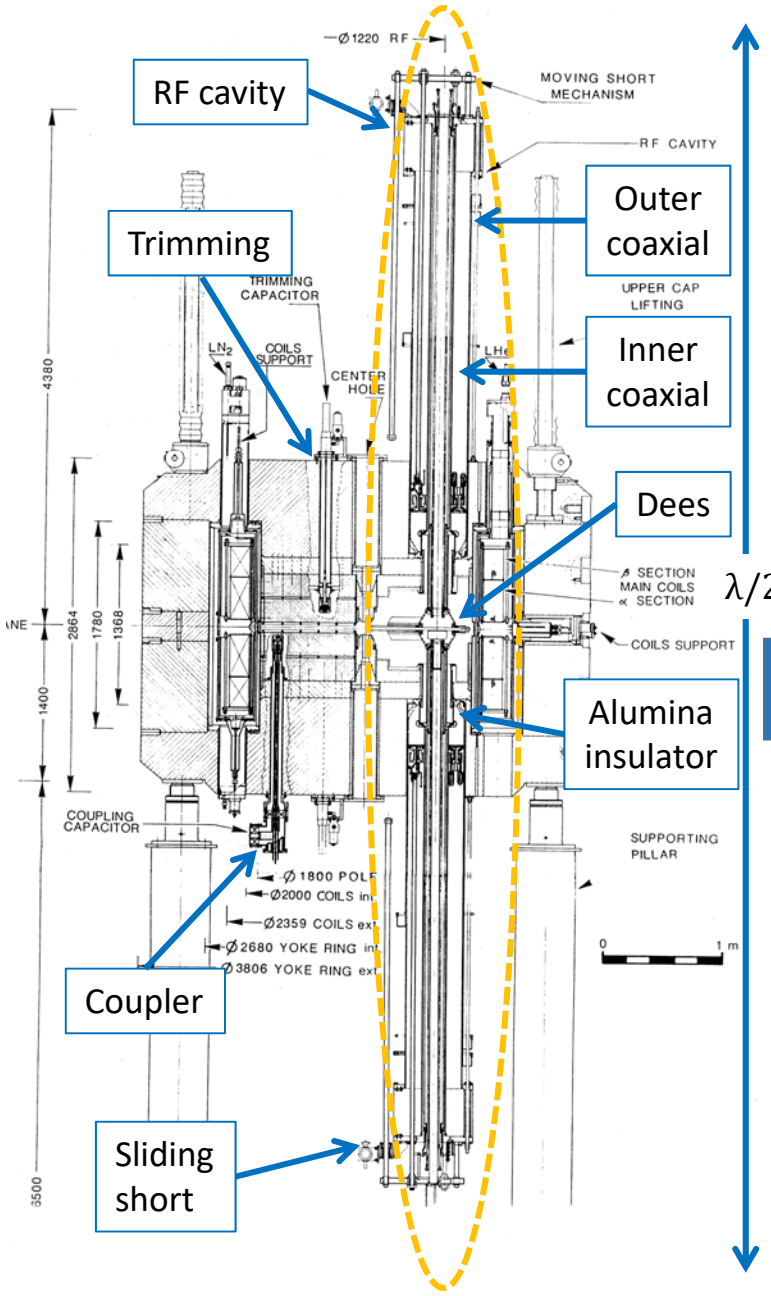



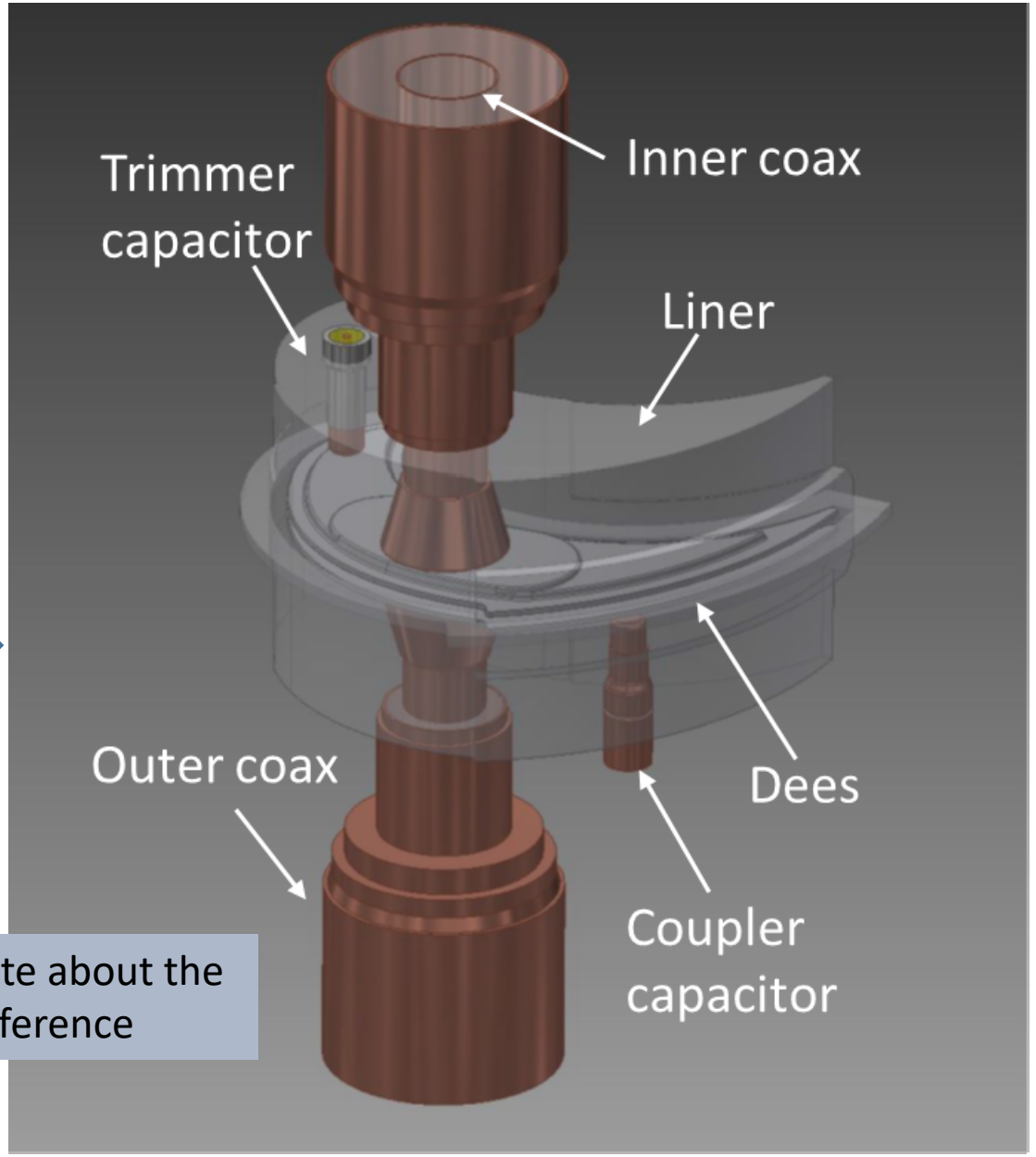
Courtesy of L.Piazza

**At the maximum Dee voltage of 100 kV the alumina insulator dissipation should not exceed 200 W, careful we are 3 mm closer!**




VERTICAL CROSS SECTION OF THE CAVITY

3D model




3D MODEL OF THE CAVITY

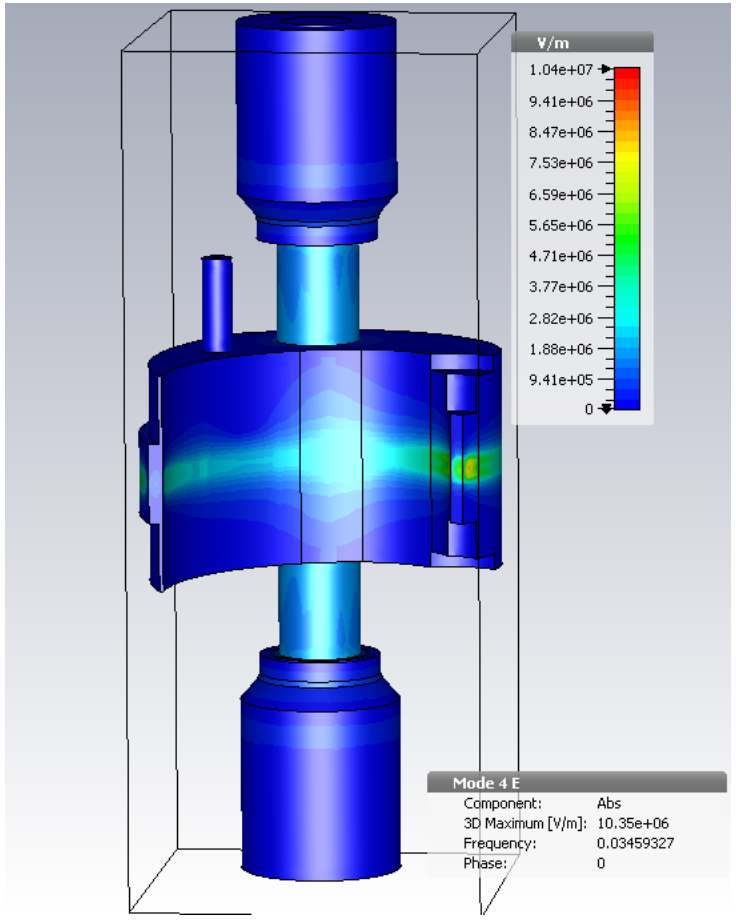
To investigate about the upgrade difference

For this reason, a **detailed 3D numerical simulation of the modified RF cavity**, using 3D commercial electromagnetic simulators, CST Microwave Studio [7] and COMSOL multiphysics [8] comparing them to significant experimental results, through network analyser measurements, has been done

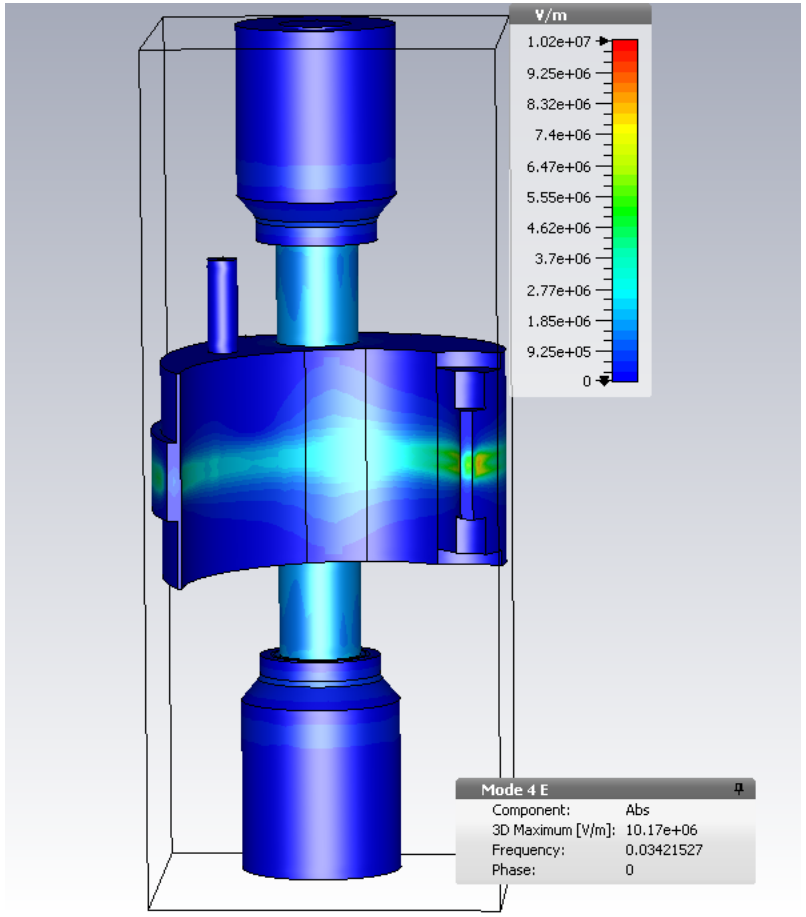
SPECIFIC TALK ON FRIDAY BY L. NERI

G. Torrisi, **L. Neri,** *et al.*, 3D Radio frequency simulation of the LNS superconducting cyclotron, in Proc. 22th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'19), Cape Town, South Africa, Sep. 2019, FRB03, this conference.

gap=0 mm



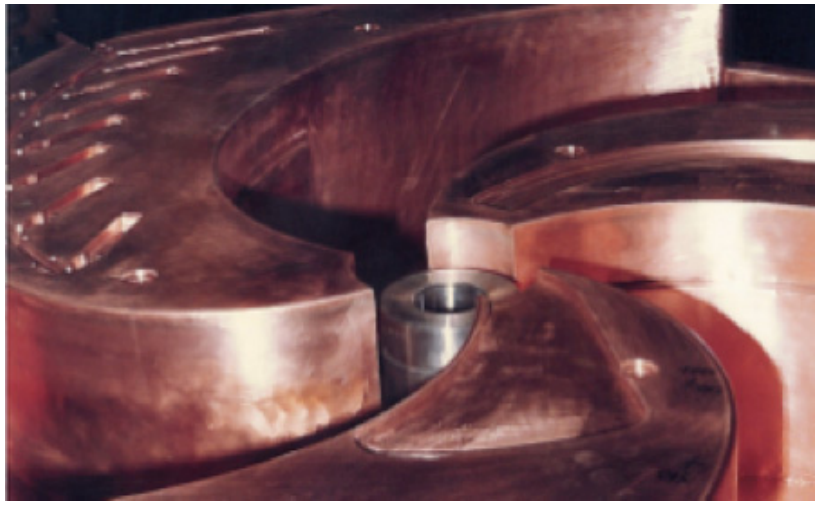

gap=6 mm

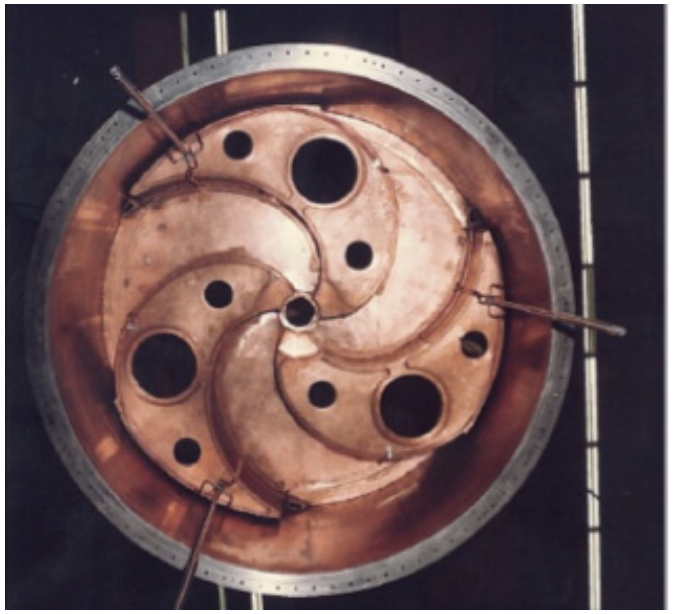



Verified:

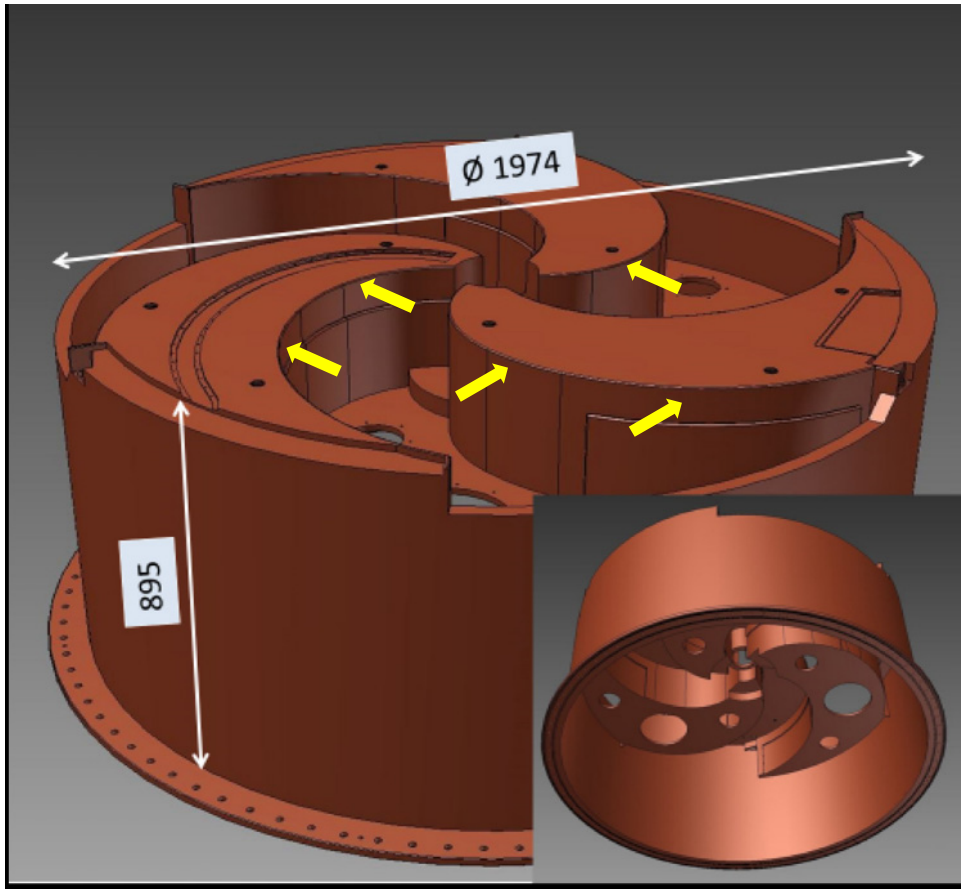
- Bandwidth
- Field distribution
- Including the main ceramic area
- Impedance
- Coupler
- Liner

**Another important modification**, to increase the vertical gap in the acceleration chamber, **is related to the liner**. The modification of the present one is not possible and a **new LINER has been redesigned**. We are confident, using modern construction techniques, of reducing the present 14 mm thickness of 3 mm and of greatly minimizing the welding points too, in order to prevent **leaks in the acceleration vacuum chamber**





The current vacuum LINER level of 1 mbar with a pumping system of 300 $m^3/h$ is nowhere near the value of $10^{-1}$ mbar with a pumping system of 30 $m^3/h$, of only 4-5 years ago.



The table below, from RF point of view, means a new optimization of the amplifier parameter to increase the power up to 40-50 kW. Some preliminary tests are in progress and we are confident to adopt soon the proper modifications to increase the final power.

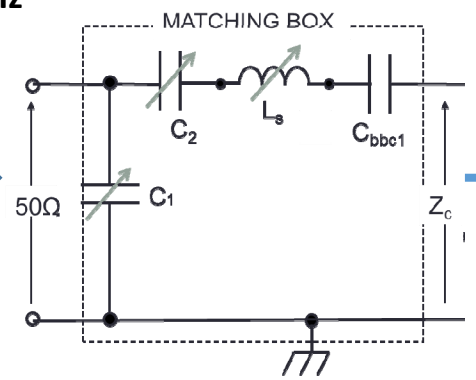
| Ion | Energy | RF Frequency | $V_{RF}$ | I extracted | I extracted | P extracted |
|---|---|---|---|---|---|---|
| | AMeV | **MHz** | **KV** | emA | pps | watt |
| $^{12}C^{4+}$ | 18 | **22.9** | **30** | 90 (6+) | $9.4 \cdot 10^{13}$ | 3240 |
| $^{12}C^{4+}$ | 30 | **27.5** | **42** | 90 (6+) | $9.4 \cdot 10^{13}$ | 5400 |
| $^{12}C^{4+}$ | 45 | **33.74** | **63** | 90 (6+) | $9.4 \cdot 10^{13}$ | 8100 |
| $^{12}C^{4+}$ | 60 | **38.34** | **82** | 90 (6+) | $9.4 \cdot 10^{13}$ | 10800 |
| | | | | | | |
| $^{18}O^{6+}$ | 20 | **22.9** | **30** | 80 (8+) | $6.2 \cdot 10^{13}$ | 3600 |
| $^{18}O^{6+}$ | 29 | **27.5** | **42** | 80 ($8^{+}$) | $6.2 \cdot 10^{13}$ | 5220 |
| $^{18}O^{6+}$ | 45 | **33.74** | **63** | 80 ($8^{+}$) | $6.2 \cdot 10^{13}$ | 8100 |
| $^{18}O^{6+}$ | 60 | **38.34** | **82** | 80 ($8^{+}$) | $6.2 \cdot 10^{13}$ | 10800 |
| $^{18}O^{7+}$ | 70 | **41.1** | **81** | 34.3 (8+) | $2.7 \cdot 10^{13}$ | 5400 |
| | | | | | | |
| $^{20}Ne^{4+}$ | 15 | **20.1** | **37** | 223 (10+) | $1.4 \cdot 10^{14}$ | 6690 |
| $^{20}Ne^{7+}$ | 28 | **27.5** | **40** | 85.7 ($10^{+}$) | $5.3 \cdot 10^{13}$ | 4800 |
| $^{20}Ne^{7+}$ | 60 | **38.34** | **78** | 85.7 ($10^{+}$) | $5.3 \cdot 10^{13}$ | 10280 |

An important **refurbishment of the main power amplifiers has been completed** recently. The insertion of a **solid state amplifier (SSA) has substituted the obsolete first stage of the full tube RF power amplifier**. All the 3 power amplifiers of the RF system are equipped with this solid state driver configuration plus a matching box to adapt the standard 50 Ω output of the 1st SSA stage with the final stage of the tube amplifier

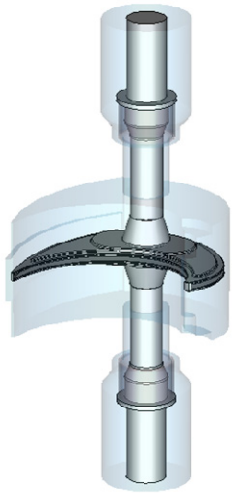

**LDMOS Transistor**
**>1 kW, 2-600 MHz**

$RF_{in}$

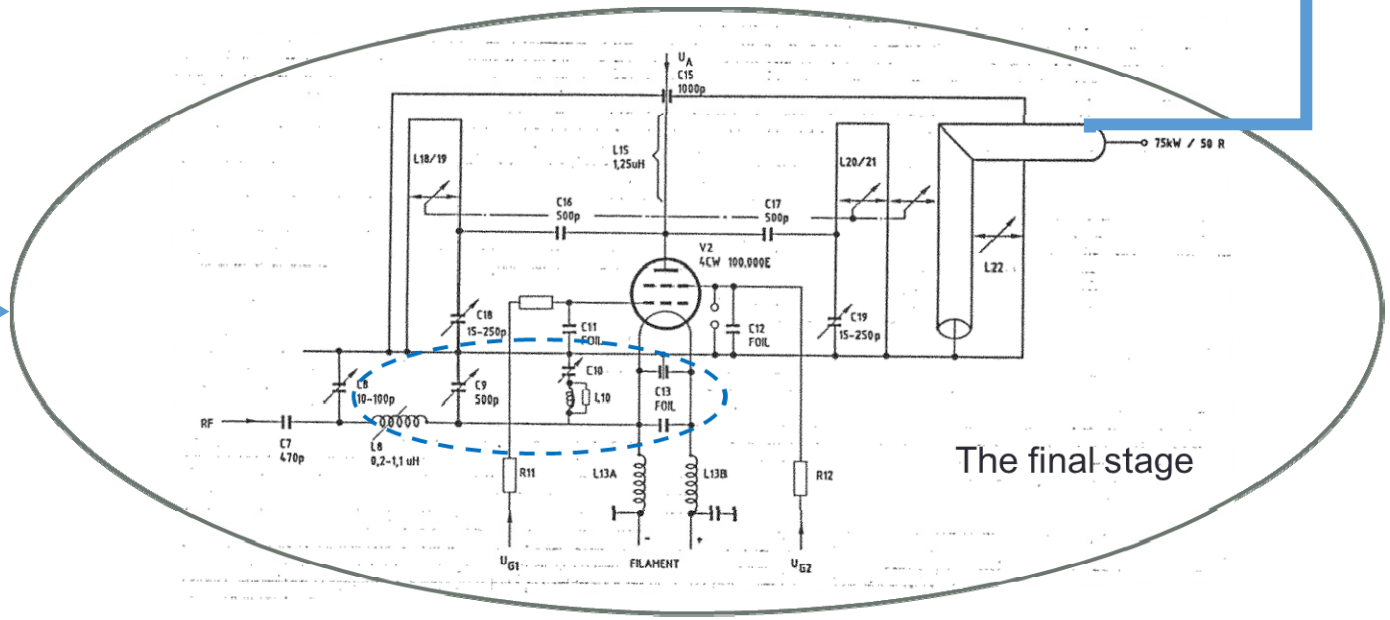
50Ω



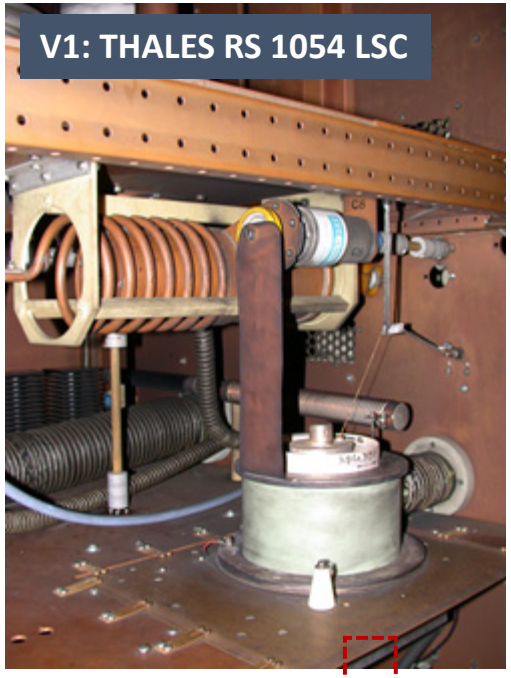

Cyclotron cavity

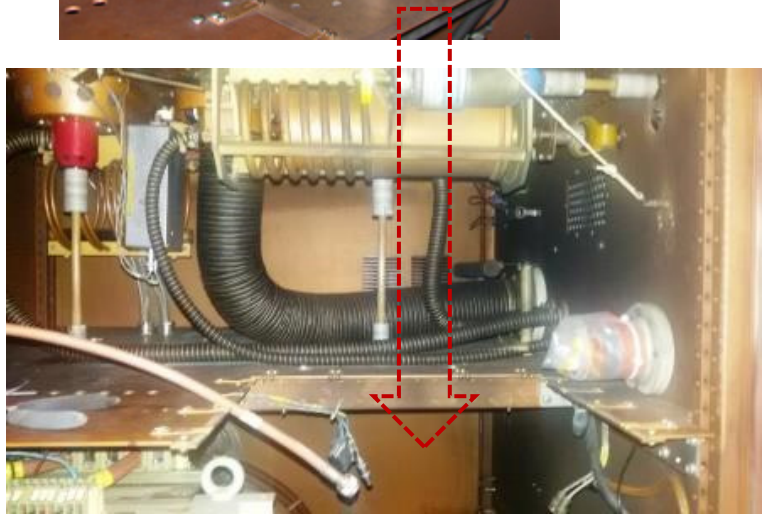


$Z_{in} = R \pm jX$



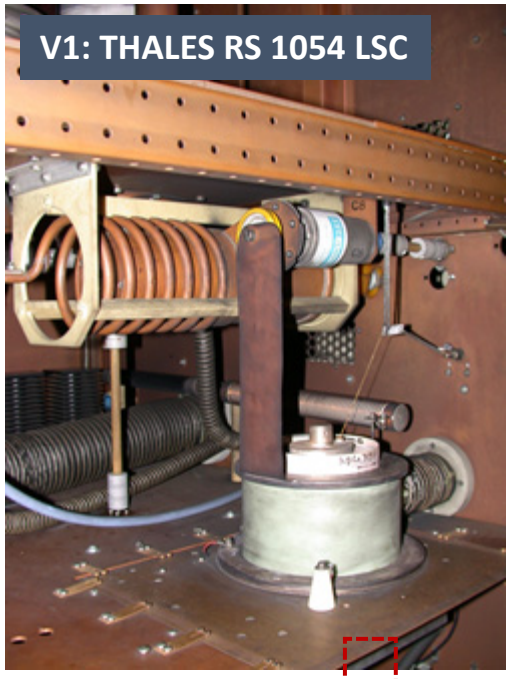
## V1: THALES RS 1054 LSC

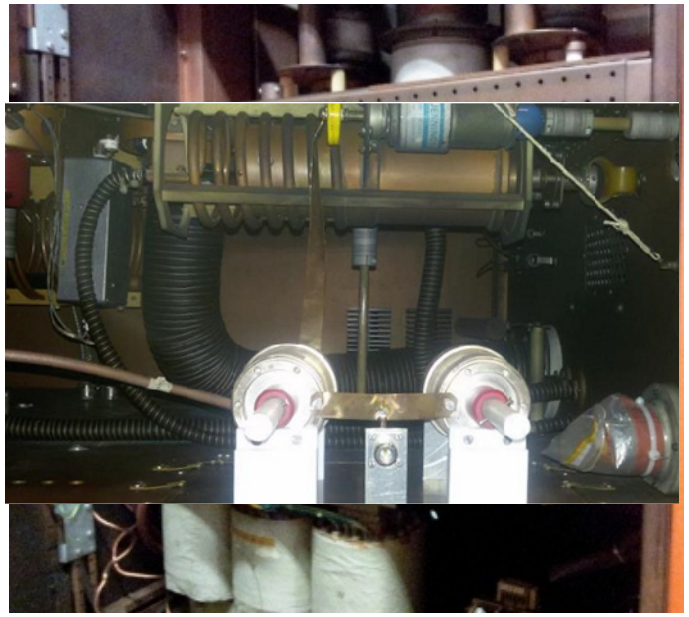


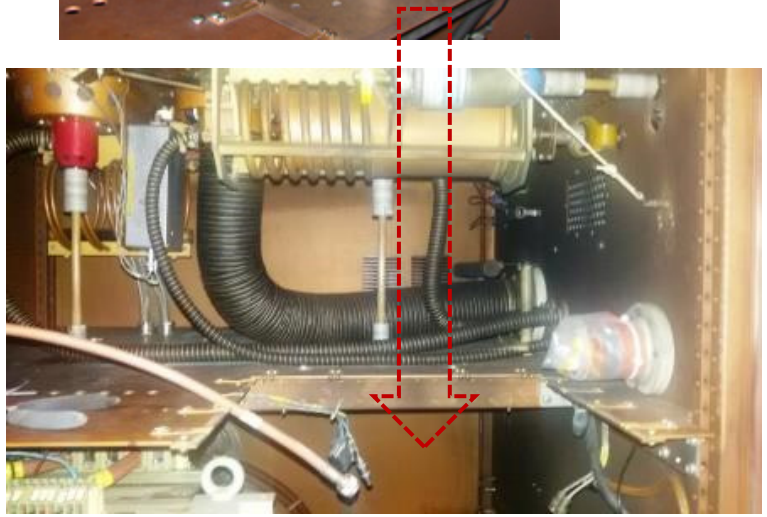


The matching box already installed instead of the 1st stage RS1054LSC in all the 3 amplifiers

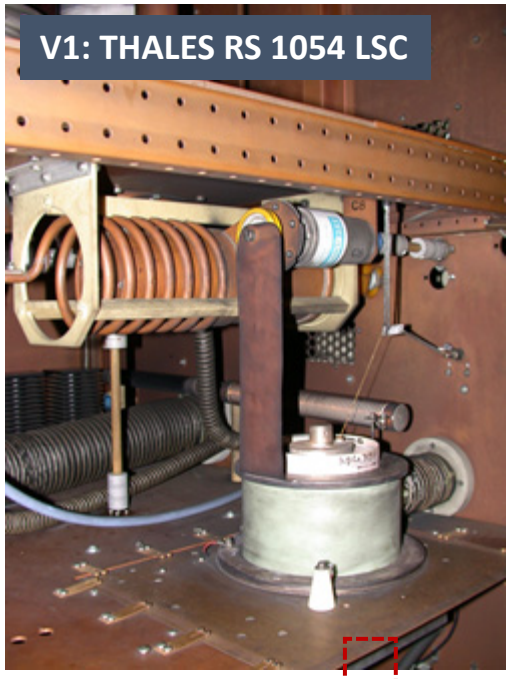
## V1: THALES RS 1054 LSC

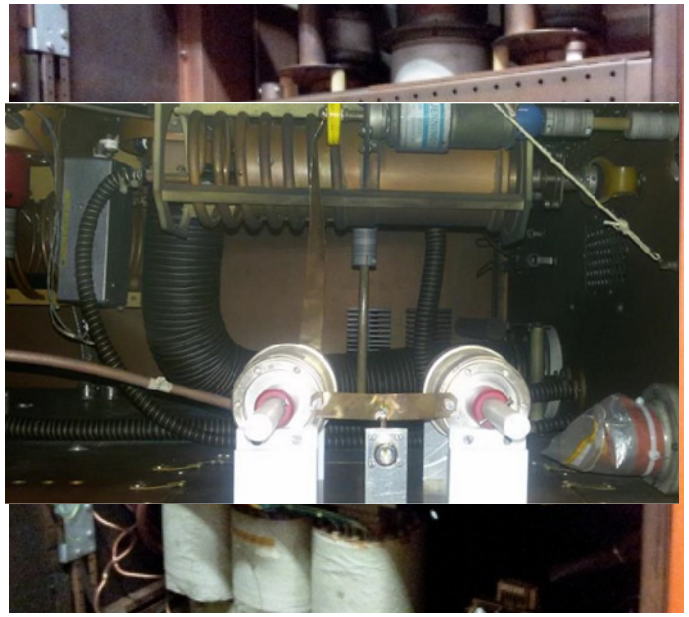


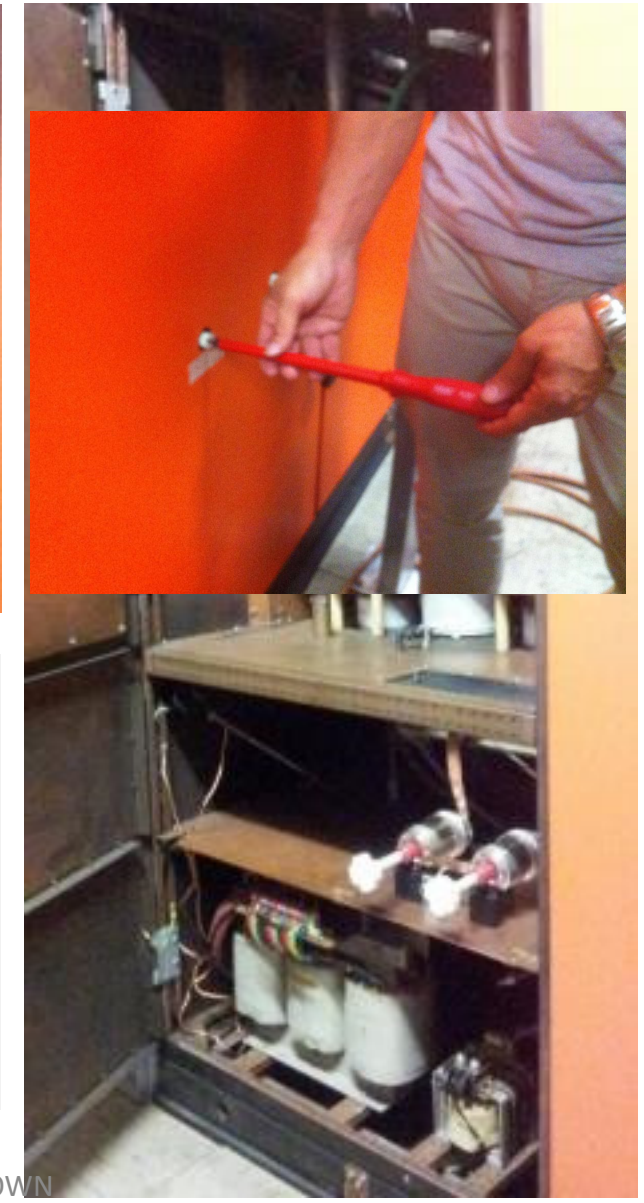


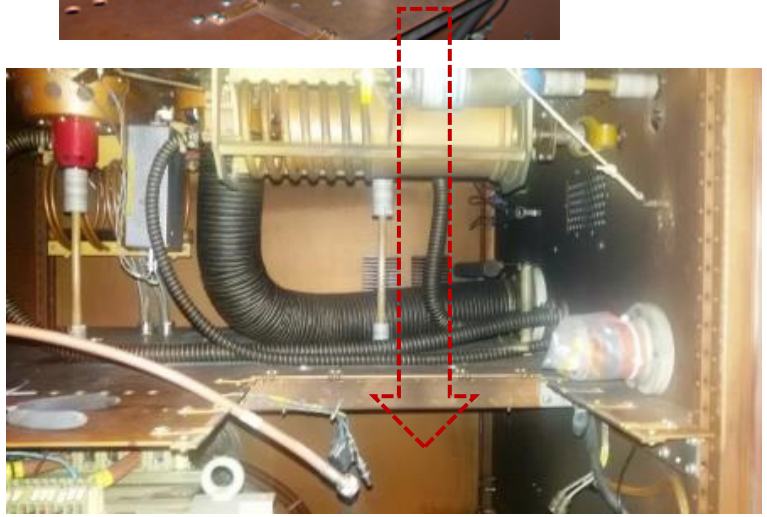


The matching box already installed instead of the 1st stage RS1054LSC in all the 3 amplifiers

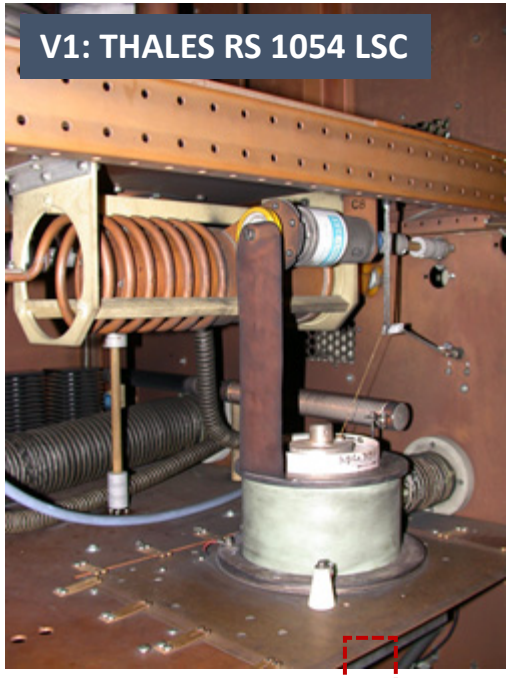


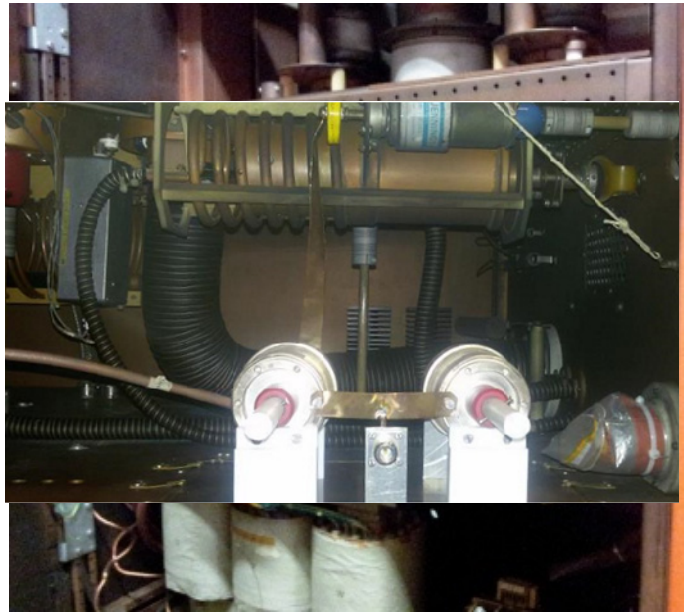



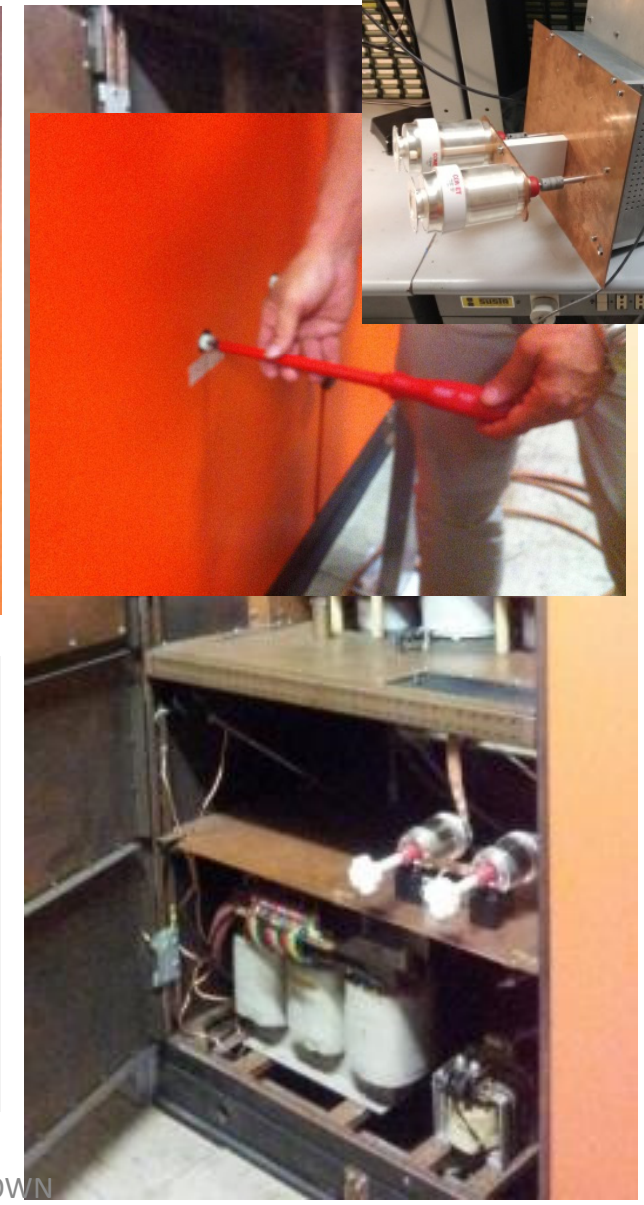


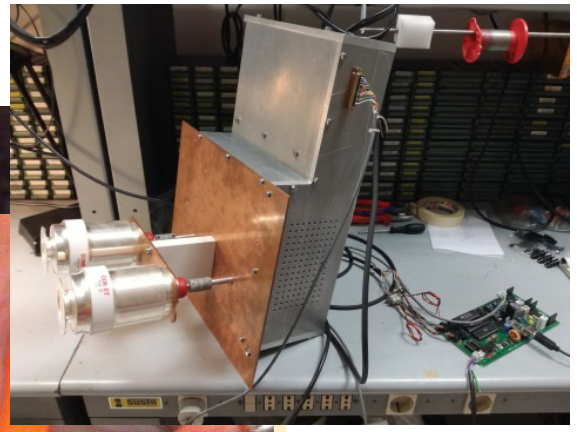


The matching box already installed instead of the 1st stage RS1054LSC in all the 3 amplifiers

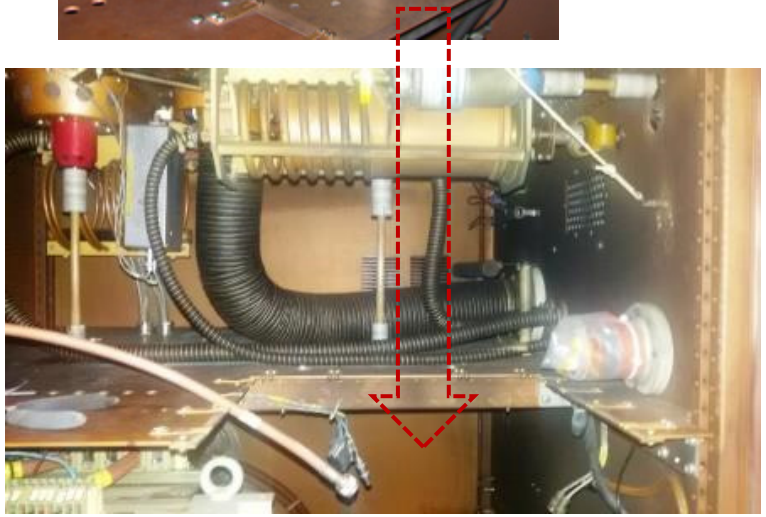






An automatic matching box, to adapt the impedance between the 1st and 2nd stage of the amplifier is ready on the test bench.



The matching box already installed instead of the 1st stage RS1054LSC in all the 3 amplifiers

The LLRF is following the same refurbishment and upgrade trend [11]. The migration from the platform Visual Basic to LabView is on the way, the complete substitution of old and obsolete part of the hardware is in progress, a new automatic tool of phase and amplitude adjustment in order to maximize the output beams is under developing

# CONCLUSIONS

The developing of the RF system related to the cyclotron upgrade is already planned and most of the points are on the way. Since the expected time to dismount and to assemble the cyclotron is about 18 months, we expect the restart the RF system and the cyclotron in two years.

# Thank you for your kind attention



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