Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DEL SUD

Sistemi RF per CS e fasci ionici dei LNS

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- Reparto Dispositivi Meccanici, E. Zappalà, Esteban G. Messina

- Giuseppe Torrisi
- Lorenzo Neri

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Talking points

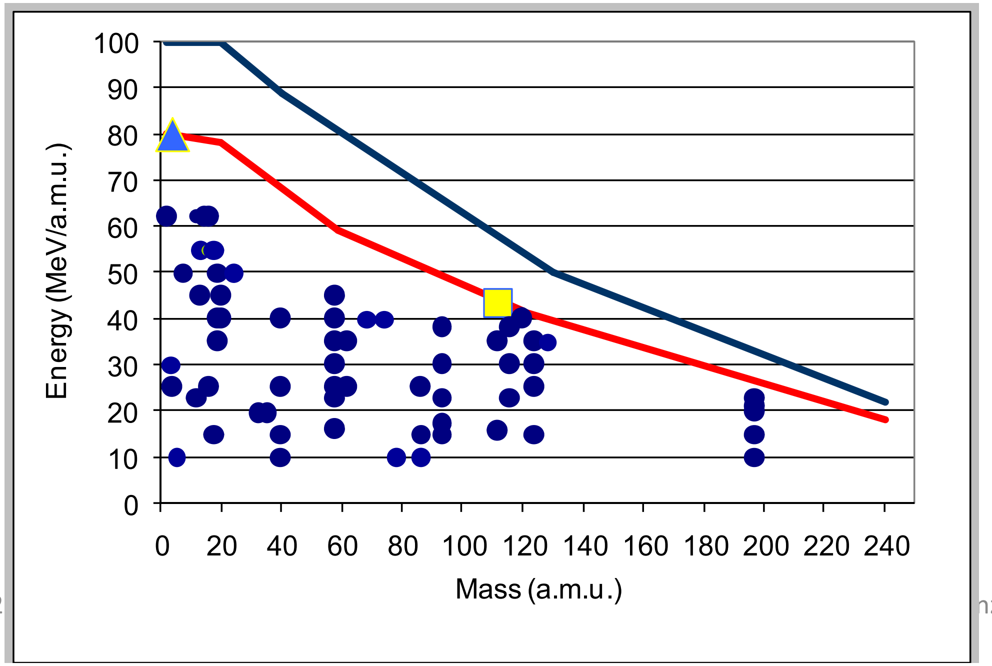
- Panoramica dell’RF superconducting cyclotron, cenni upgrade pot_lns
- Sistemi di pulsaggio
- Collaborazioni
- Strumentazione
- Competenze
- Limiti

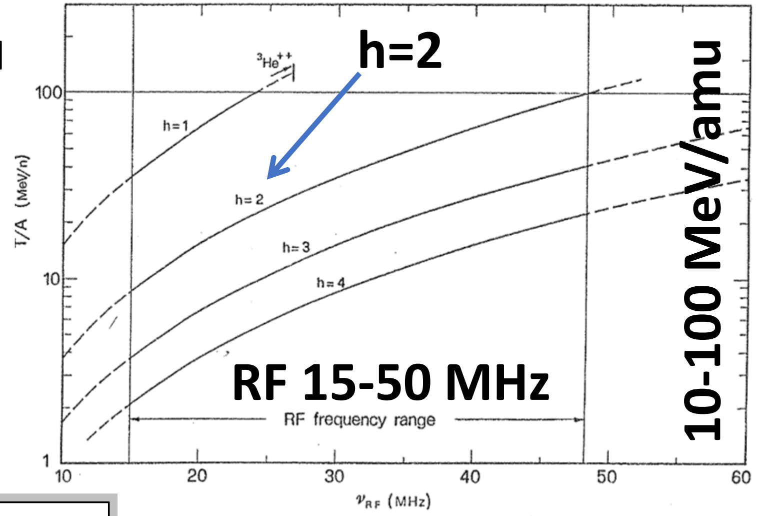
The Superconducting Cyclotron

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**

The introduction of the axial injection (1999) and the consequent new design of the central region geometry has meant the cyclotron operates in constant orbit mode with the harmonic mode of acceleration h=2 only.

Beams developed in the Superconducting Cyclotron





The operative diagram shows the ions energy as a function of the accelerating frequency for the original four harmonic modes.

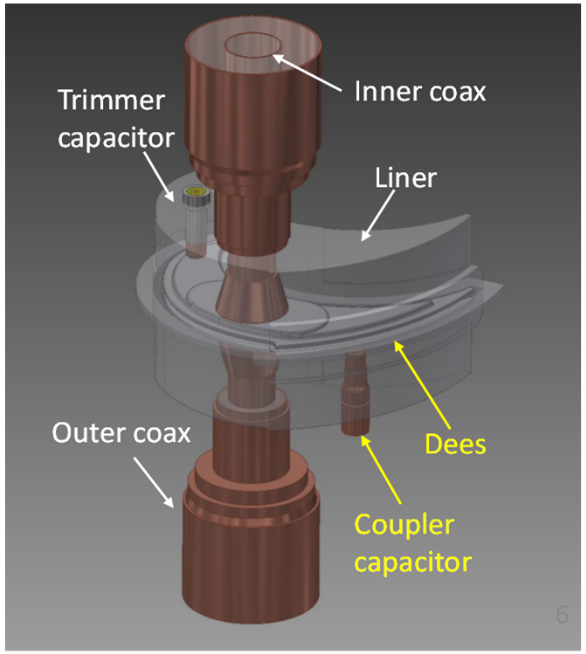
a continuous working in progress…resumed in 3 parts

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.

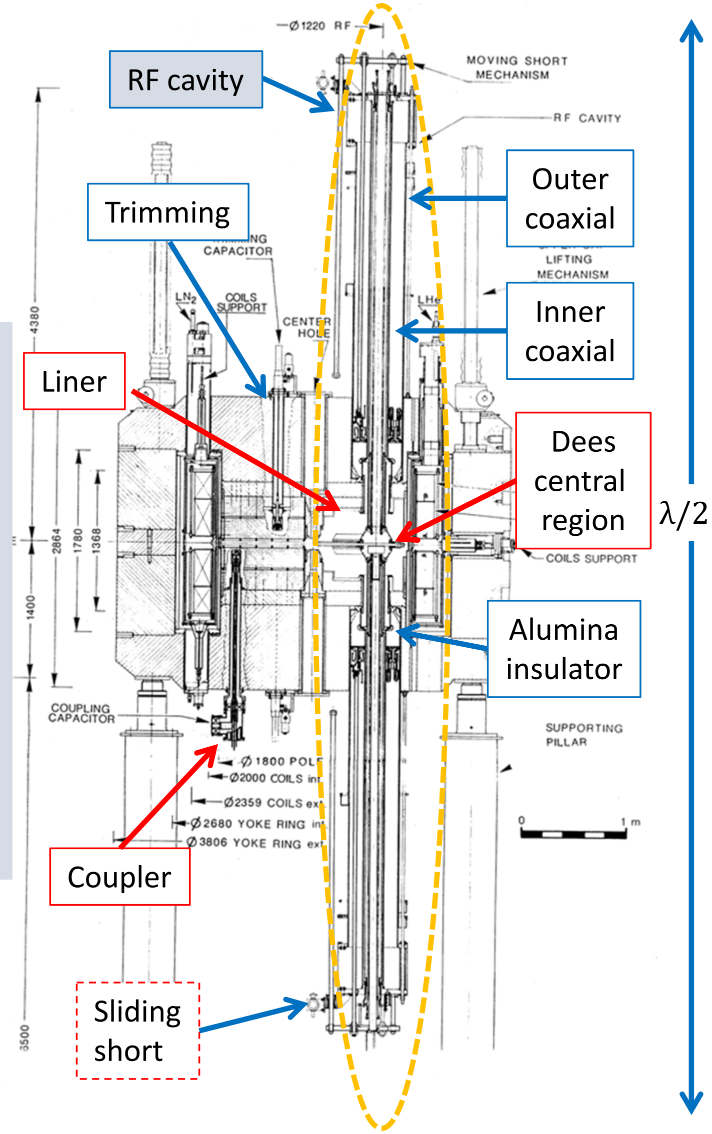
We are used to change, evolving the systems…

Analog to Digital LLRF

SSA – Tube amplifier

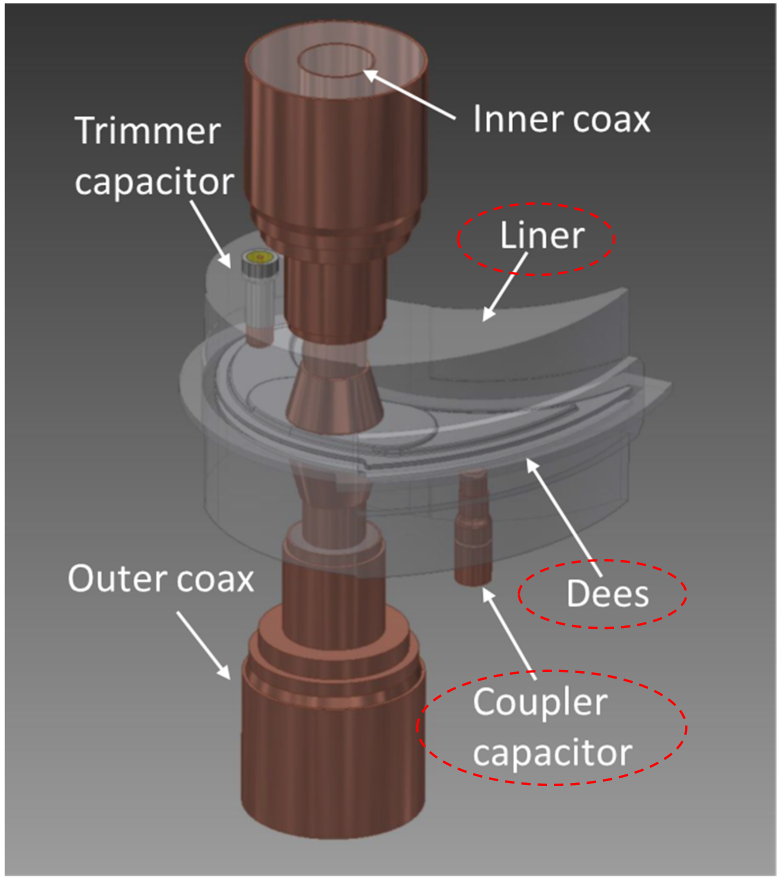


R F - C A V I T Y

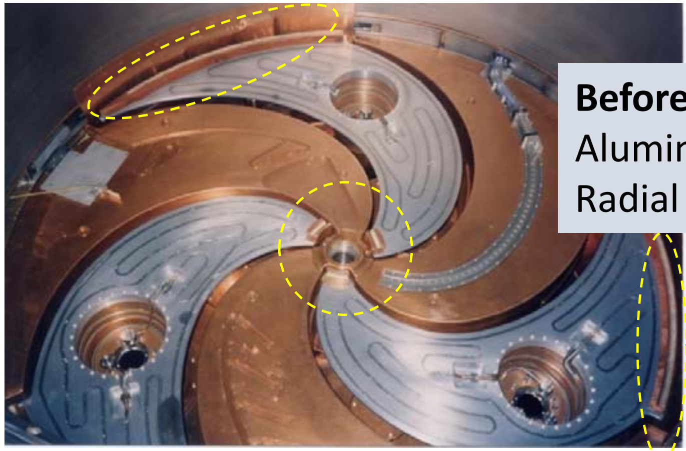


VERTICAL CROSS SECTION OF THE RF CAVITY

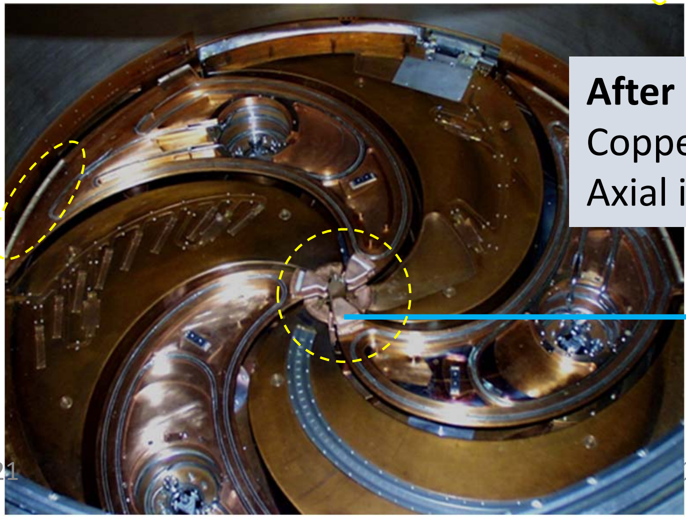
The RF system consists of three symmetrical coaxial resonators. Each resonator is two vertical ¼ λ cylindrical cavities connected at the centre by Dees placed in valleys.



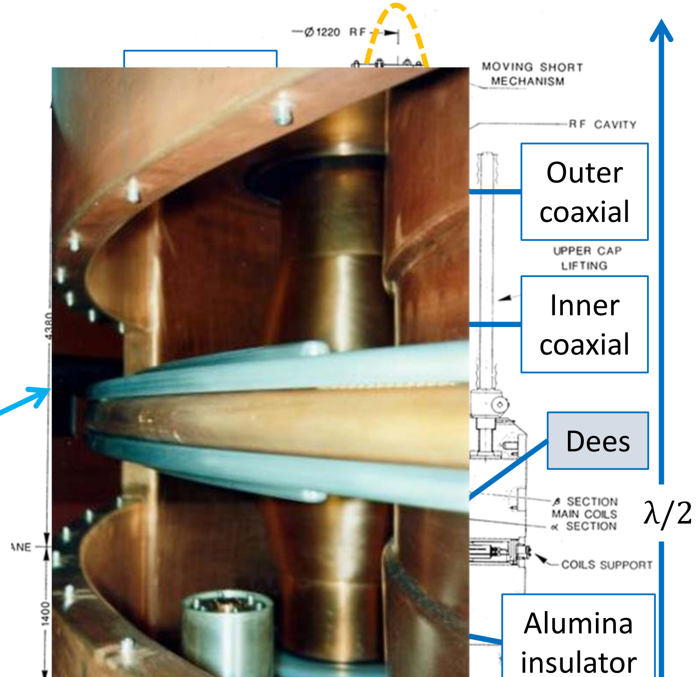
The DEES



Before 2000
Aluminium Dees
Radial injection



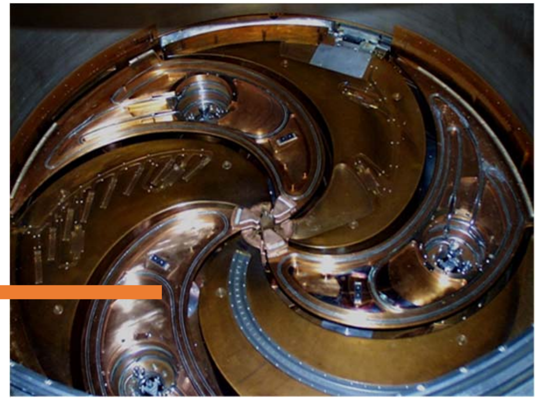
After 2000
Copper Dees
Axial injection

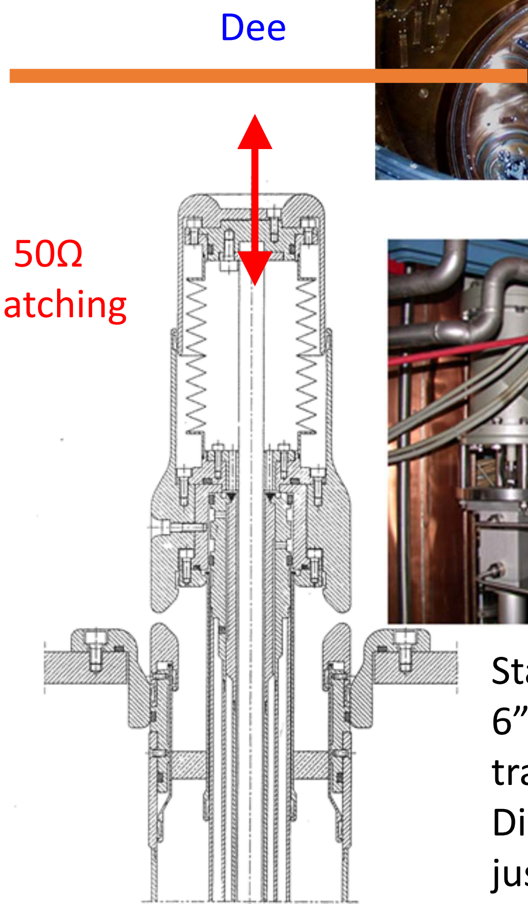


The two half Dees are electrically connected at the extraction and in the central region.

Coupling Capacitor after 1995

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

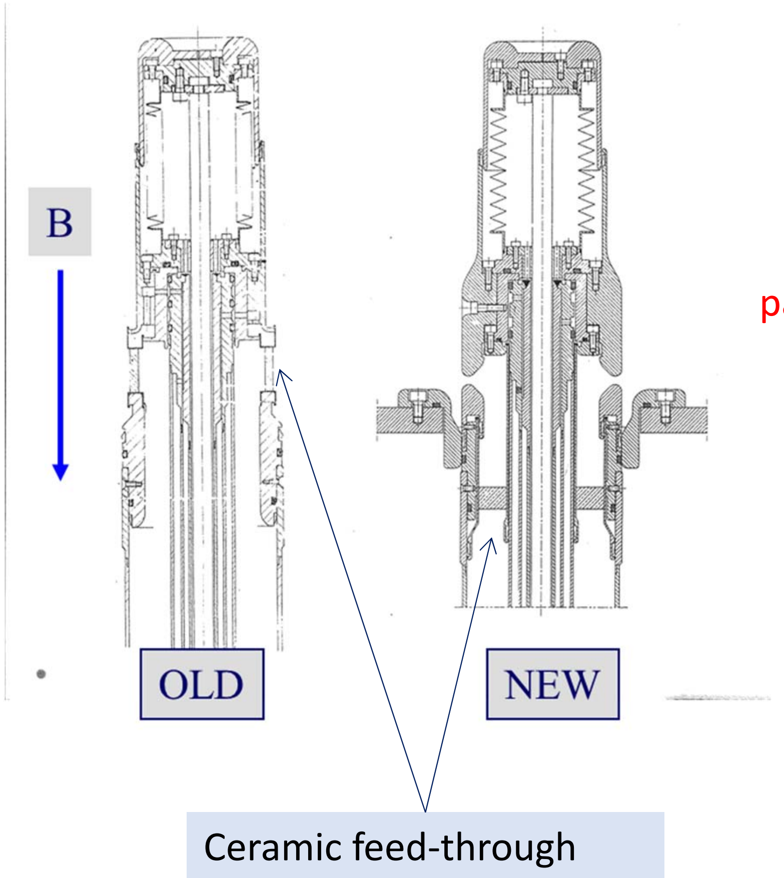




Standard
6”1/8 coaxial rigid
transmission line,
Directional coupler
just before the coupler

Coupler capacitor under the Dee

Something to strongly avoid



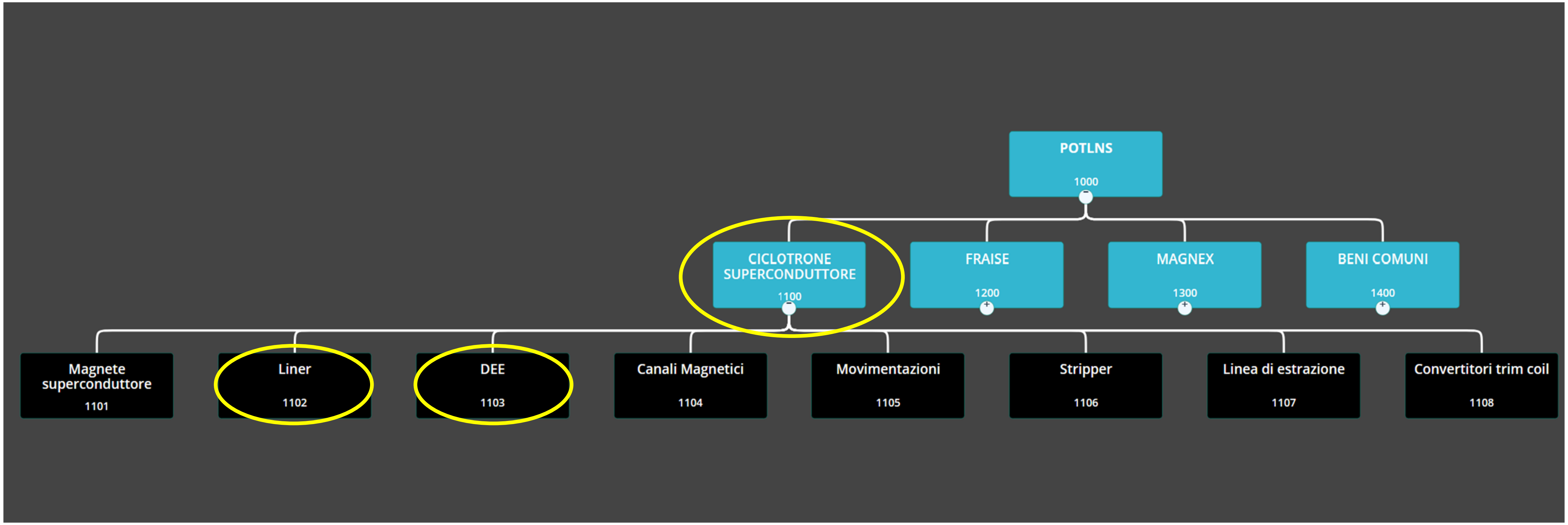
avoid ceramic insulator
parallel to magnetic field

PON Ricerca e Innovazione 2014-2020

Progetto POTLNS - Codice PIR01_00005

Soggetto proponente : Istituto Nazionale di Fisica Nucleare (INFN)

Unità Operativa : Laboratori Nazionali del Sud (LNS)



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

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].

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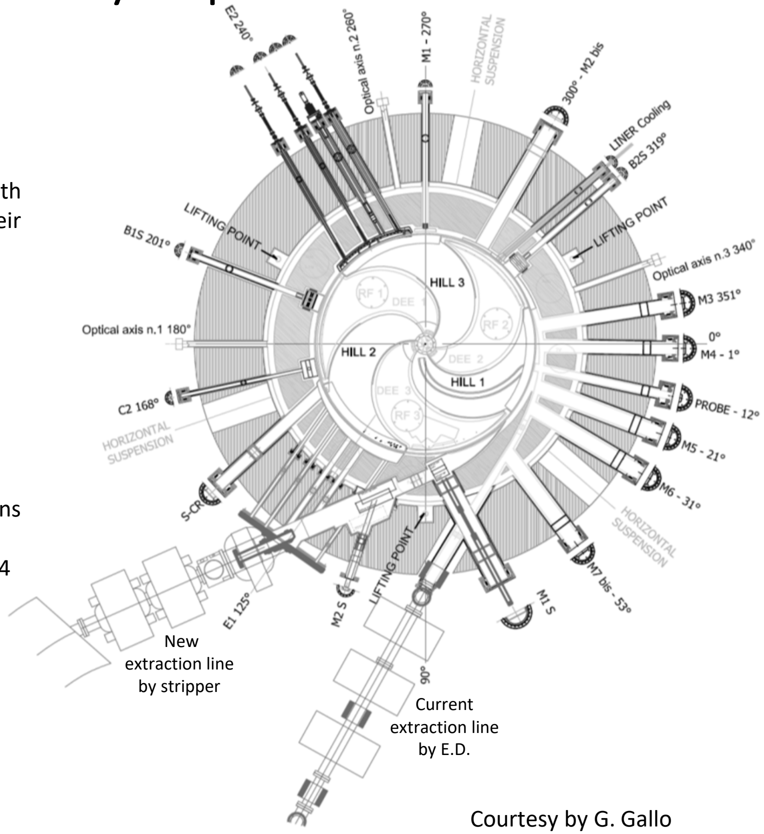
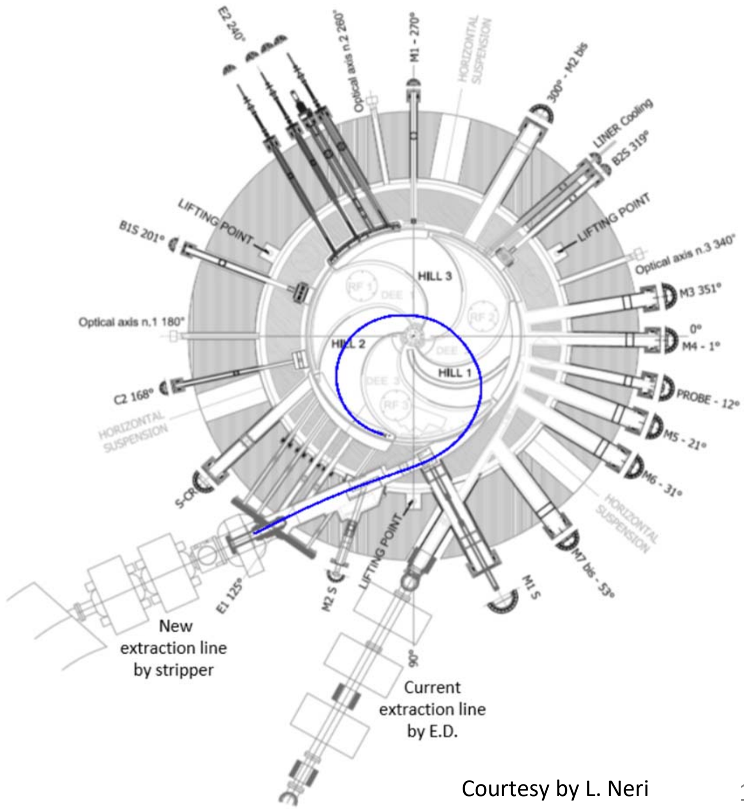
The main difference between the present configuration of the cyclotron and the future upgraded one, is the **introduction of a second extraction technique by stripping**. In this way **the extraction efficiency (>99%) is enough to achieve the high intensity requests.**

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.

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

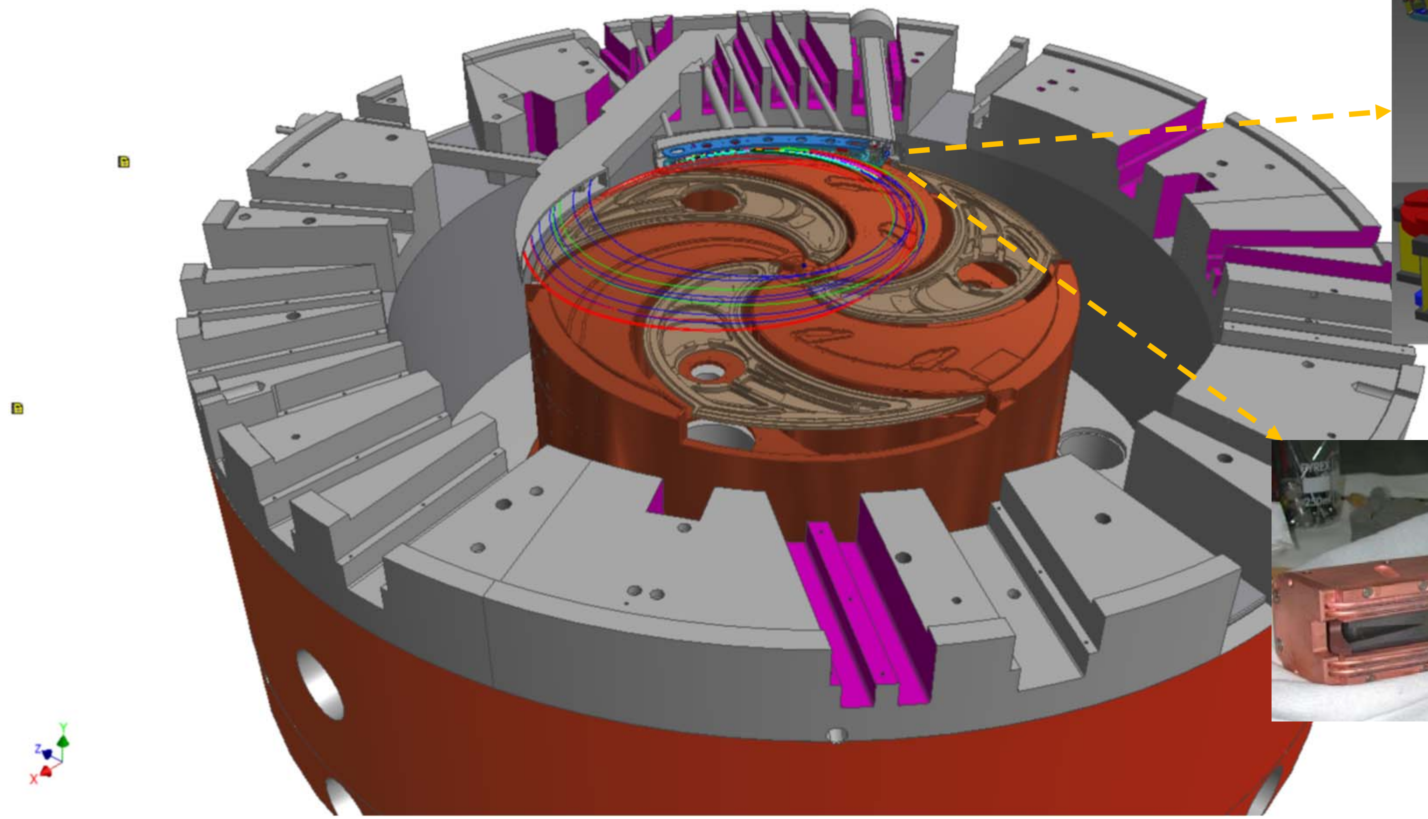


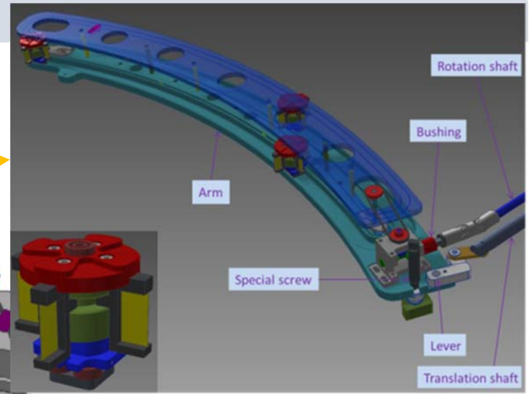
Courtesy by G. Gallo



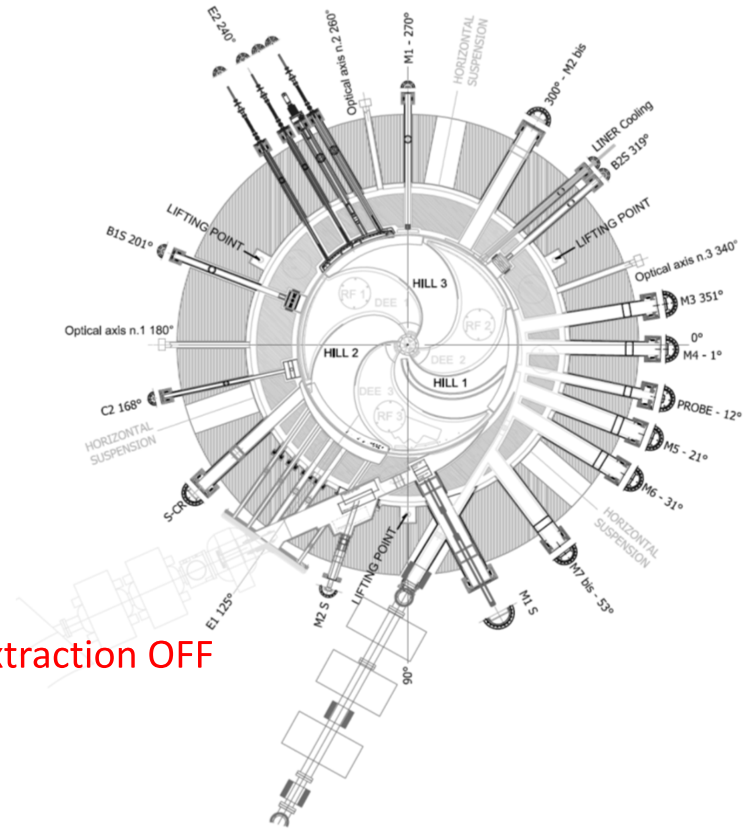
Courtesy by L. Neri

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]





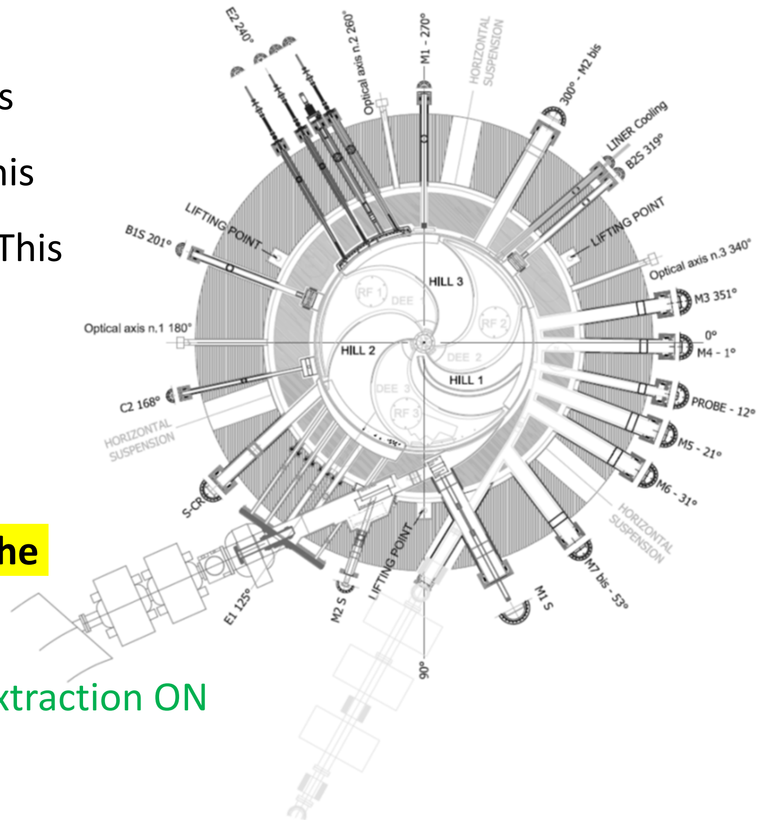
Two different operation mode: stripper and ED



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.**



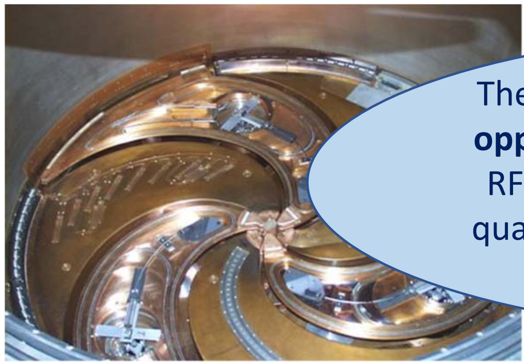
Stripper extraction ON

ED extraction OFF

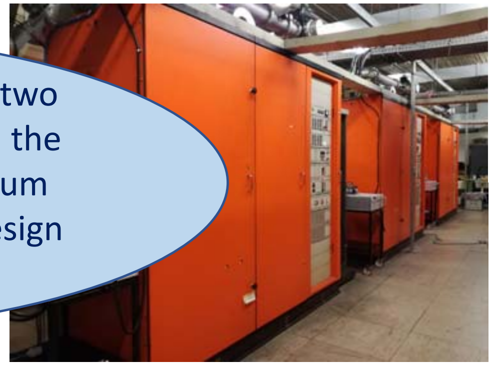
The most important reasons for **changing something in the RF system are mostly related to the power and size of the stripped beam** during the acceleration phase, inside the median plane and subsequently in the extraction channel.

related to the new geometry of the median plane

related to the final dissipated power.



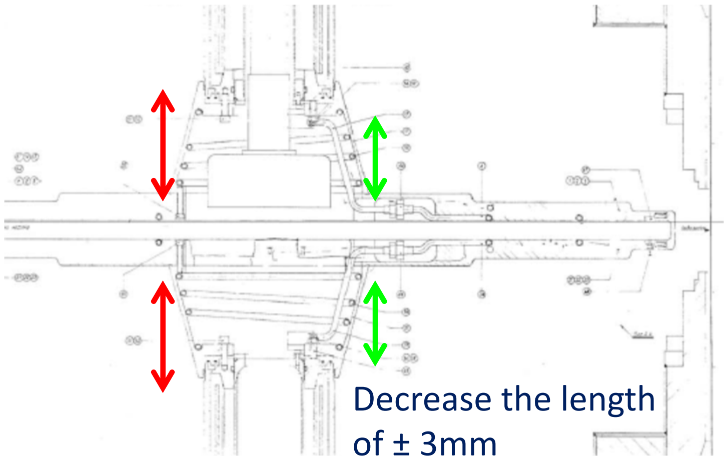
These **two** reasons can also be seen as two **opportunities** to improve and refurbish the RF system in terms of mechanics, vacuum quality improvement, with new liner design and high/low level electronic

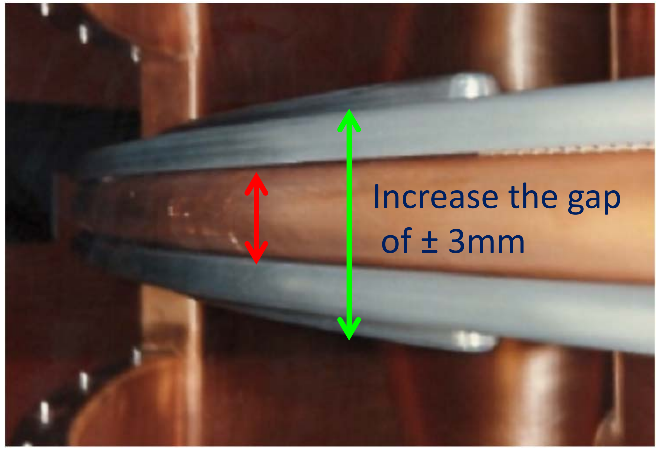


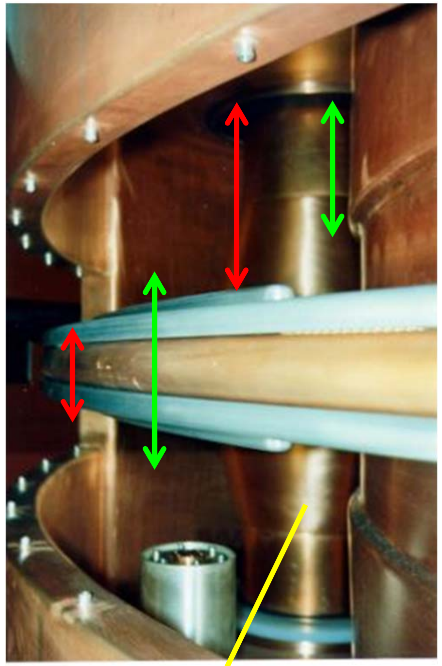
Mechanic modifications

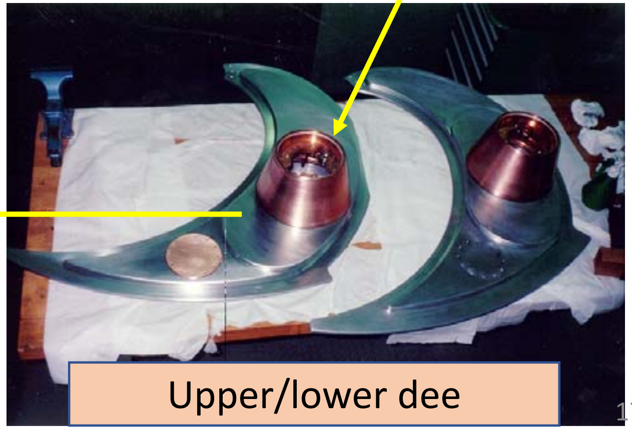
Electronic modifications (LLRF-HLRF)

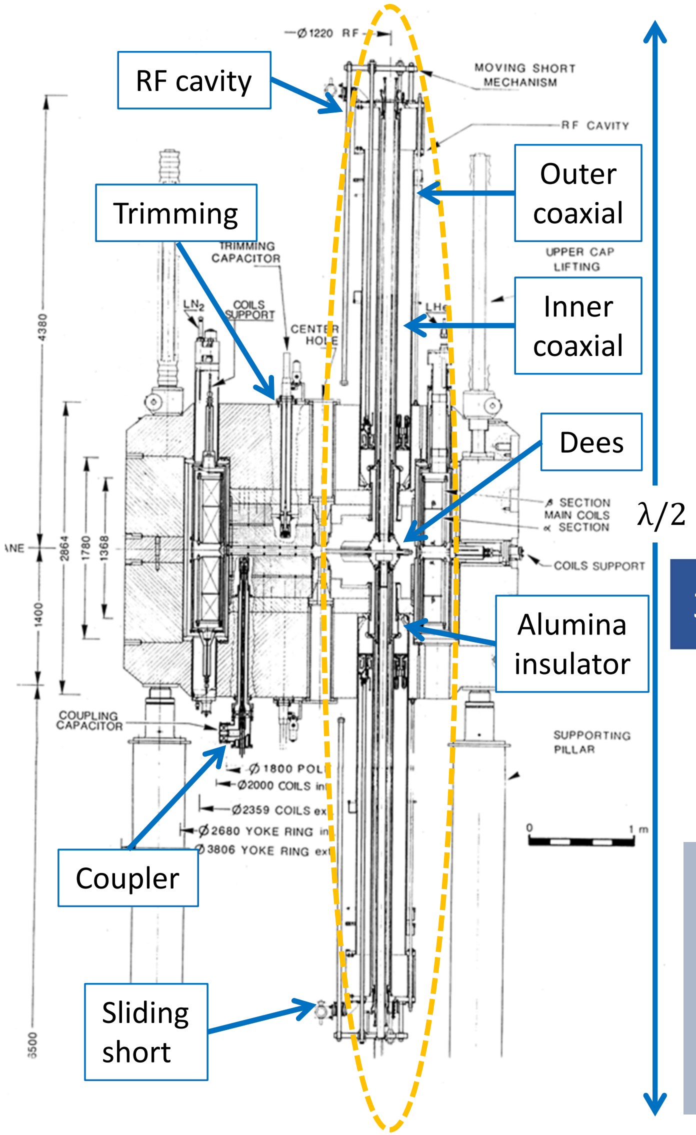
To increase the distance between the acceleration electrodes, from 24 to 30 mm, a reduction of the upper and lower conical connection length between the dees and the inner coaxial of ±3 mm has to be made.





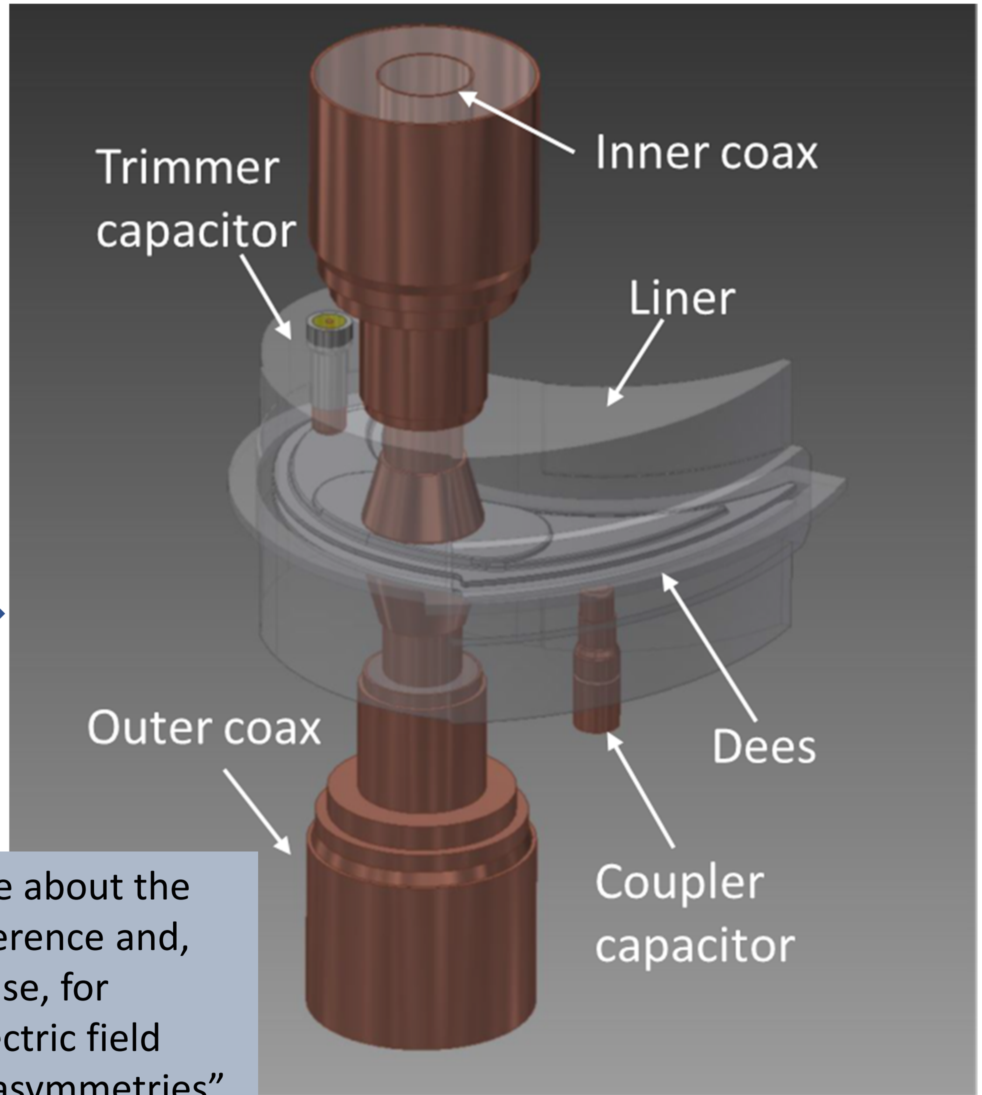






VERTICAL CROSS SECTION OF THE CAVITY

3D model

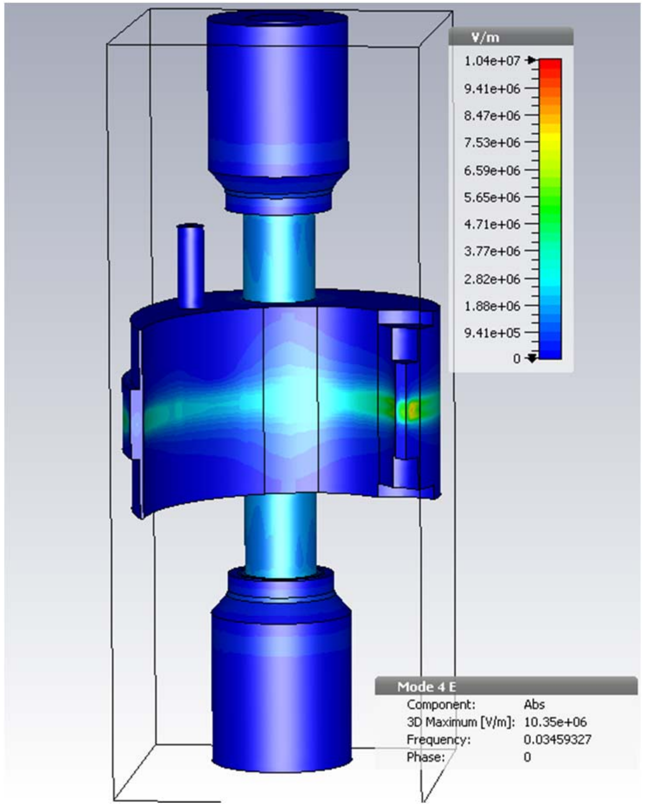


3D MODEL OF THE CAVITY

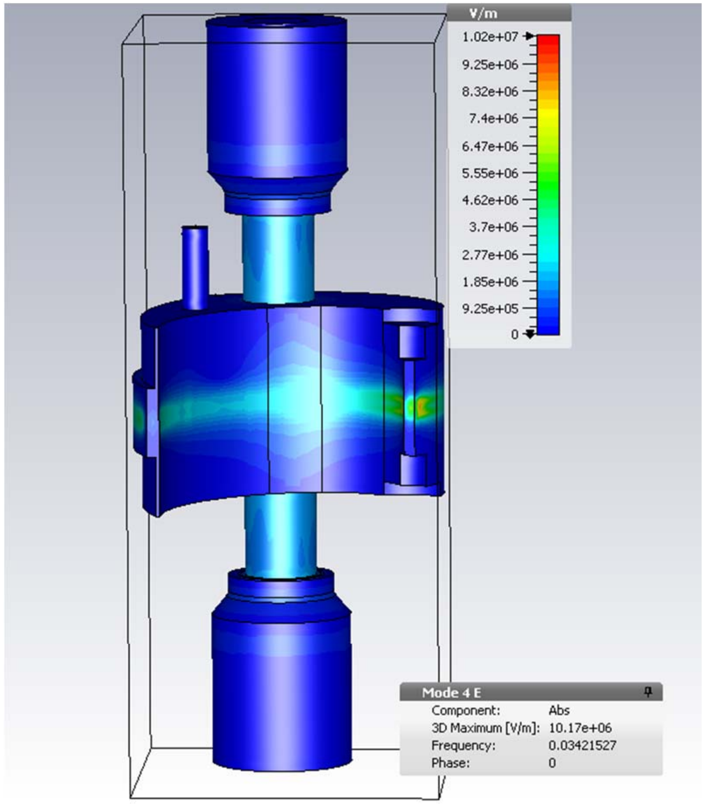
To investigate about the upgrade difference and, something else, for example "electric field distribution asymmetries"

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

gap=0 mm



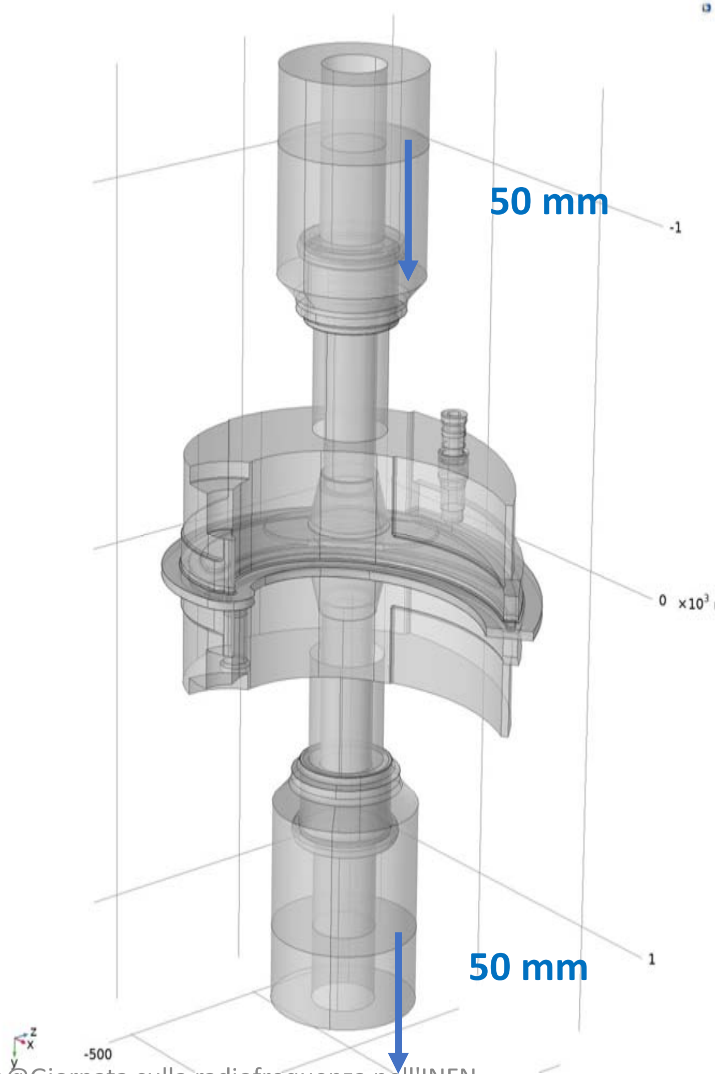
gap=6 mm



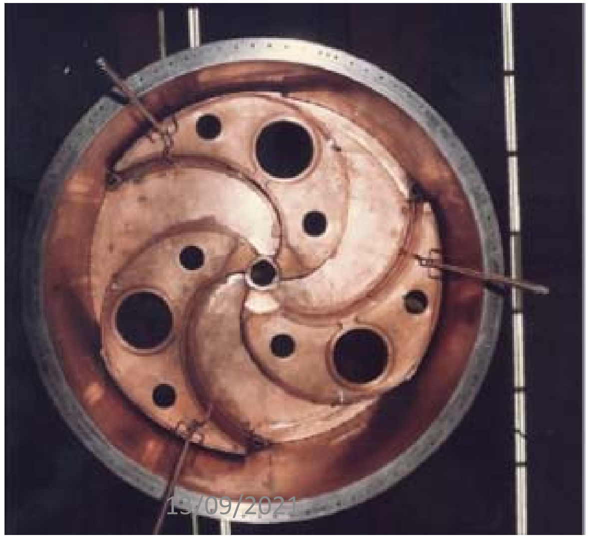
Verified:

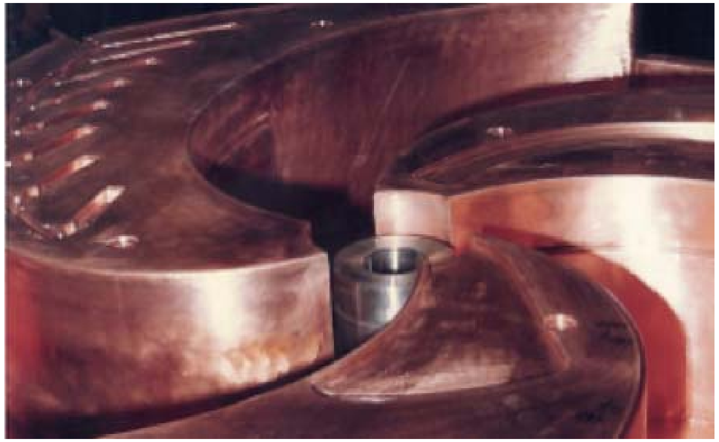
- Bandwidth
- Field distribution
- Including the main ceramic area
- Impedance
- Coupler
- Liner

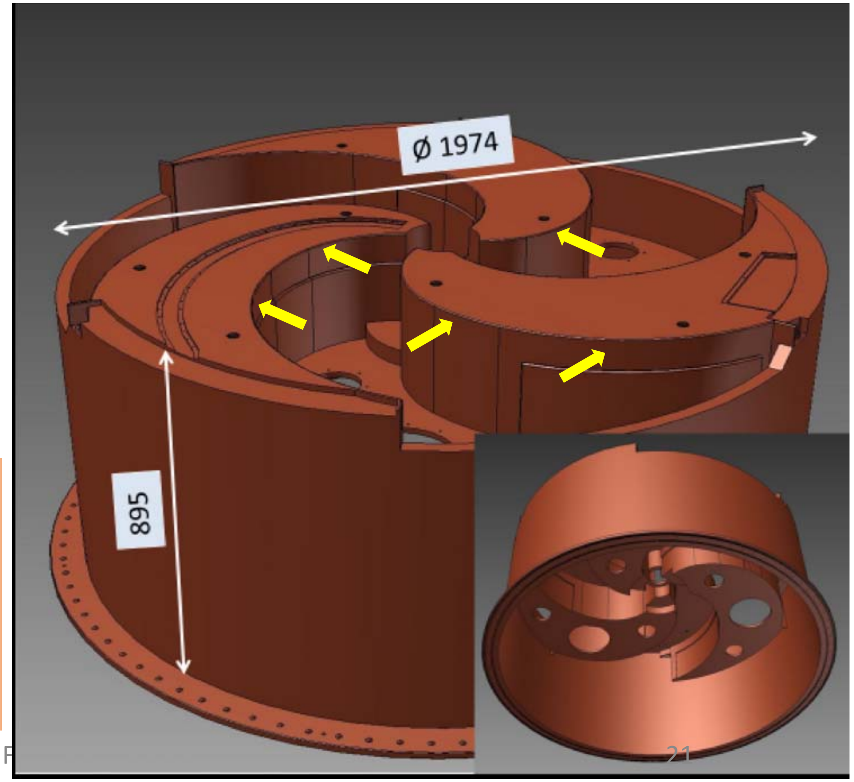
50 mm sliding shorts asymmetry



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**





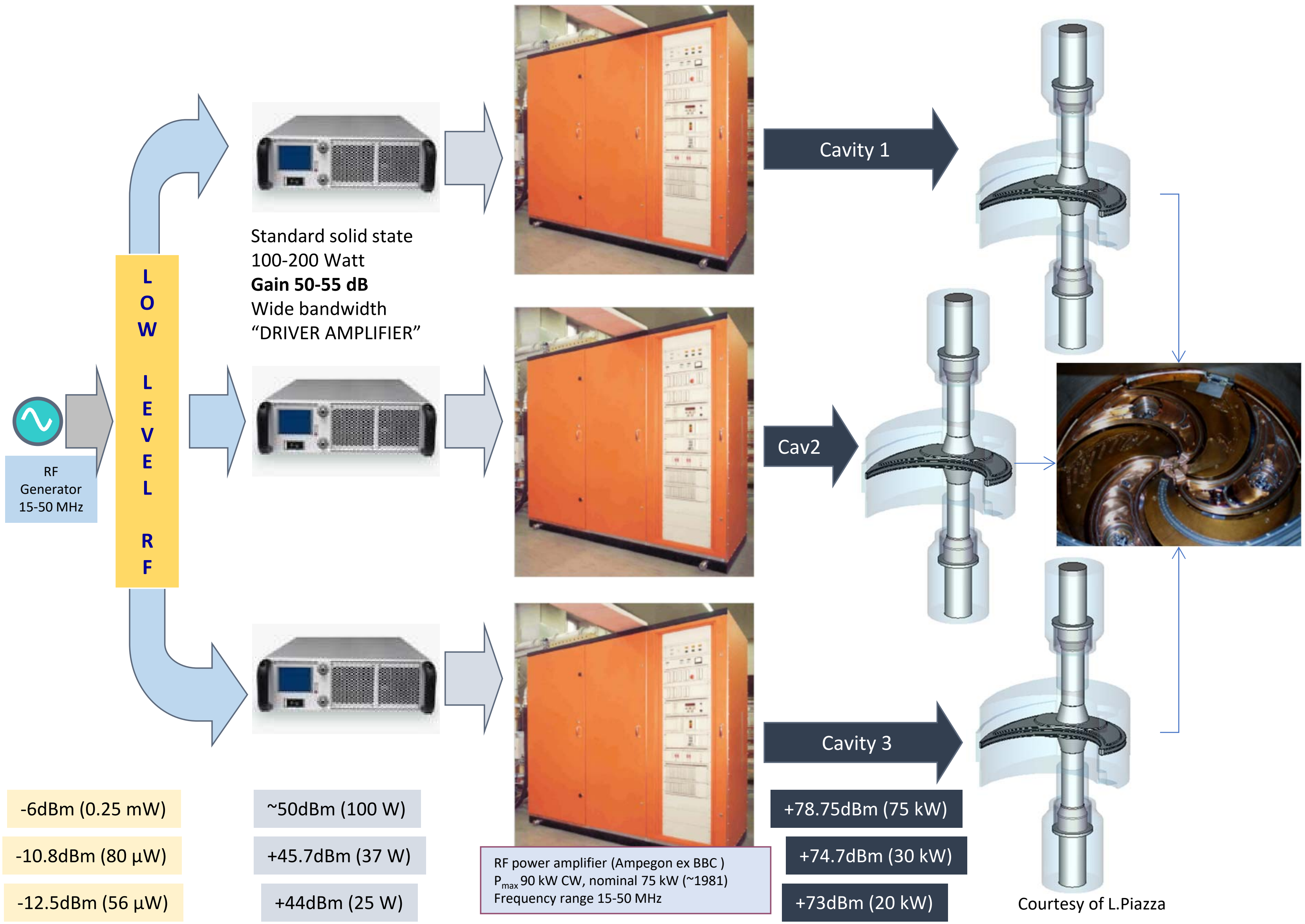


The current vacuum LINER level of 1 mbar with a pumping system of 300 m^3/h is nowhere near the value of 10^{-1} mbar with a pumping system of 30 m^3/h, of only 4-5 years ago.

New stripper extraction technique means more voltage on the dees. Consequently more power from the main RF amplifiers. The table below shows the relation between frequency, dee voltage and related beam.

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+)	$9.4 \bullet 10^{13}$	3240
$^{12}C^{4+}$	30	**27.5**	**42**	90 (6+)	$9.4 \bullet 10^{13}$	5400
$^{12}C^{4+}$	45	**33.74**	**63**	90 (6+)	$9.4 \bullet 10^{13}$	8100
$^{12}C^{4+}$	60	**38.34**	**82**	90 (6+)	$9.4 \bullet 10^{13}$	10800
$^{18}O^{6+}$	20	**22.9**	**30**	80 (8+)	$6.2 \bullet 10^{13}$	3600
$^{18}O^{6+}$	29	**27.5**	**42**	80 (8^{+})	$6.2 \bullet 10^{13}$	5220
$^{18}O^{6+}$	45	**33.74**	**63**	80 (8^{+})	$6.2 \bullet 10^{13}$	8100
$^{18}O^{6+}$	60	**38.34**	**82**	80 (8^{+})	$6.2 \bullet 10^{13}$	10800
$^{18}O^{7+}$	70	**41.1**	**81**	34.3 (8+)	$2.7 \bullet 10^{13}$	5400
$^{20}Ne^{4+}$	15	**20.1**	**37**	223 (10+)	$1.4 \bullet 10^{14}$	6690
$^{20}Ne^{7+}$	28	**27.5**	**40**	85.7 (10^{+})	$5.3 \bullet 10^{13}$	4800
$^{20}Ne^{7+}$	60	**38.34**	**78**	85.7 (10^{+})	$5.3 \bullet 10^{13}$	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

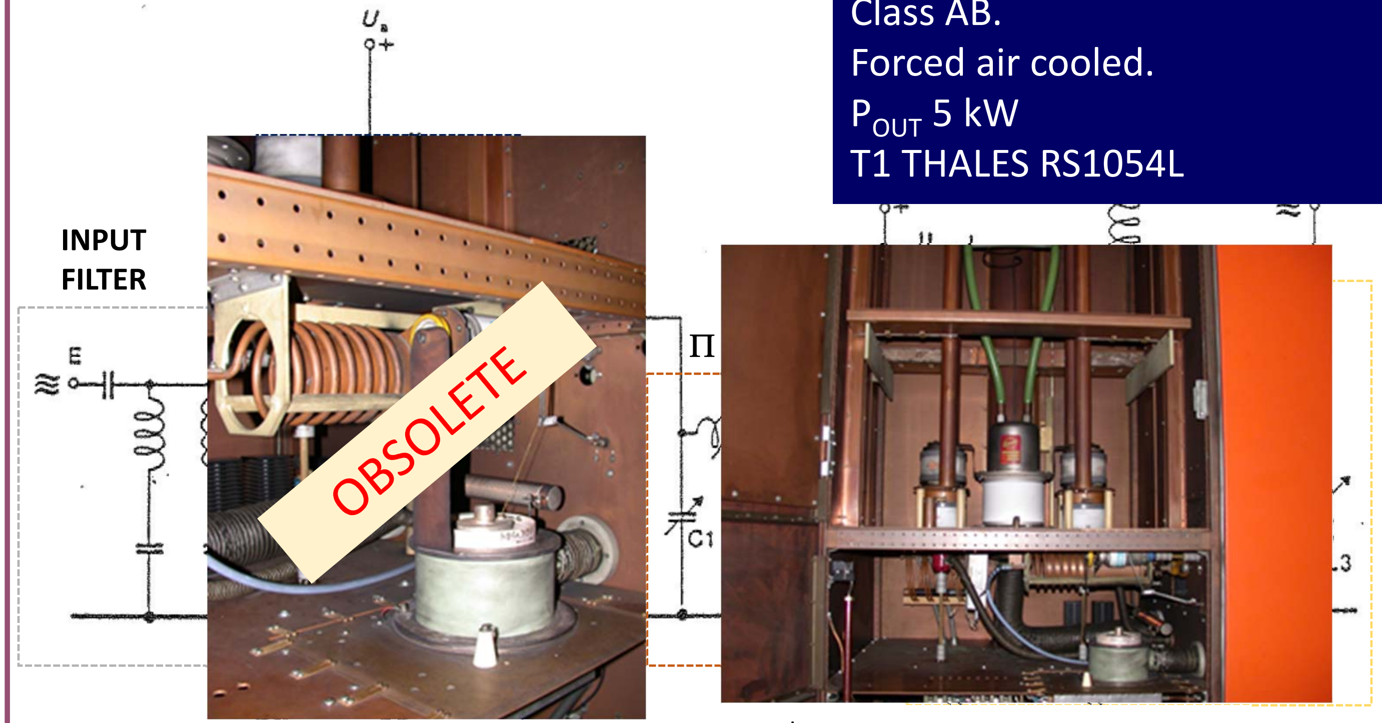

RF
Generator
15-50 MHz
L O W L E V E L R F
Standard solid state
100-200 Watt
Gain 50-55 dB
Wide bandwidth
"DRIVER AMPLIFIER"
Cavity 1
Cav2
Cavity 3
-6dBm (0.25 mW)
-10.8dBm (80 µW)
-12.5dBm (56 µW)
~50dBm (100 W)
+45.7dBm (37 W)
+44dBm (25 W)
RF power amplifier (Ampegon ex BBC)
P_{max} 90 kW CW, nominal 75 kW (~1981)
Frequency range 15-50 MHz
+78.75dBm (75 kW)
+74.7dBm (30 kW)
+73dBm (20 kW)
Courtesy of L.Piazza

Input filter stag
• wide band
• adapts from 2
tetrode and Dr
•The RF power
on the parallel
•No tuning is required

The 2nd stage (T2=4CW100000):
common-grid configuration, high isolation between the in/out sections. Filament input. Water cooled. The load is a ¼ λ cavity plus a capacity.

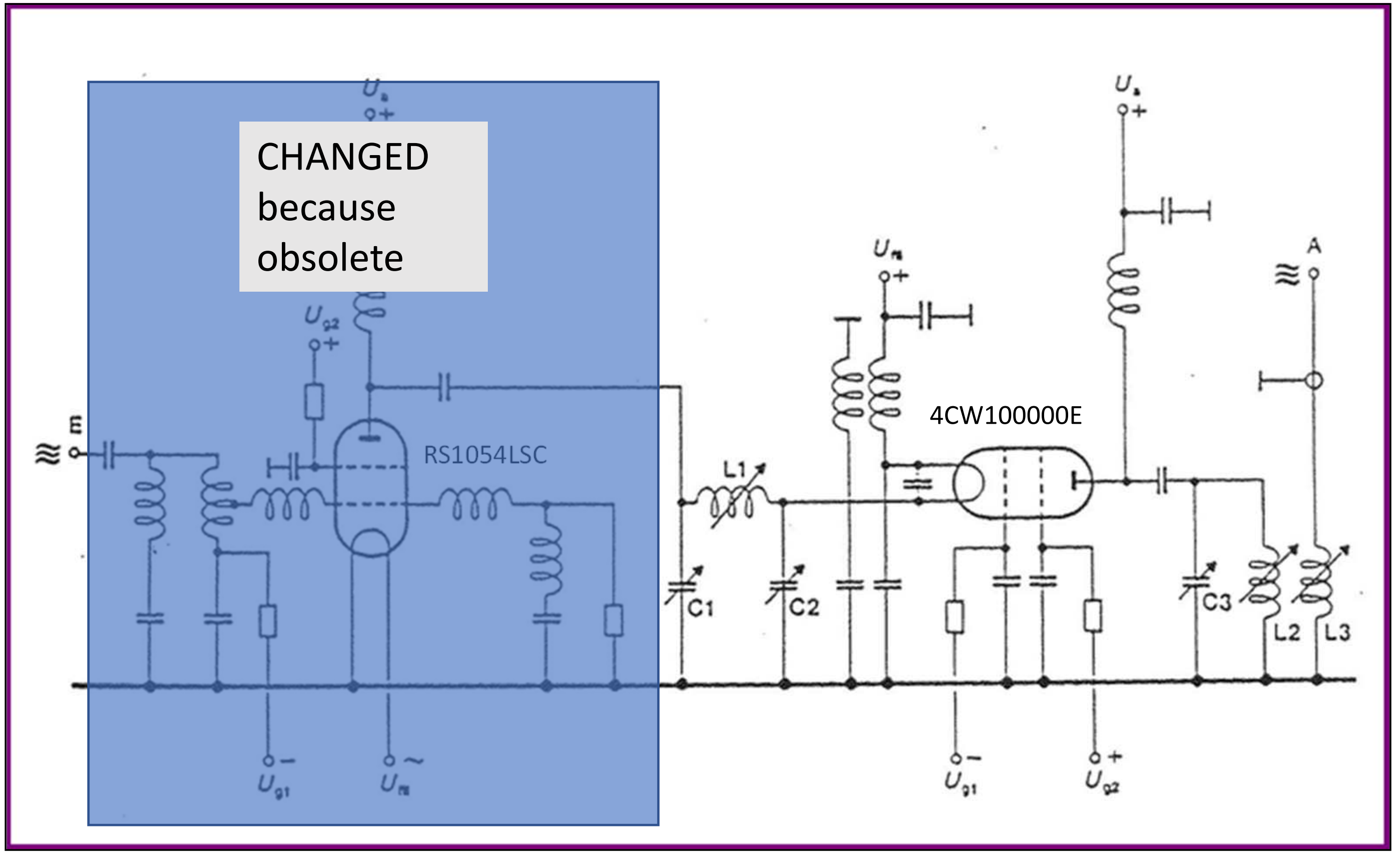
two stages
he 1st stage
npedance of
time. All
ve and

stage is a **ground-cathode**
ration. In general this
ration is very reliable, shows
v technical problems and a
rably low number of
ents.
Grid-control input.
Class AB.
Forced air cooled.
P_{OUT} 5 kW
T1 THALES RS1054L



1st stage (THALES RS1054LSC)

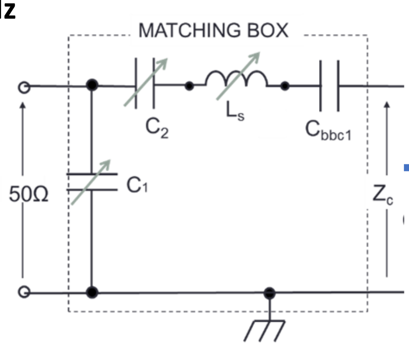
2nd stage (CPI-4CW100000E)


CHANGED
because
obsolete
RS1054LSC
4CW100000E
L1
C1
C2
C3
L2
L3
A

LDMOS Transistor
>1 kW, 2-600 MHz

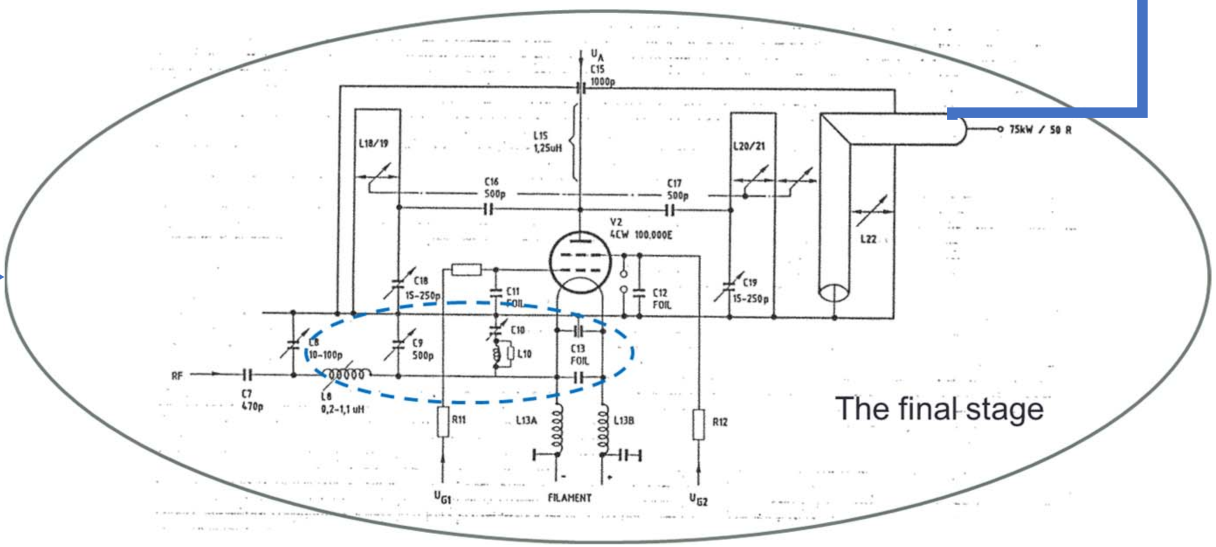
RF_{in}

50Ω

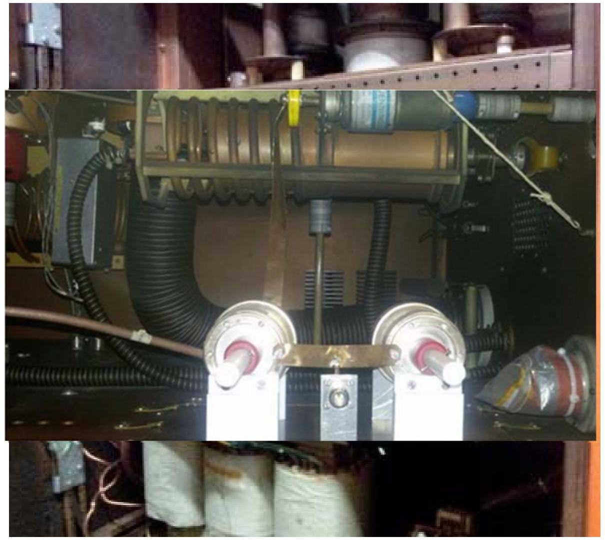


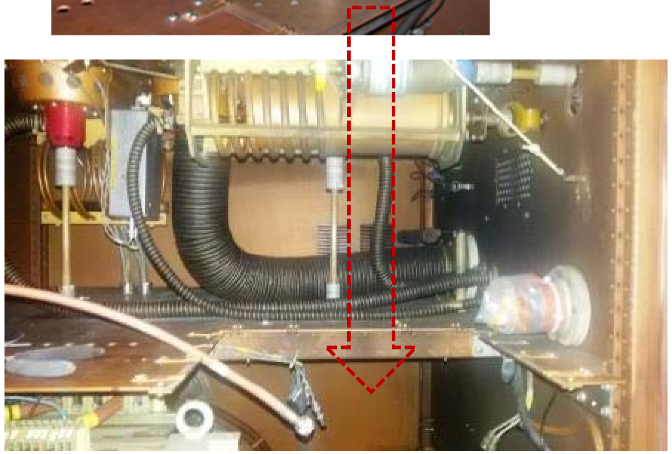
Cyclotron cavity

$$Z_{in} = R \pm jX$$

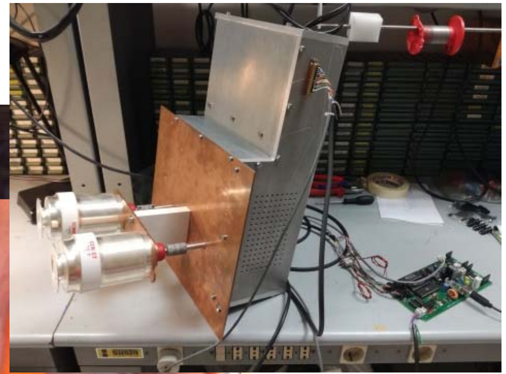


V1: THALES RS 1054 LSC





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



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

A USEFUL TOOL

Directiona
coupler

Power switch

RF amplifier

Dummy load

Nuovi trasformatori di media tensione

The LLRF is following the same refurbishment and upgrade trend. 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

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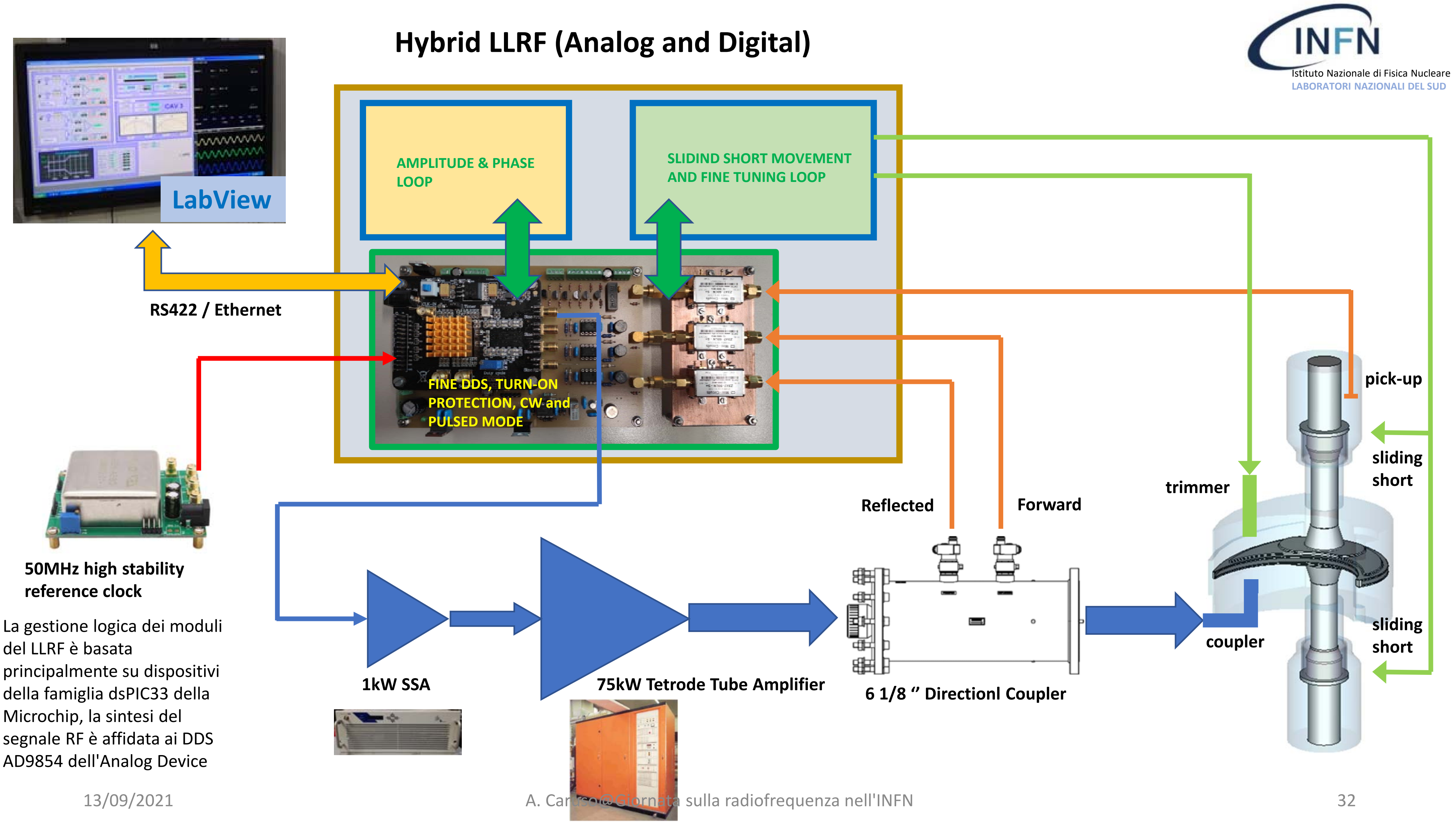
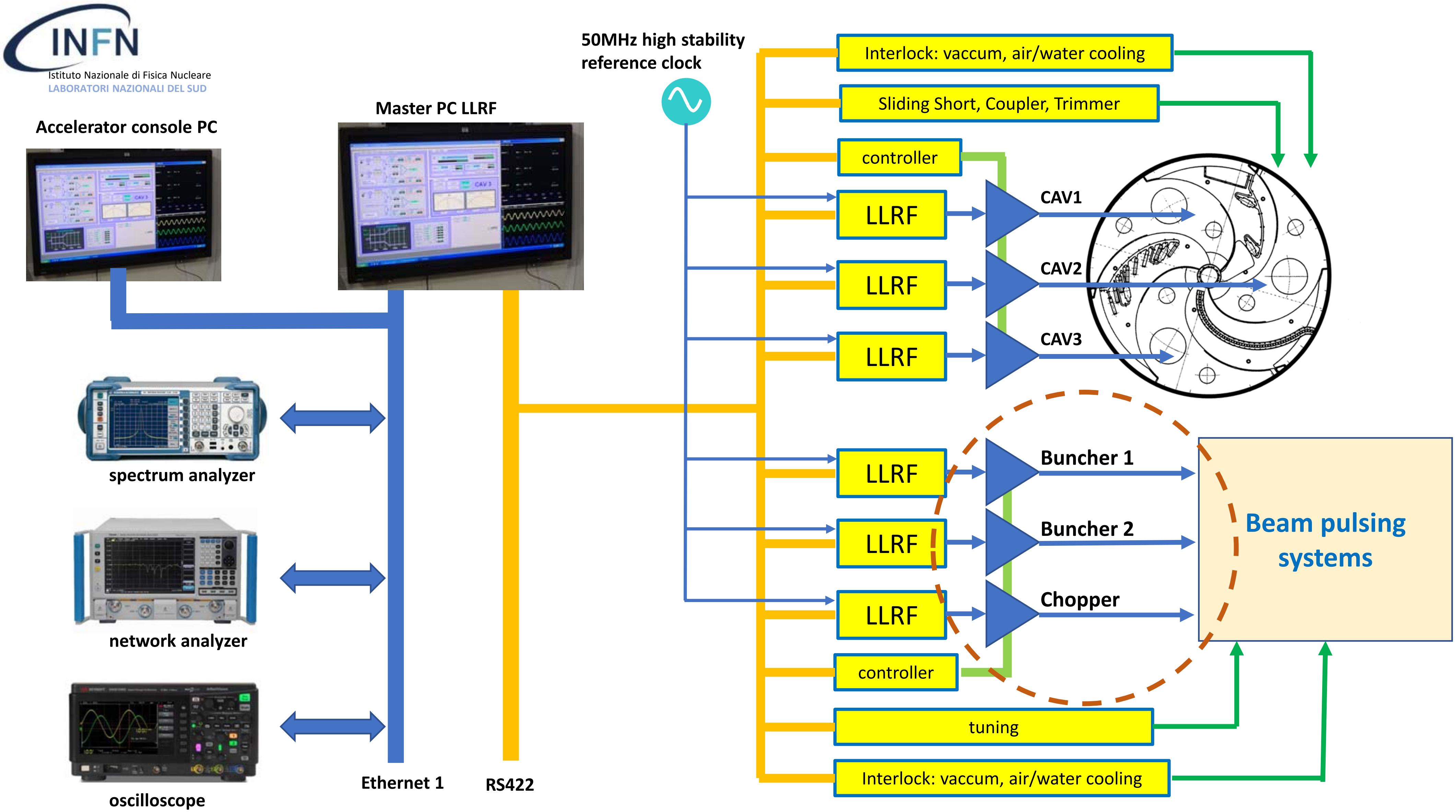
Hybrid LLRF (Analog and Digital)



La gestione logica dei moduli del LLRF è basata principalmente su dispositivi della famiglia dsPIC33 della Microchip, la sintesi del segnale RF è affidata ai DDS AD9854 dell'Analog Device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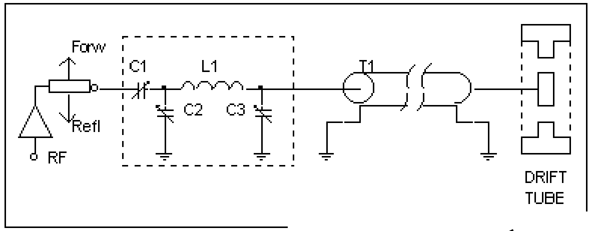
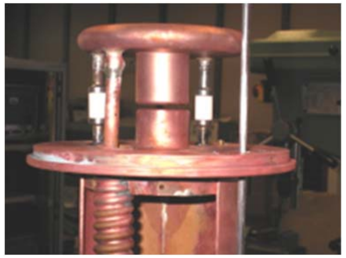
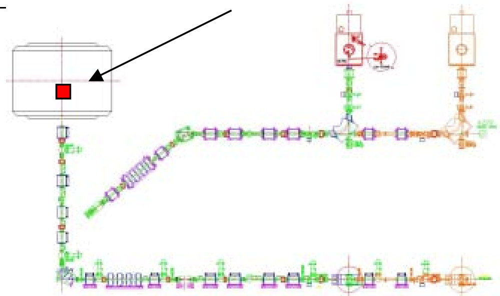
Accelerator console PC
Master PC LLRF
50MHz high stability reference clock
Interlock: vaccum, air/water cooling
Sliding Short, Coupler, Trimmer
controller
LLRF
CAV1
LLRF
CAV2
LLRF
CAV3
LLRF
Buncher 1
LLRF
Buncher 2
LLRF
Chopper
Beam pulsing systems
controller
tuning
Interlock: vaccum, air/water cooling
spectrum analyzer
network analyzer
oscilloscope
Ethernet 1
RS422

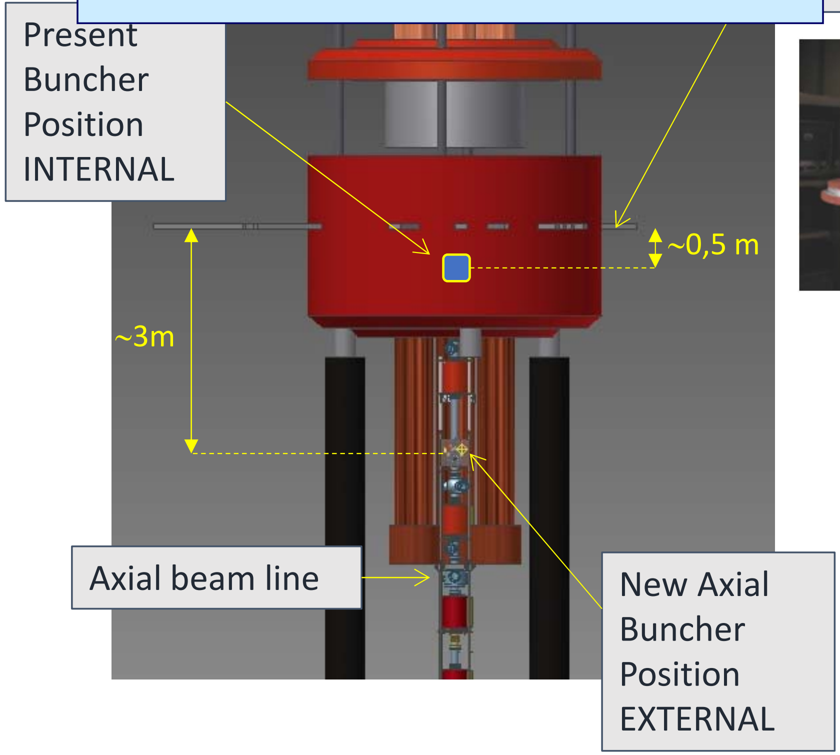
Axial Buncher

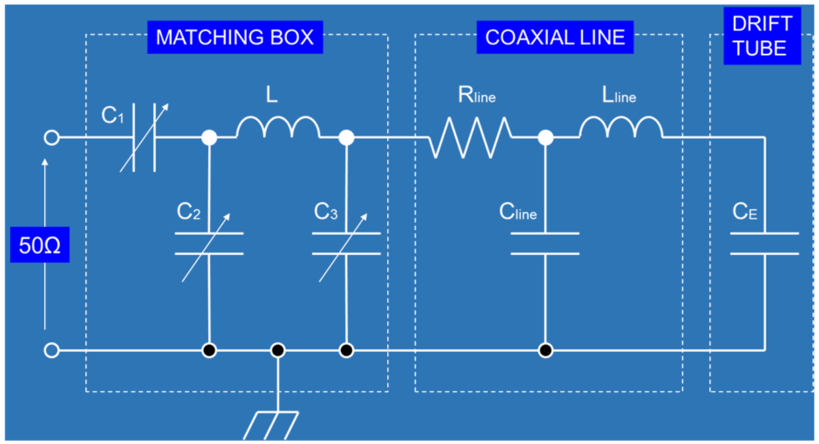
- Drift tube solution inside the CS yoke
- ½ meter from median plane
- Frequency range 15-50 MHz
- Electrode length 41 mm $L=2\pi R_i/2h$
- Efficiency measured 3.5-4.5



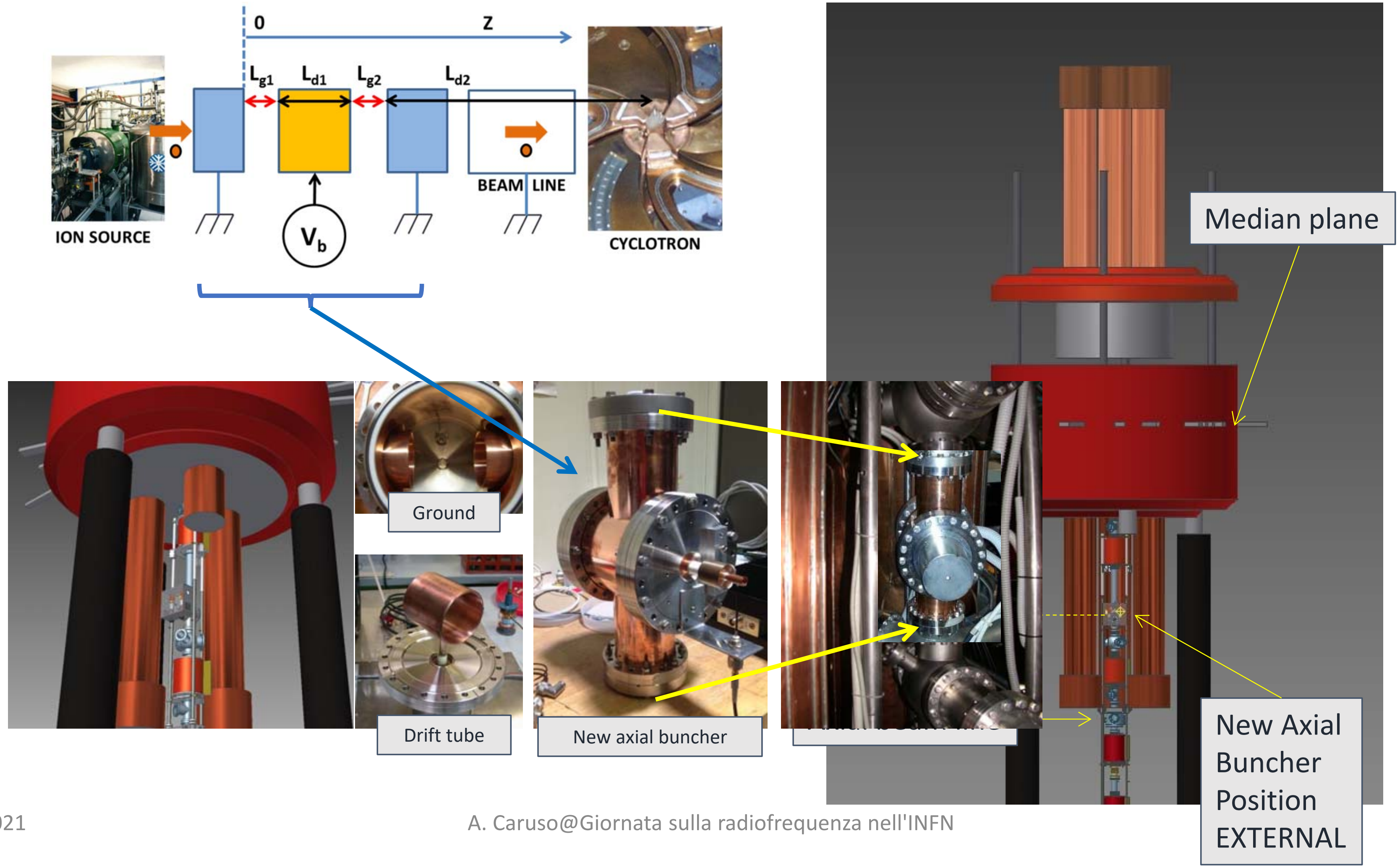






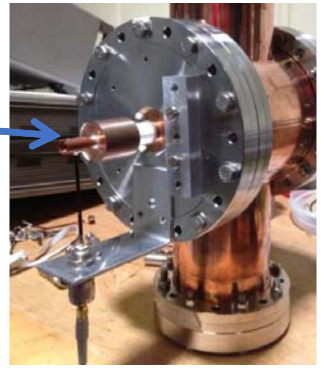


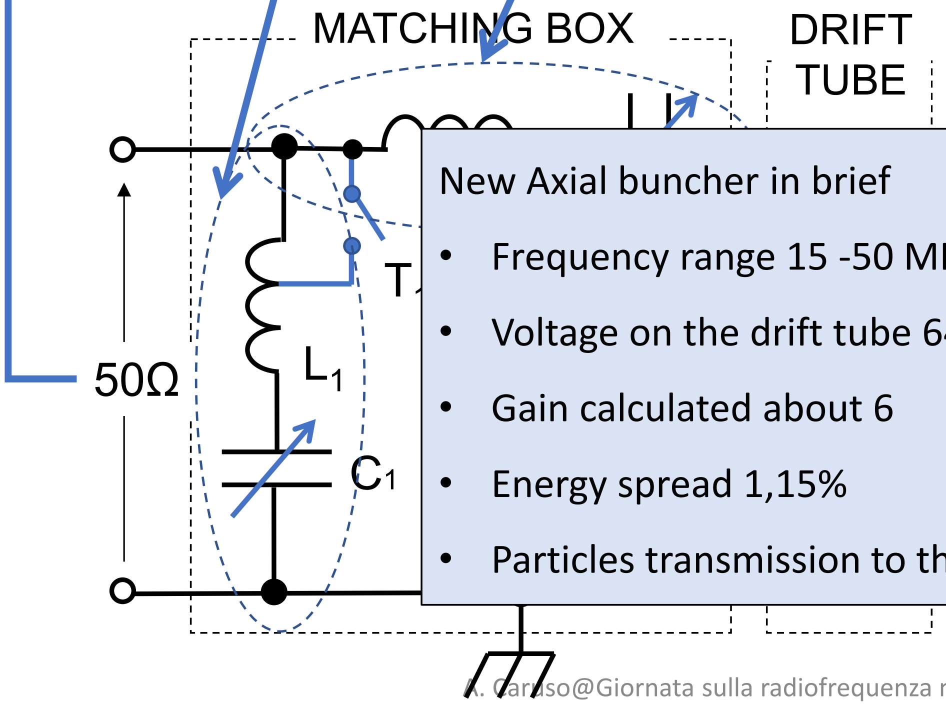
The new Axial Buncher

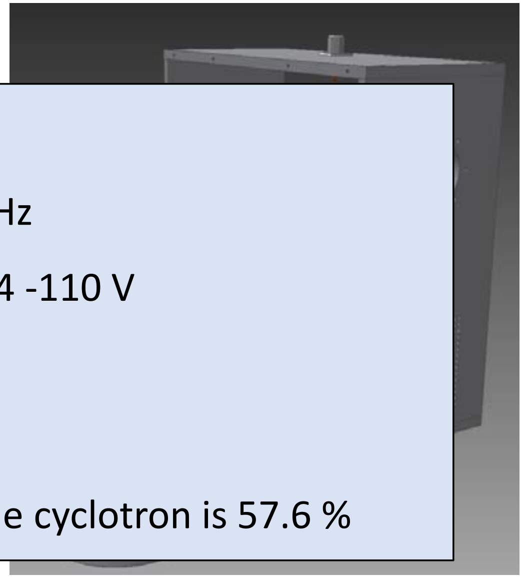


Impedance transformer from Z_0 to buncher impedance Z_b

$$Z_{in} = \frac{Z_{shunt} \cdot (Z_{series} + Z_b)}{Z_{shunt} + (Z_{series} + Z_b)}$$







New Axial buncher in brief

- Frequency range 15 -50 MHz
- Voltage on the drift tube 64 -110 V
- Gain calculated about 6
- Energy spread 1,15%
- Particles transmission to the cyclotron is 57.6 %

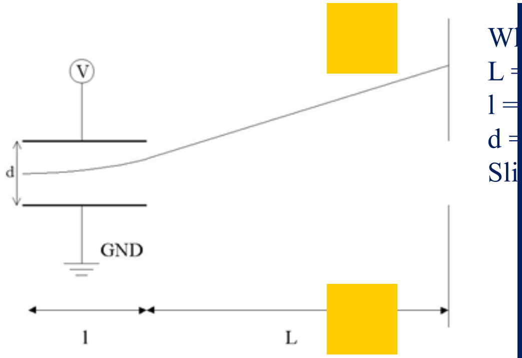
The high energy chopper

Extraction beam line

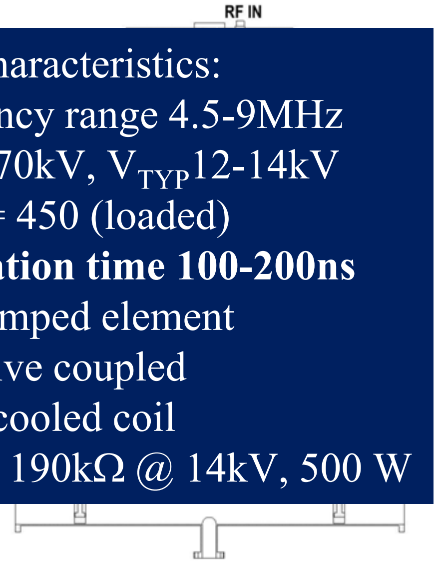
Chopper OFF

Chopper ON

Chopper ON

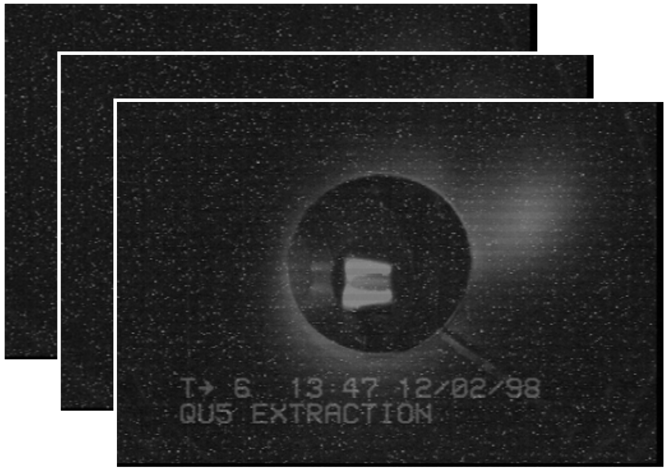


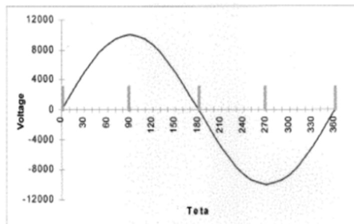
Steerer magnets

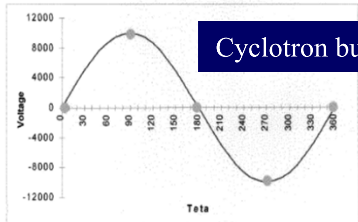


Main Characteristics:

- frequency range 4.5-9MHz
- V_{MAX} 70kV, V_{TYP}12-14kV
- Q_{factor}= 450 (loaded)
- **separation time 100-200ns**
- L-C lumped element
- inductive coupled
- water cooled coil
- R_{shunt}≈ 190kΩ @ 14kV, 500 W

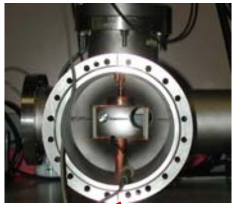


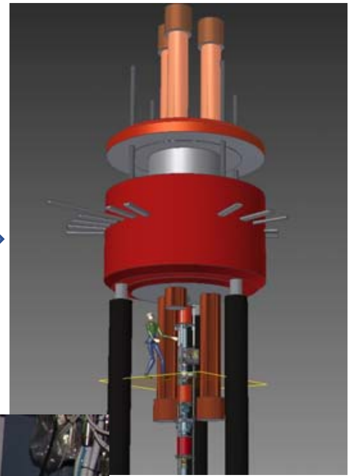


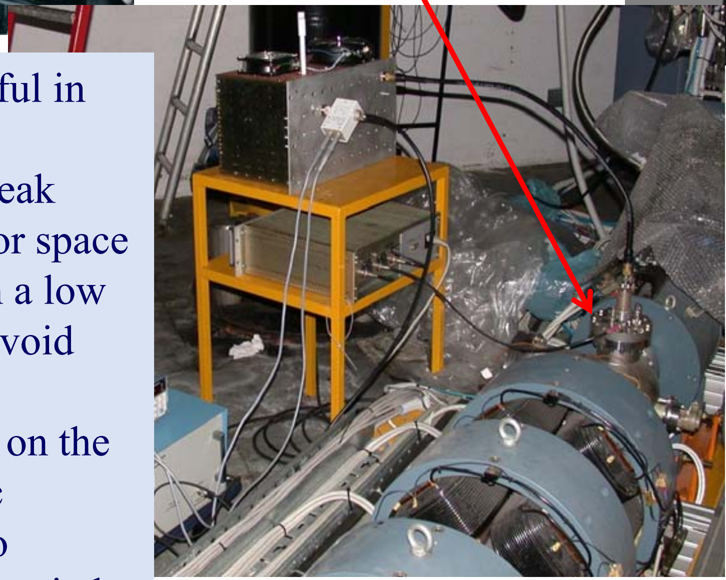


Cyclotron bunches

The Low Energy Chopper





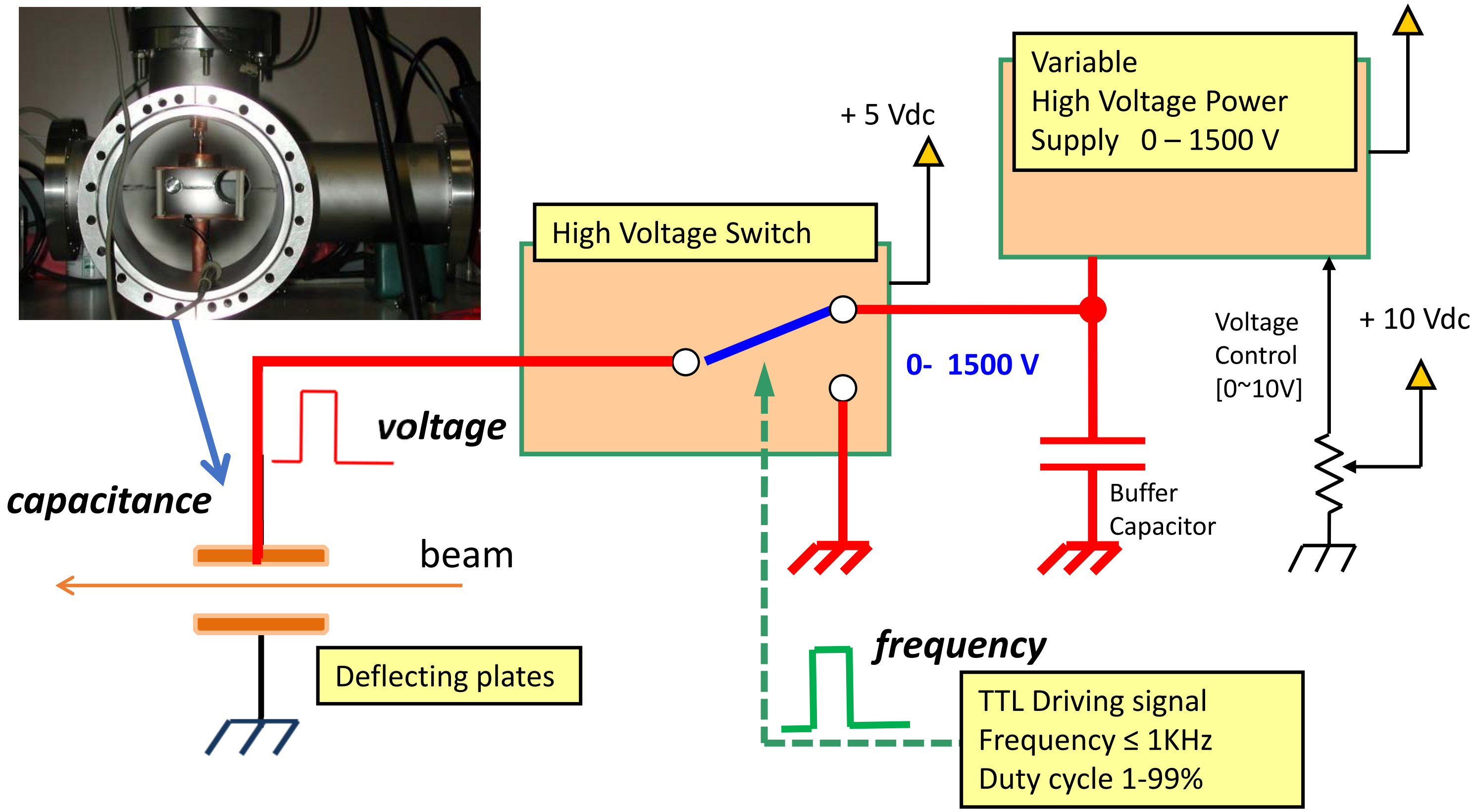


This device is very useful in setting the cyclotron parameters with high peak current to investigate for space charge effects, but with a low duty cycle in order to avoid activation inside the accelerator chamber or on the wall of the electrostatic deflector. It is used also directly by the users to switch very fast off/on the beam.

The low energy chopper is used as a variable attenuator of the injected beam.

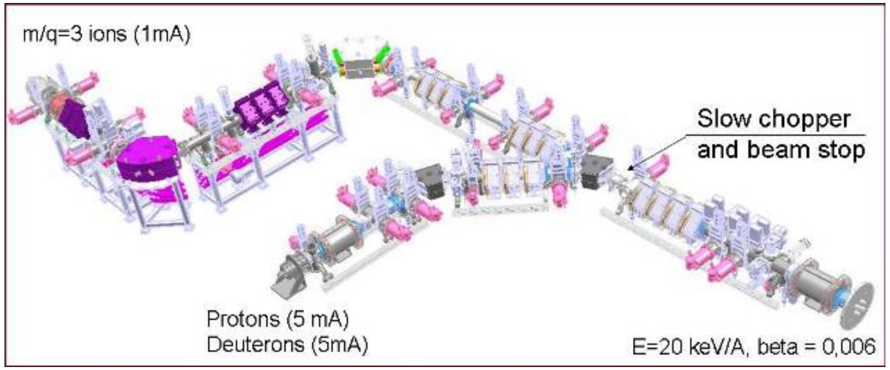
- Distance plates 50 mm
- Length is 100mm
- Width is 70 mm
- C is about 43 pF
- V_{max} 1500 V_{Pulse}
- Duty cycle 1-99%

The Low Energy Chopper



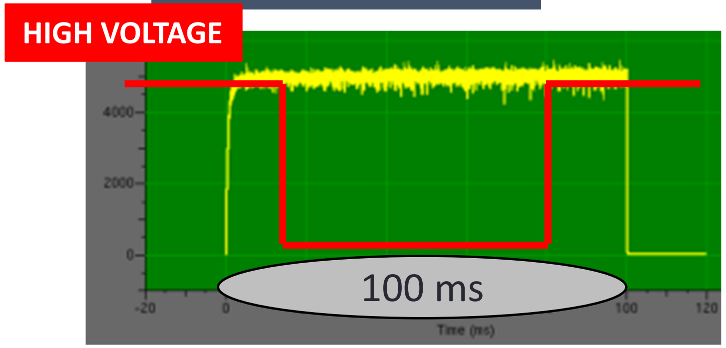
Starting point of SPIRAL 2 (GANIL) LEBT CHOPPER

The Spiral2 driver uses a slow chopper situated in the common section of the **low energy beam transport line (LEBT)**

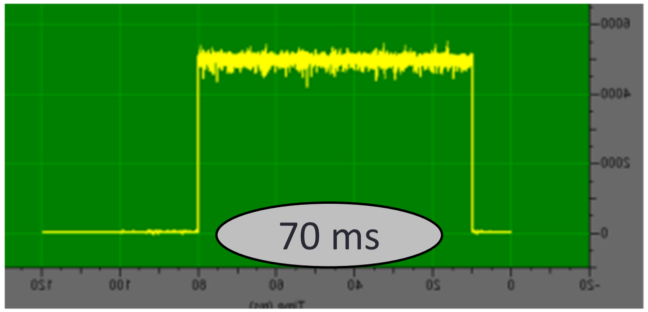


- **To change the beam intensity**
- **To cut off the beam in case of critical loss (MPS)**
- **To avoid hitting the wheel structure of rotating targets**

SUCCESSFUL RESULT



5 mA Protons Beam from ions source



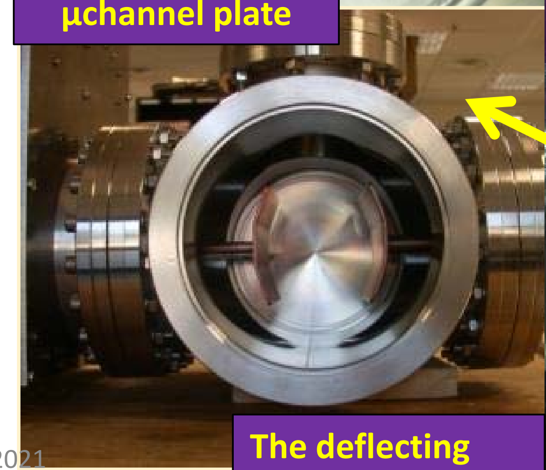
1st beam chopped, 5 mA of protons at 2 kV, at CEA-Saclay on December 2011.

the beam is deviated on the beam dump according to the voltage applied to the deflecting electrodes.

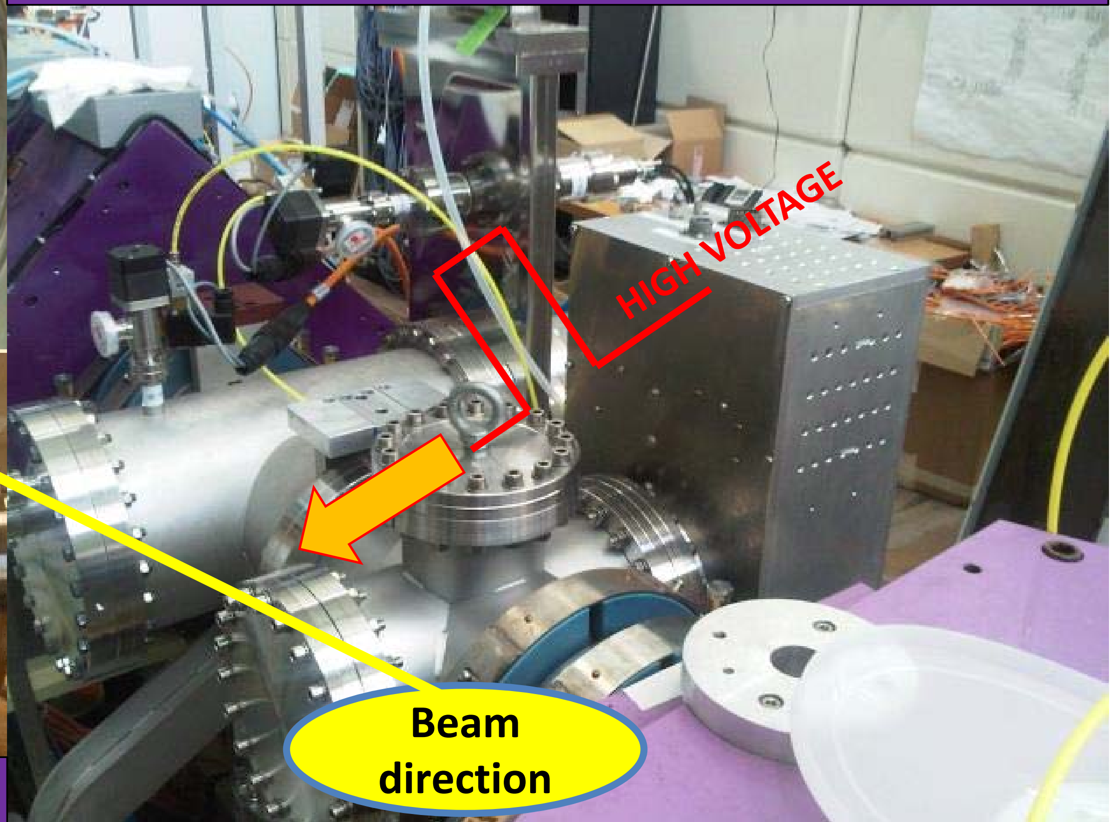
The vacuum chamber with the electrodes and the power electronic system was installed at CEA-Saclay in June 2011. Successful tests on the beam were achieved between the end of November and beginning of December 2011.

The slow chopper on the beam line at CEA Saclay

Beam Stop and µchannel plate

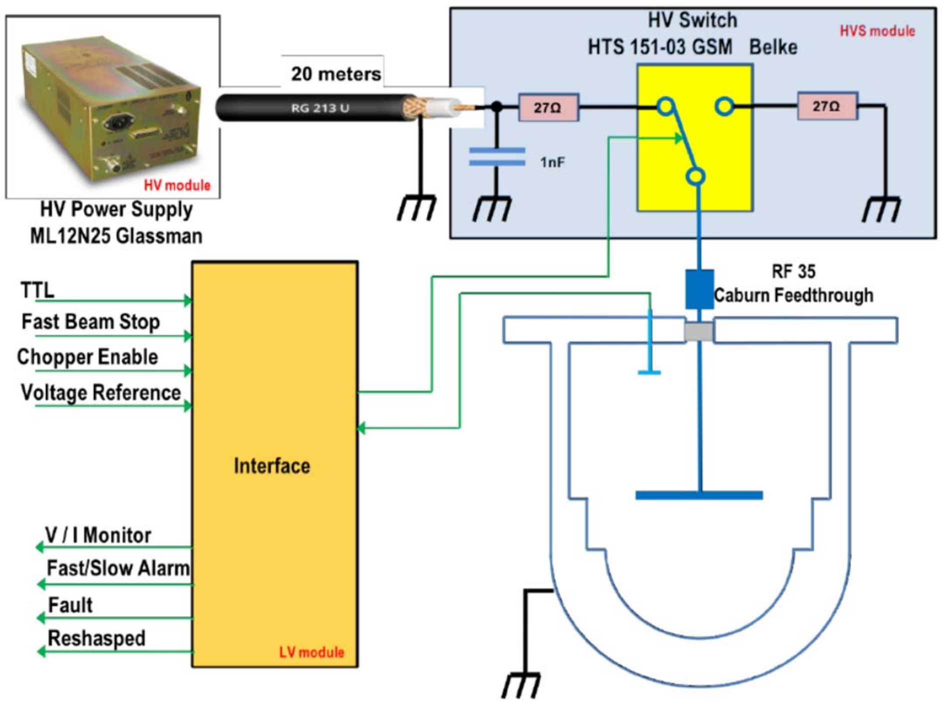


The deflecting electrodes



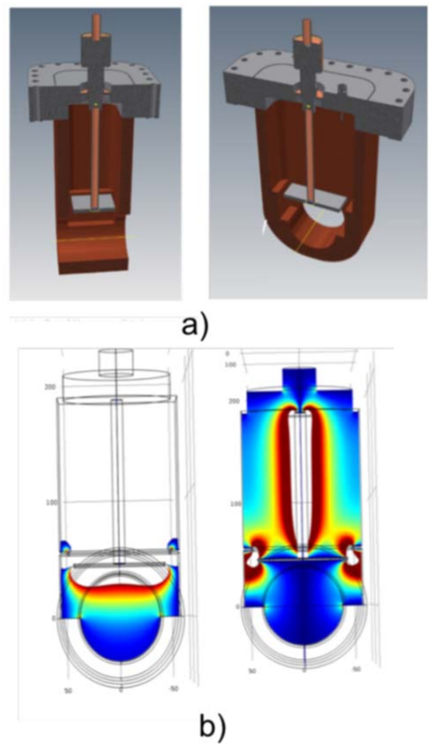
ESS CHOPPER

The ESS requires a high intensity proton beam (70 mA pulsed at 14 Hz of repetition rate),
with fast Beam pulse rise/fall time (< 20 us).
In order to meet the project requirement, an electrostatic chopping system has been used in the LEBT.



Design parameters for the chopper power circuit

- Maximum Voltage 10 kV
- Voltage rise/fall time <100 ns
- Beam rise fall time < 20 us
- Duty Cycle 4 %
- Rep. Rate 14 Hz



Strumentazione e dispositive RF

network analyzer	HP	8753E	30kHz-6GHz
network analyzer	Agilent	E5072A	30kHz-8.5GHz
spectrum analyzer	R&S	FSL	9kHz- 3GHz
spectrum analyzer	HP	8594E	9kHz- 2.9GHz
spectrum analyzer	R&S	FSVA4	10Hz - 4GHz
spectrum analyzer	R&S	FSAS	100Hz - 1.8GHz

amplifier	Thamway	T145-4567B	10-60 MHz , 30W
amplifier	ENI	3200L	250KHz-150MHz, 250W
amplifier	ENI	550L	1.5-400MHz , 50W
amplifier	ENI	3100A	250KHz-150MHz , 150W
amplifier	ENI	A500	300kHz-35MHz , 500W
amplifier	ENI	500LA	1.5-520MHz , 1W
amplifier	Herfurth	HV1K1-100	1-100MHz , 2x500W
amplifier	AR	100A250	10KHz-250MHz , 100W
vector voltmeter	R&S	ZPV	0.3MHz-2GHZ
vector voltmeter	HP	8405A-opt. 002	
amplifier	Empower	2071	1-100MHz , 300W
amplifier	Sonoma	310	9KHz- 1GHz, 1W
amplifier	Innovaction	custom	65-110MHz , 1kW
amplifier	DB	custom	15-50MHZ , 1kW
amplifier	BBC	custom	15-50MHz, 90kW
amplifier	**Thomson**	**custom**	**65-110MHz , 50kW**
amplifier	HP	8347D	100KHz- 1.3GHz
amplifier	HP	8347A	100KHz- 3GHz

amplifier	**Thomson**	**custom**	**65-110MHz , 50kW**

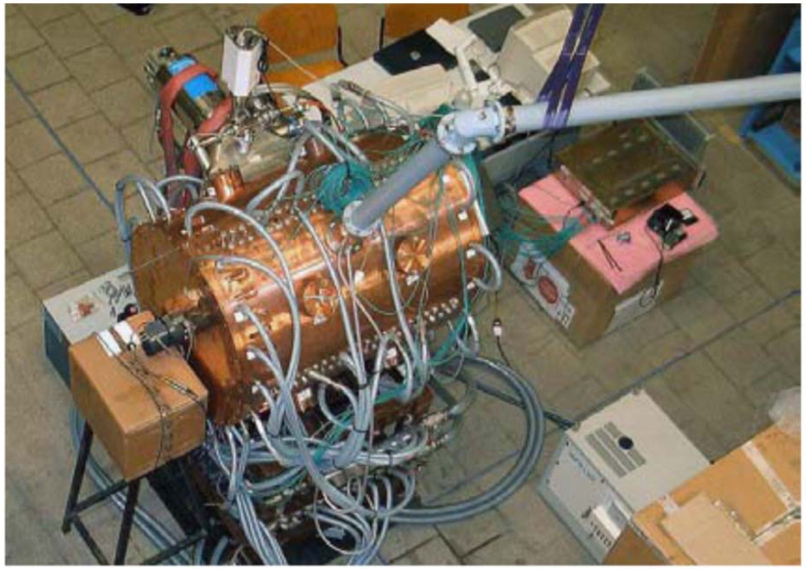


Figure 2: RFQ installation in INFN LNS.

SPIRAL 2 RFQ PROTOTYPE FIRST TESTS

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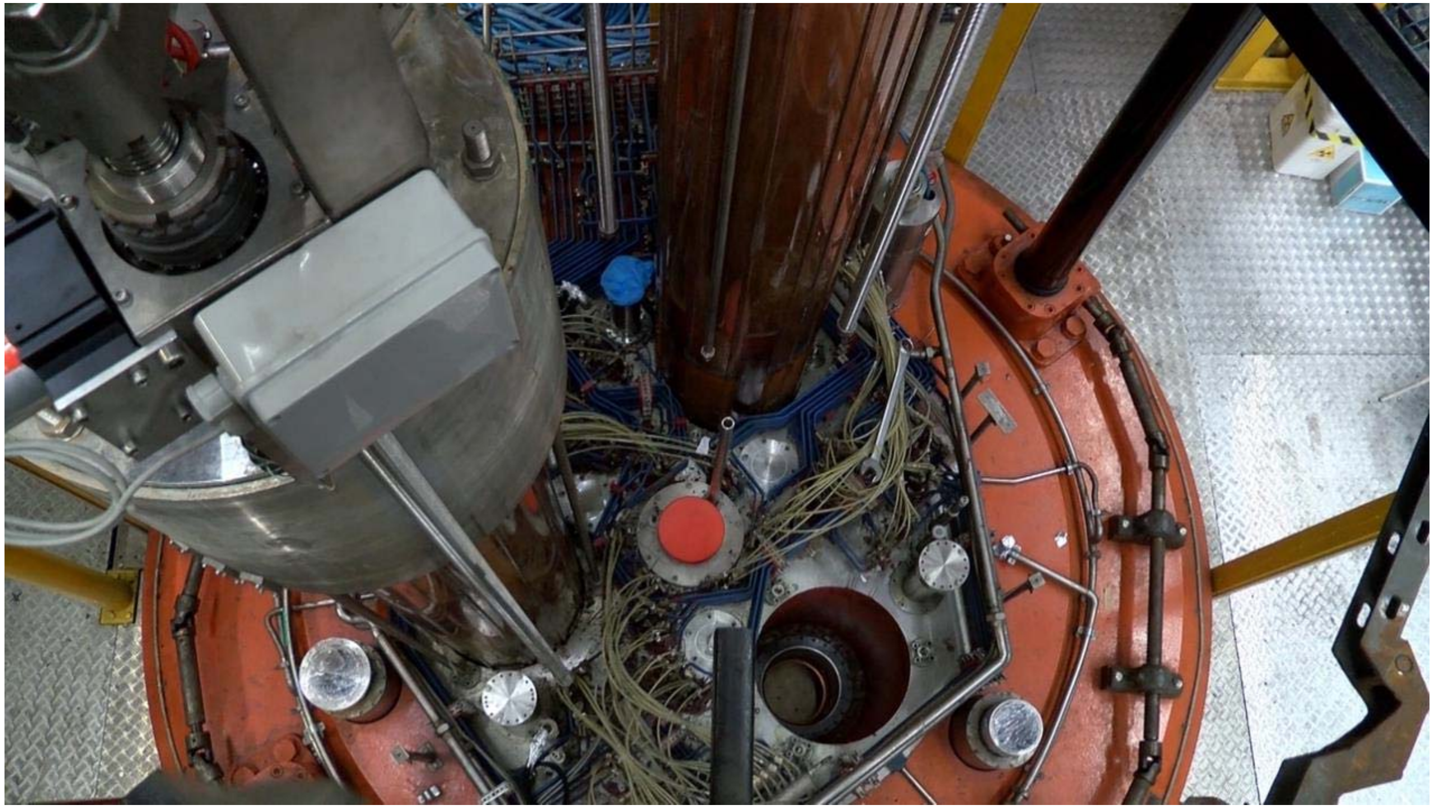
Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

control system analyzer	HP	3563A	0-200kHz
signal generator	HP	8662A	10kHz-1280MHz
signal generator	HP	8647A	250kHz- 1GHz
signal generator	R&S	SMT02	5KHz - 1.5GHz
function generator	Tektronix	AFG310	
function generator	Tektronix	AFG3021	
function generator	HP	8116A	50MHz
power meter	R&S	NRVD	
level meter	R&S	URV35	
millivoltmeter	R&S	URV5	
LCR meter	Agilent	4263D	
power supply	TDK Labda	GEN60-25	0-60V , 0-25A
power supply	TDK Labda	GEN150-5	0-150V , 0-5A
power supply	TDK Labda	GEN150-100	150V , 100A
power supply	Glassman	Series ER	10mA- 30KV
power supply	Glassman	Series ET8R250	400mA- 5KV

dummy load	Spinner	BN527743	1kW 50 Ohm
RF attenuator	Bird	8329-300	2-4kW 50 Ohm, 30dB
RF tunable band pass filter	K&L	5BT-3/6	3-6MHz
RF tunable band pass filter	K&L	5BT-6/12	6-12MHz
RF tunable band pass filter	K&L	5BT-12/24	12-24MHz
RF tunable band pass filter	K&L	5BT-15/30	15-30MHz
RF tunable band pass filter	K&L	5BT-30/76	30-76MHz
RF tunable band pass filter	K&L	5BT-65/125	65-125MHz
noise source	Noise Com Inc.	NC346A-OPT1	10MHz - 18GHz
universal counter	Agilent	53131A	3GHz

CONCLUSIONI:

ottima iniziativa, quella di creare questa rete nazionale.
Da estendere ad altri settori. Penso al Vuoto, Criogenia, Power Converters, etc




BRUKER


INFN
LNS

GRAZIE PER L’ATTENZIONE