HYBRID CONFIGURATION, SOLID STATE – TUBE, REVAMPS AN OBSOLETE FULL TUBE AMPLIFIER FOR THE INFN K-800 SUPERCONDUCTING CYCLOTRON

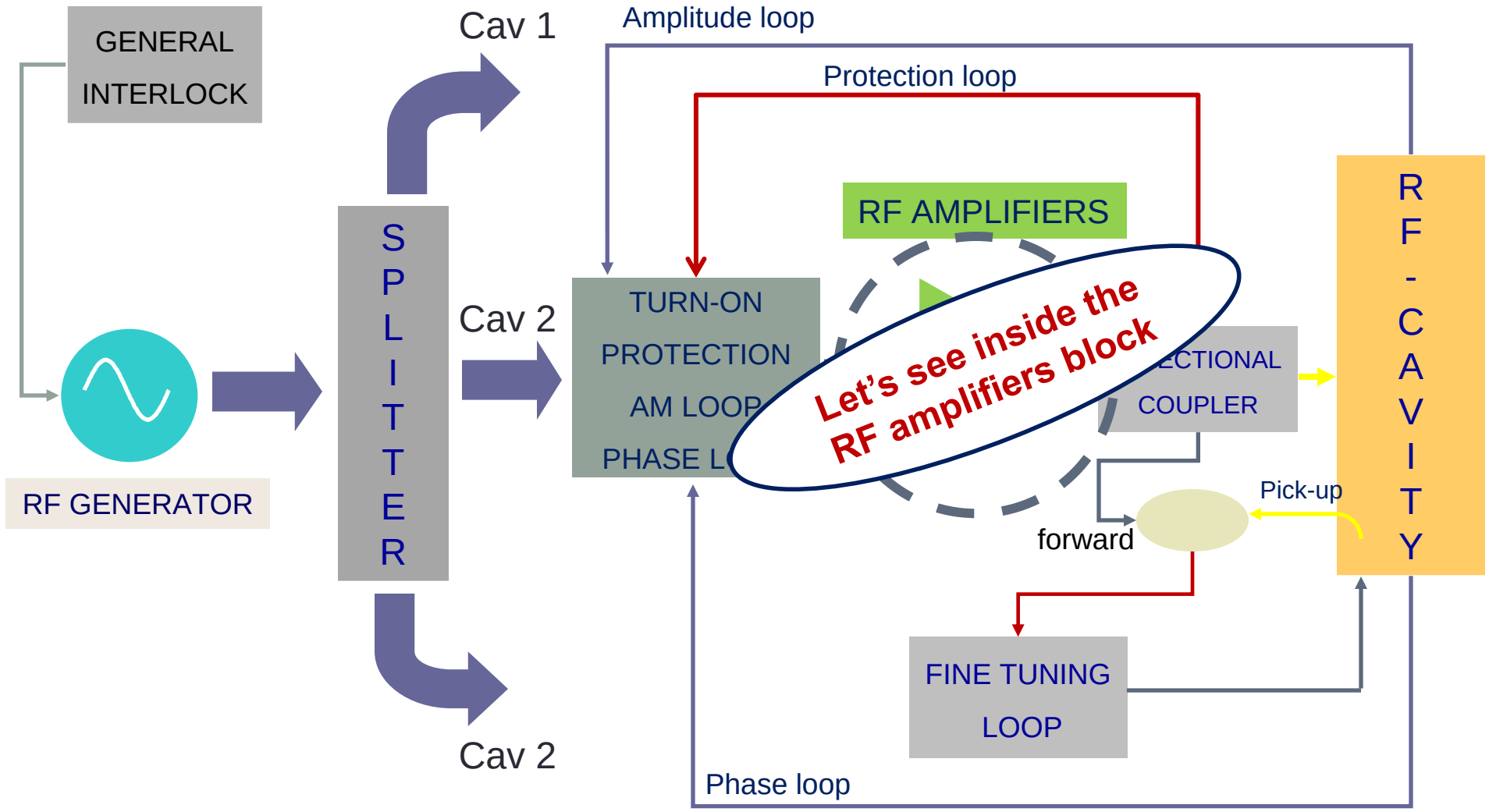
Antonio Caruso
INFN-LNS

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud

Talking points

- **Overview of the block diagram and RF amplification stages**
- **Main reasons to modify the existing amplifiers;**
- **Solid state vs tube amplifier as 1st stage;**
- **Matching between the new 1st stage and the existing 2nd "tube" stage;**
- **Test, measurements and operation with our cyclotron;**
- **Conclusion;**
- **References and discussion.**

The general RF system block diagram



RF Generator 15-50 MHz

LOW LEVEL RF

Standard solid state
100-200 Watt
Gain 50-55 dB
Wide bandwidth
"DRIVER AMPLIFIER"

RF power amplifier (Ampegon ex BBC)
P_{max} 90 kW CW, nominal 75 kW (~1981)
Frequency range 15-50 MHz

Cavity 1

Cav2

Cavity 3

Courtesy of L.Piazza

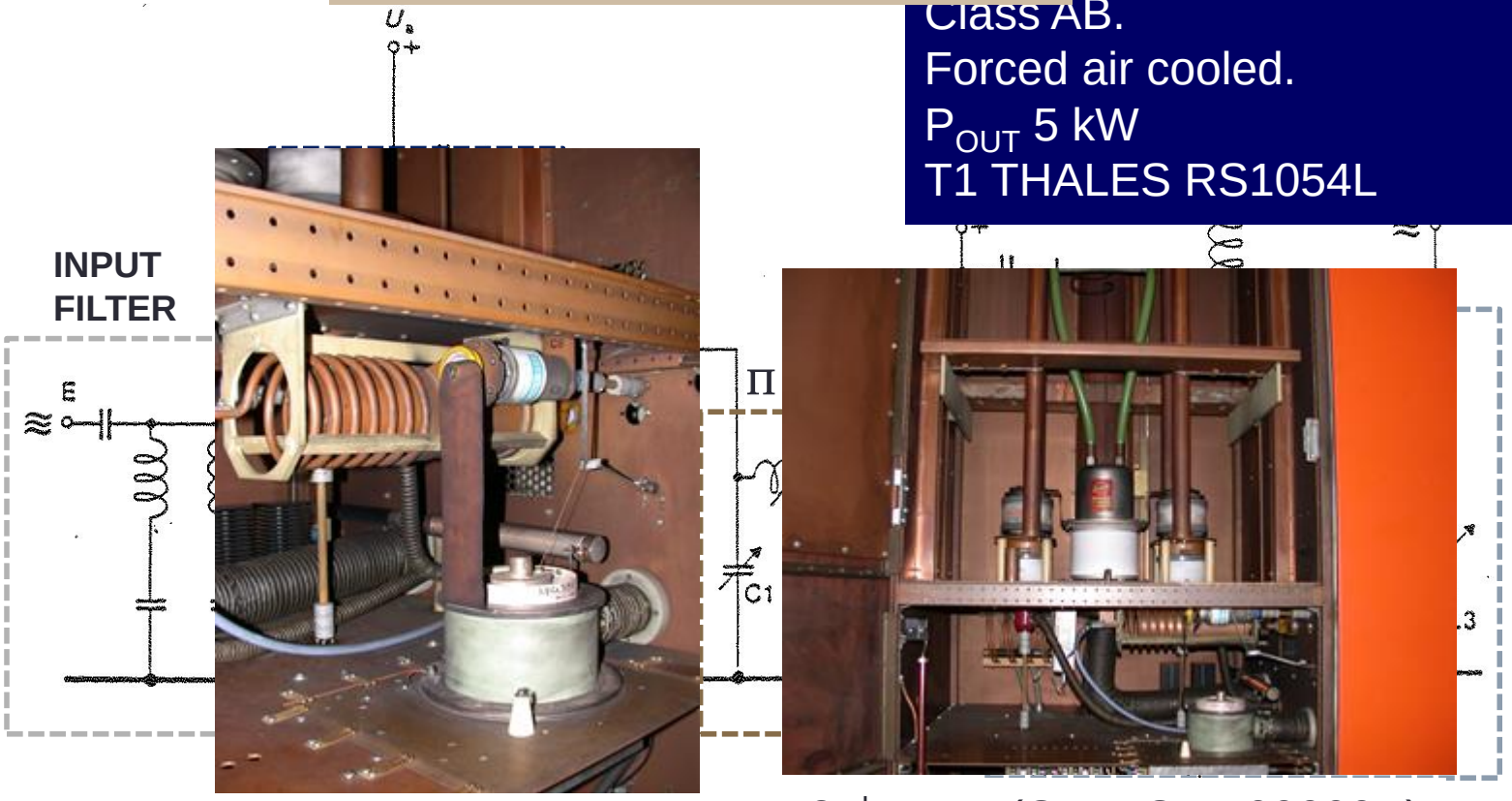
-6dBm (0.25 mW)	~50dBm (100 W)	+78.75dBm (75 kW)
-10.8dBm (80 µW)	+45.7dBm (37 W)	+74.7dBm (30 kW)
-12.5dBm (56 µW)	+44dBm (25 W)	+73dBm (20 kW)

Input filter sta
• wide band
• adapts from
tetrode and D
•The RF powe
dissipated on
•No tuning is

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.

e two
load for the
the input
tage at the
ponents,
e are

stage is a **ground-cathode**
ration. In general this
ration is very reliable,
very few technical
ns and a considerably low
r of components.
ntrol input.
Class AB.
Forced air cooled.
P_{OUT} 5 kW
T1 THALES RS1054L



1st stage (THALES RS1054LSC)

2nd stage (CPI-4CW100000E)

THALES

Microwave & Imaging Sub-Systems
2, rue Marcel Dassault - BP 23
78141 Vélizy-Villacoublay Cedex
France
Tél : + 33 (0) 1 30 70 35 00
Fax : + 33 (0) 1 30 70 35 35
www.thalesgroup.com

Subject : End of production – Ceramic tubes for

THALES

Microwave & Imaging Sub-Systems
2, rue Marcel Dassault - BP 23
78141 Vélizy-Villacoublay Cedex
France
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Fax : + 33 (0) 1 30 70 35 35
www.thalesgroup.com

To the attention of M. Caruso
Istituto Nazionale Di Fisica Nucleare
Laboratori Nazionali del Sud
fia 62
ATANIA – Italy

8. LUG. 2010 13:34 I. N. F. N. - L. N. S. CT NR. 626 P. 2/10

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud

Istituto Nazionale di Fisica Nucleare
AOO: Laboratori Nazionali del Sud
Partenza
Prot.N. 0003462 - 08/07/2010 - Tit. 9.3
Dest. Princ. THALES ELECTRON DEVICES
Dest. CC.

SPETT.LE
Thales Electron Devices SA
2, Rue Marcel Dassault – BP 23
78141 Velizy – Villacoublay Cedex
France

Oggetto: PROCEDURA NEGOZIATA PER LA FORNITURA DI N. 3 TETRODI RS1054L COME RICAMBI DEGLI AMPLIFICATORI DI POTENZA RF DEL CICLOTRONE.

(IMPORTO TOTALE € 47 000,00 + IVA + ONERI) COD.CIG. 0503991287.

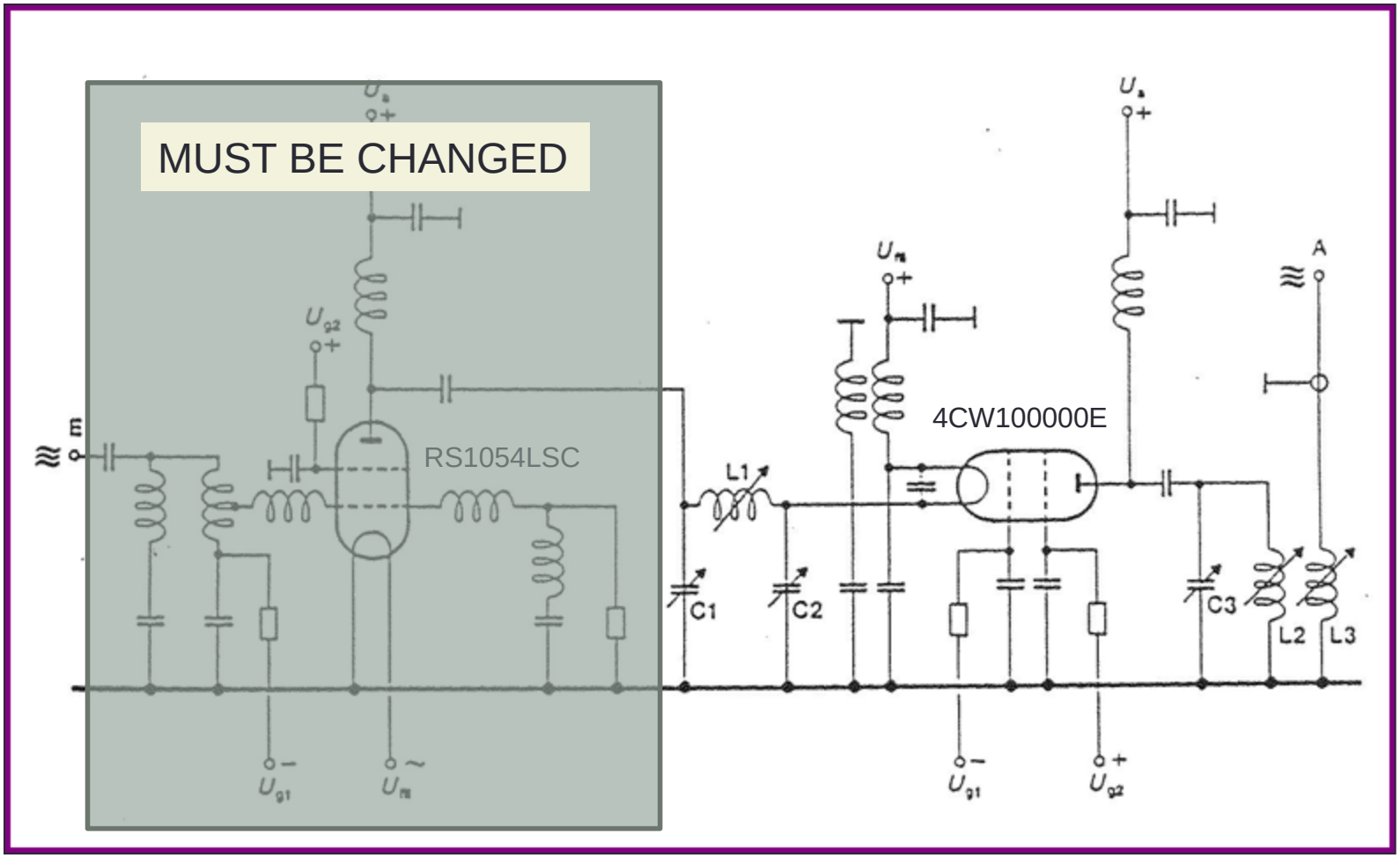
~60k€, not on SALE…

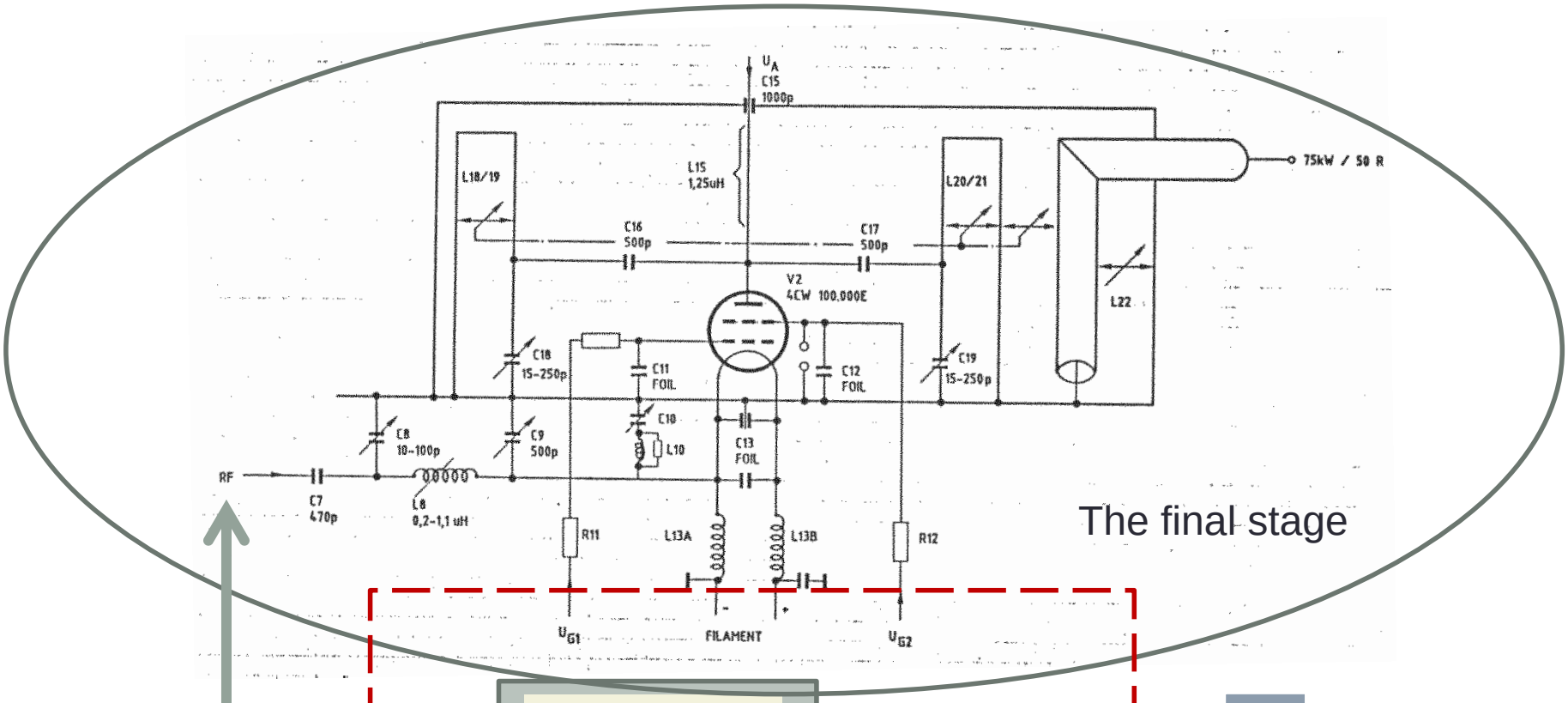
Dear Mister Caruso,

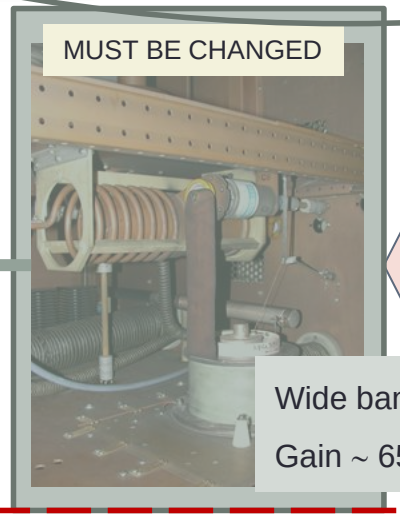
On May 18th, 2010 T… …e end of electron tube ref. RS1054LS… …in the worldwide market and offered … …ough an Last-buy order (LBO) procedu…

Leading to a Last Pr… …cedure is planned to close at receipt of …

However, considering our very good business relationships with INFN Catania over the past years, TED agrees to postpone the above deadline for the electron tube RS1054LSC and kindly accepts to receive your last order for this very reference by **January 31st, 2011** according to our offer S…


MUST BE CHANGED
RS1054LSC
4CW100000E
L1
C1
C2
C3
L2
L3
A
m





LOW LEVEL RF

RF Generator 15-50 MHz

Wide band stage 15-50 MHz

Gain ~ 65-70 dB

Tetrodes

Reference	General characteristics					Heather power supply		Maximum ratings			Dimensions			Cooling	Cavity
	Output power	Gain	Anode voltage	Screen grid voltage	Anode current	Filament voltage (2)	Filament current	Anode voltage	Power dissipation: Anode	Power dissipation: Screen grid	Diameter	Height	Weight		
	kW	dB	kV	V	A	V	A	kV	kW	W	mm	mm	kg		
YL 1057	1.1	17.5	3.4	600	0.75	3.8	20	3.8	2.2	30	95	110	1.1	forced air	-
TH 347	2.2	15	4.5	400	1.15	5.8	34	5	4.5	25	110	135	2.3	forced air	TH 18363
TH 393	2.5	15.5	5.5	600	1.6	6	65	6	7.5	75	135	145	3.6	forced air	TH 18665
RS 1054 L	2.6	16	4.6	800	1.5	2.8	135	5	5	80	120	117	1.9	forced air	-
RS 1054 SK	2.6	16	4.6	800	1.5	2.8	135	5	5	80	98	141	1.9	water (4)	-
TH 382	5.25	15.5	5.5	600	2.7	4.2	125	6.5	12.5	120	170	158	7	forced air	TH 18482
RS 1034 L	6.3	16	5.1	800	2.8	4.5	200	5.5	13	180	160	154	5.3	forced air	-
TH 582	10.5	15	5.5	600	3.45	4.2	146	7.5	25	120	128	166	4.1	water (4)	TH 18582
RS 1036 L	11.5	15	6	800	3.7	4.5	200	7	20	180	200	152	7.8	forced air	-
RS 1034 SK	12.6	15.5	6.3	800	3.9	4.5	200	7.5	25	180	160	152	7	water (4)	-
TH 563	31.5	14.5	8.5	800	6.45	4.2	210	9	42	200	126	190	6.5	water (3)	TH 18550

(1) Common amplification

Ref.	Output power	Typical operating conditions: Anode: Gain	Anode: Voltage	Anode: Current	Screen grid: Voltage	Heater power supply: Filament: Voltage	Filament: Current	Maximum ratings: Anode voltage	Anode: Power dissipation	Screen grid: Power dissipation	Dimensions: Diameter	Length	Weight	Cooling	Cavity	PDF
	kW	db	kV	A	V	V	A	kV	kW	W	mm	mm	kg			
TH 298	3	23	5	0.8	400	6	50	5	5	60	104	140	2	Air	-	
TH 341	10	17	7	2	400	6.5	85	8	6	150	130	150	3.5	Air	TH 18108 G	

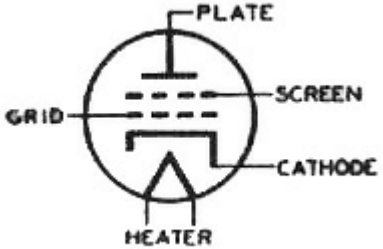
different different different

BUT TH298 COULD BE NEARLY OBSOLETE TOO…

Proposed solution by Eimac

As a possible **alternative** to the originally used RS1054L the **CPI tube 4CX3500A** has been selected. This tube is less powerful than the original one but was selected because we thought than the **final power of 30kW** was enough as regards normal cyclotron activity.

The most **critical parameter is the input capacitance of the 4CX3500A** as it influences the input circuit negatively. The existing wide band circuit has to be redesigned in order to cope with the higher tube capacitance:



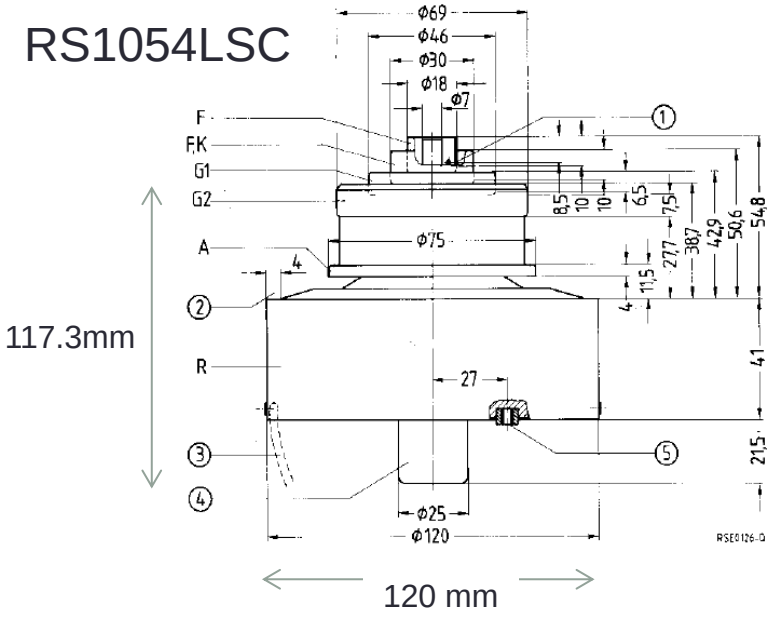
RS1054 Cin = 57 to 60 pF

4CX3500A Cin = 111 pf

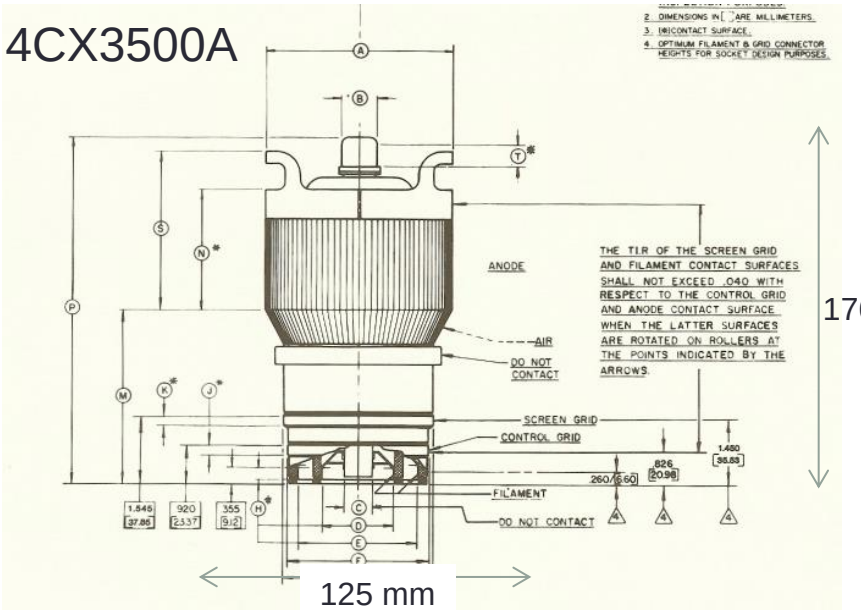
Main modifications for the installation of the 4CX3500A

- Most critical point, **input capacitance: redesign the input impedance circuit** and related board;
- The tube needs **a completely new socket** which ends up in a completely new design for the driver stage. The outline of the present module will be kept so that no major mechanical work is necessary;
- **New filament power supply;**
- Slight modification of control grid power supply (no need for screen grid);
- Insertion of new crowbar circuit in the anode power supply plus retuning of anode matching circuit

RS1054LSC



4CX3500A



Cost of the operation, to modify 3 amplifiers (including a single new tube), about 250 k€

Risks of the operation

- The tetrode manufacturer can notify the end of the production of this new tetrode in any moment. With a very short margin in terms of time, according to our experience;
- It is not possible to store a lot of spare parts, economic and vacuum tube technology;
- **The new solid state technology is going to cover the slice of market under a power of 100 kW and up to few hundred MHz of bandwidth (most important);**

Positive points

- 4CX3500 cost relatively low, high efficiency, high reliability, robustness;
- Apparently no end of production in the near future, according to the manufacture;
- Econco (CPI group), ensured us about the total assistance to rebuild the tube in case of failure (not necessary to buy a bright new tube all the time).

The total operation can be divided into two phases:

1. Design and manufacture the hardware during the cyclotron operation;
2. Installation of the new parts during a cyclotron long maintenance period .

Also the distribution of the total cost, after an agreement with the constructor, should be divided into two, or better for us, more phases…

But the whole operation was stopped due to a big failure in our cryogenic plant. So the already scheduled funding for the 1st stage RF refurbishment was forwarded to the cryogenic plant…

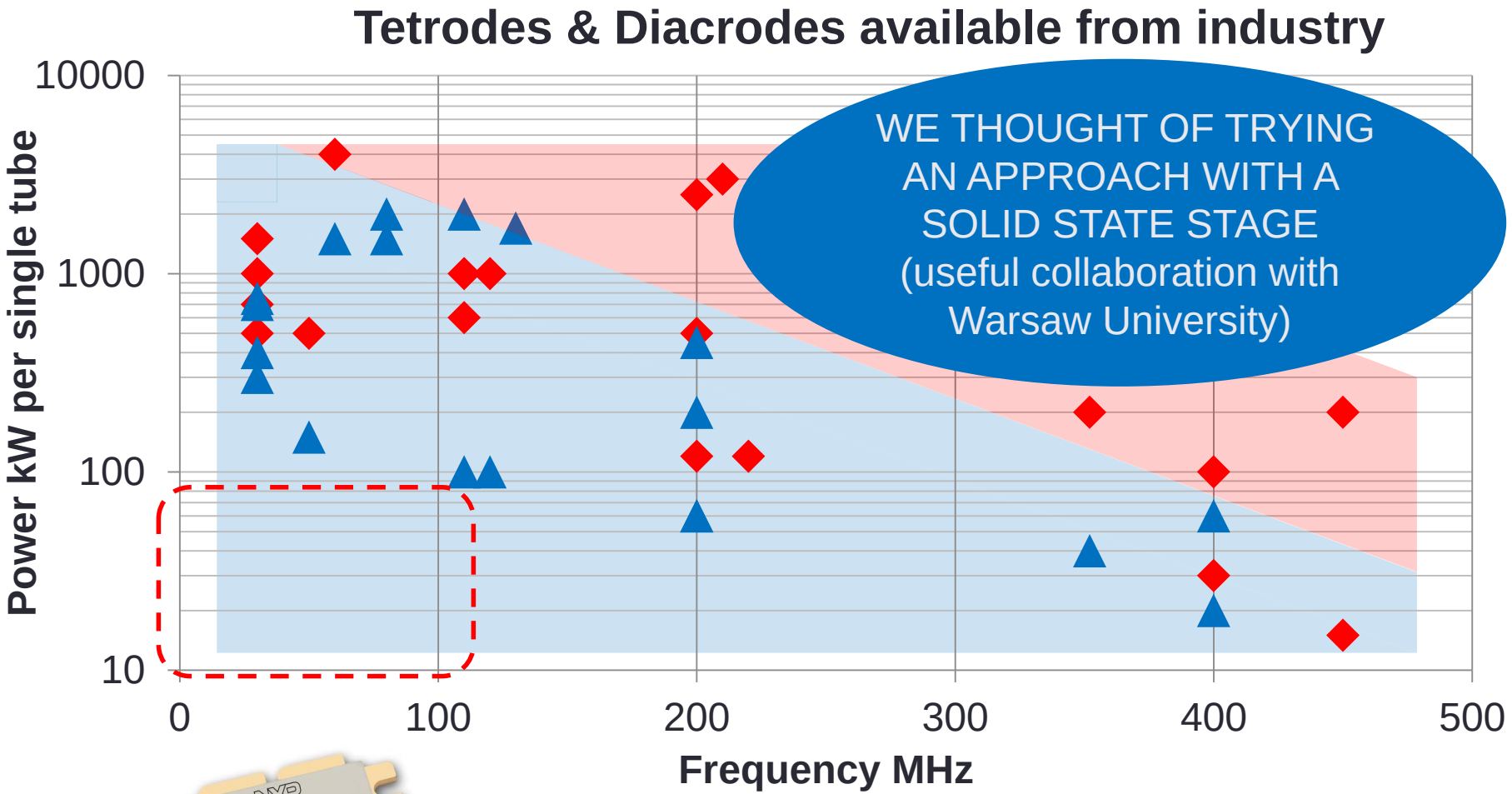
ENOUGH SPARE PARTS

make a virtue out of necessity

SOME IN-HOUSE SOLID STATE AMPLIFIERS

Frequency & Power range of tetrodes

In the meanwhile further news coming from the market …



LDMOS Transistor
>1 kW, 2-600 MHz

Courtesy of Eric Montesinos, CERN-RF

RULES OF THUMB OF THE SOLID STATE OPERATION

CHANGE THE TUBE 1ST STAGE WITH A SOLID STATE:

- MINIMIZE THE HARDWARE MODIFICATIONS, MAINLY IN THE SECOND STAGE OF THE AMPLIFIER;
- NEVER FORGET THE POSSIBILITY TO RE-INSTALL AGAIN THE OLD TUBE, IN CASE OF PROBLEMS IN A REASONABLY SHORT TIME;
- CONTAIN THE COST.

High power water cooled tetrode EIMAC 4CW100000 (final stage)

study the technical characteristics, mainly about the input circuit

4CW100,000E without SK-2100 Water Jacket

GENERAL CHARACTERISTICS[1]

ELECTRICAL

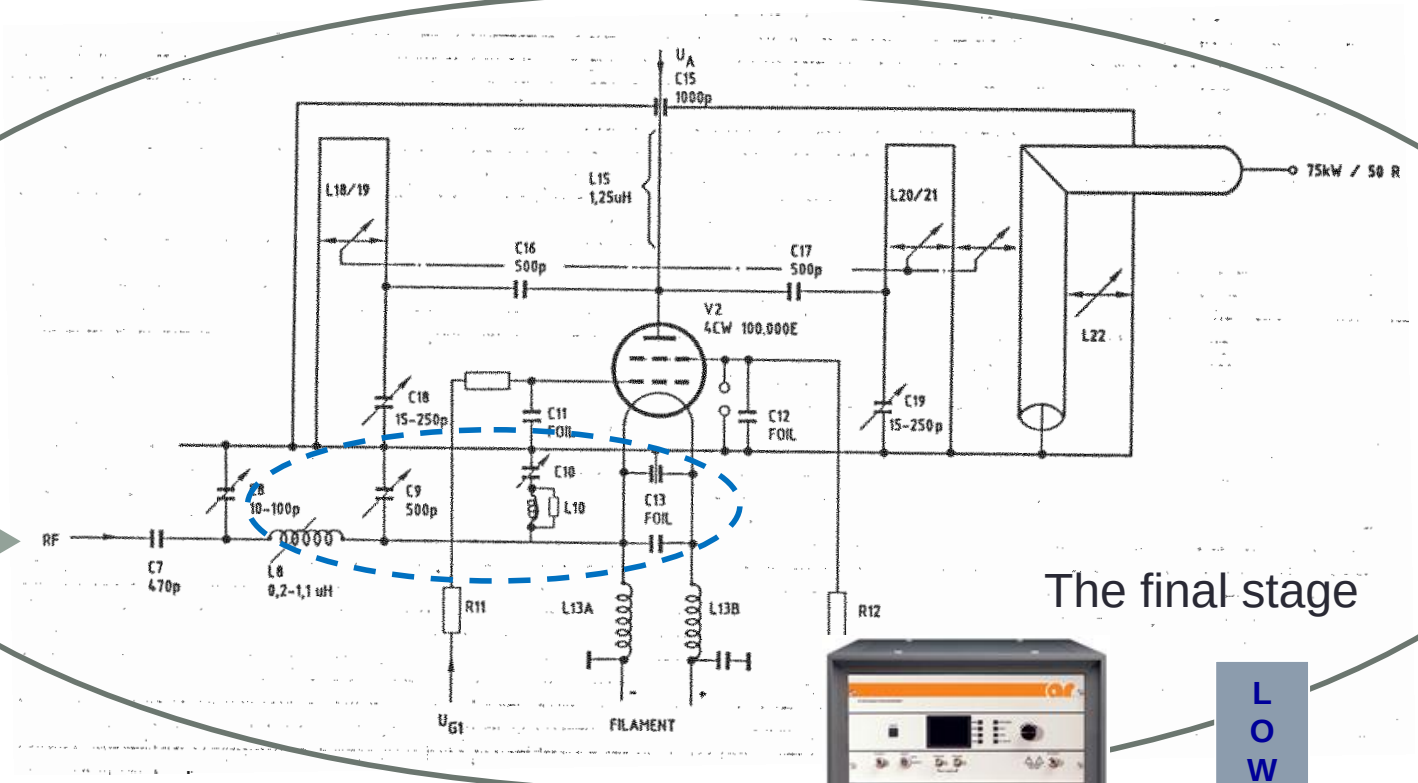
Filament: Thoriated Tungsten		
Voltage	15.5 ± 0.75	V
Current @ 15.5 V	215	A
Direct Interelectrode Capacitances (grounded cathode)		
Cin	370	pF
Cout	60	pF
Cgp	1.0	pF
Direct Interelectrode Capacitances (grounded grid)		
Cin	175	pF
Cout	60	pF
Cpk	0.35	pF
Frequency of Maximum Rating, CW	108	MHz

High power water cooled tetrode EIMAC 4CW100000, maximum and minimum rated values

RANGE VALUES FOR EQUIPMENT DESIGN

	Min.	Max.	
Filament: Current @ 15.5 volts	200	230	A
Cutoff Bias, at Eb = 25 kVdc, Ec2 = 1500 Vdc, Ib = 10 mAdc	---	-625	Vdc
Interelectrode Capacitances (grounded cathode)			
Cin	350	390	pF
Cout	55	65	pF
Cgp	---	1.2	pF
Interelectrode Capacitances (grounded grid)			
Cin	160	190	pF
Cout	55	65	pF
Cpk	---	0.5	pF

Matching the new solid state driver with the 2nd stage



The final stage

Matching network

$Z_{in} = R \pm jX$

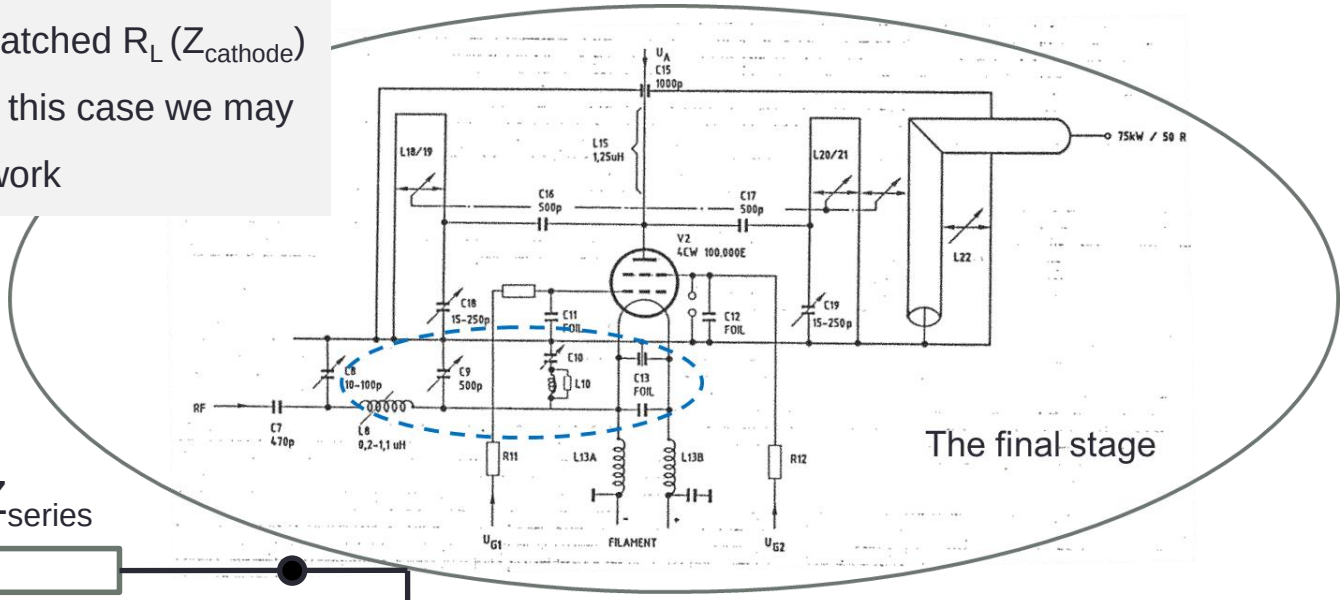
50Ω

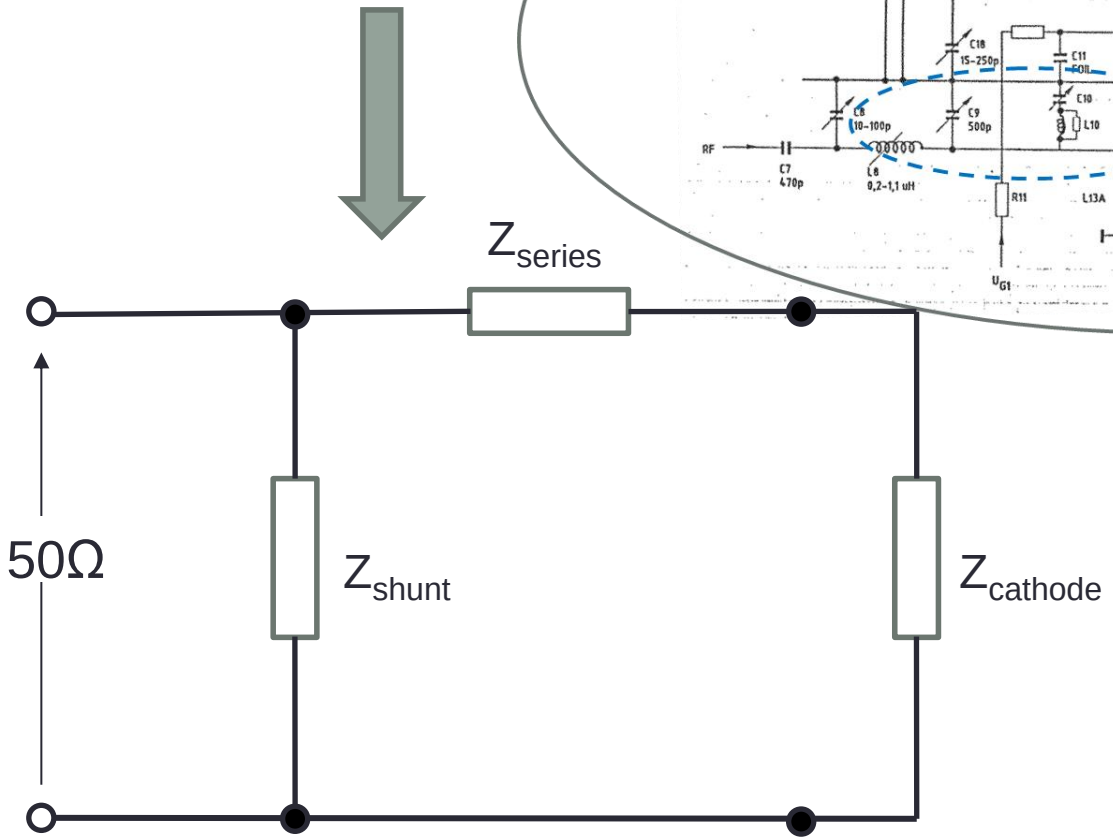
LOW LEVEL RF

RF Generator 15-50 MHz

We need a matching network as impedance transformer from Z_0 to cathode impedance Z_c

the real part of the load to be matched R_L ($Z_{cathode}$) is much lower than Z_0 (50Ω). In this case we may use the simple Γ-matching network





Impedance transformer from Z_0 to cathode impedance Z_c

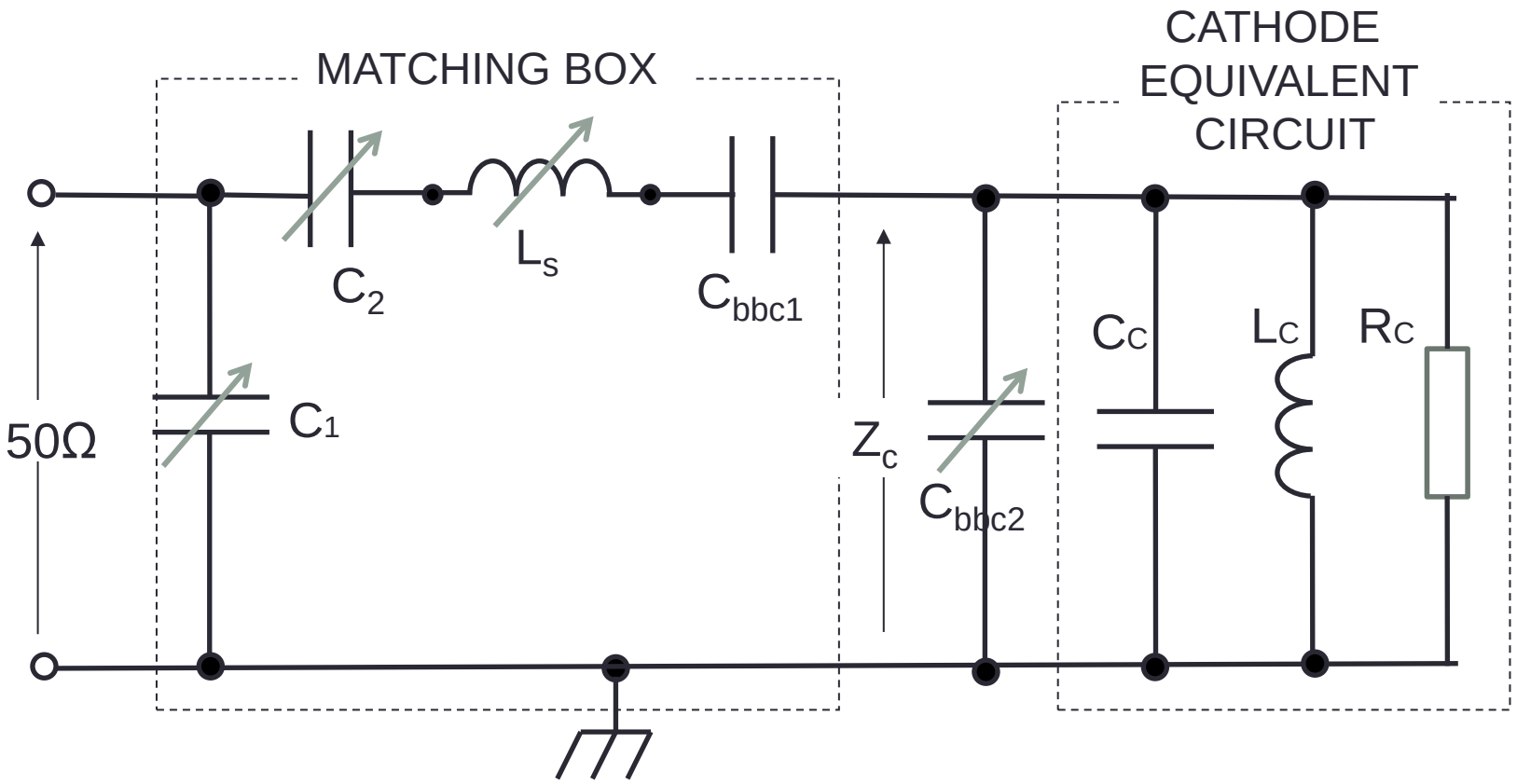
the real part of the load to be matched RL is much lower than Zo. In this case we may use the simple Γ-matching network

$C_1 = C_2 = 10\text{-}1000\ pF$

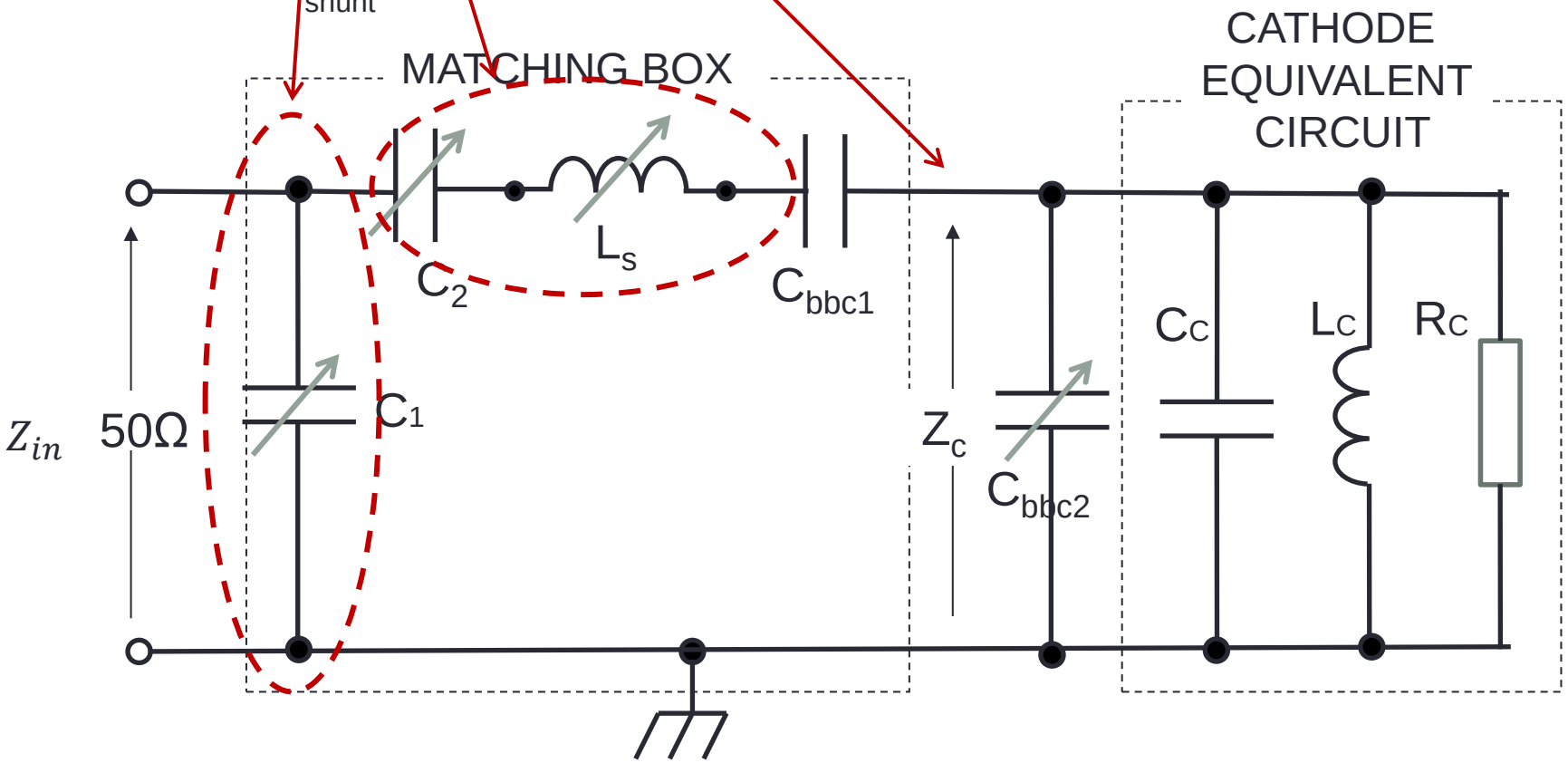
$L_S = 0.2 – 1.1\ \mu H$ (existing)

$C_{bbc1} = 470\ pF$ (existing)

$C_{bbc2} = 5\text{-}100\ pF$(recycled)

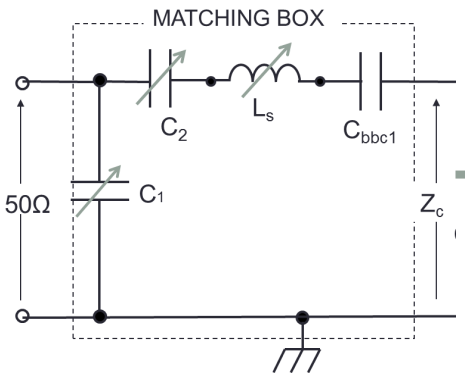


$$Y_{in} = \frac{1}{Z_{C1}} + \frac{1}{Z_{C2} + Z_L + Z_{cathode}} \qquad Z_{in} = \frac{1}{Y_{in}} \qquad Z_{in} = 50\Omega$$



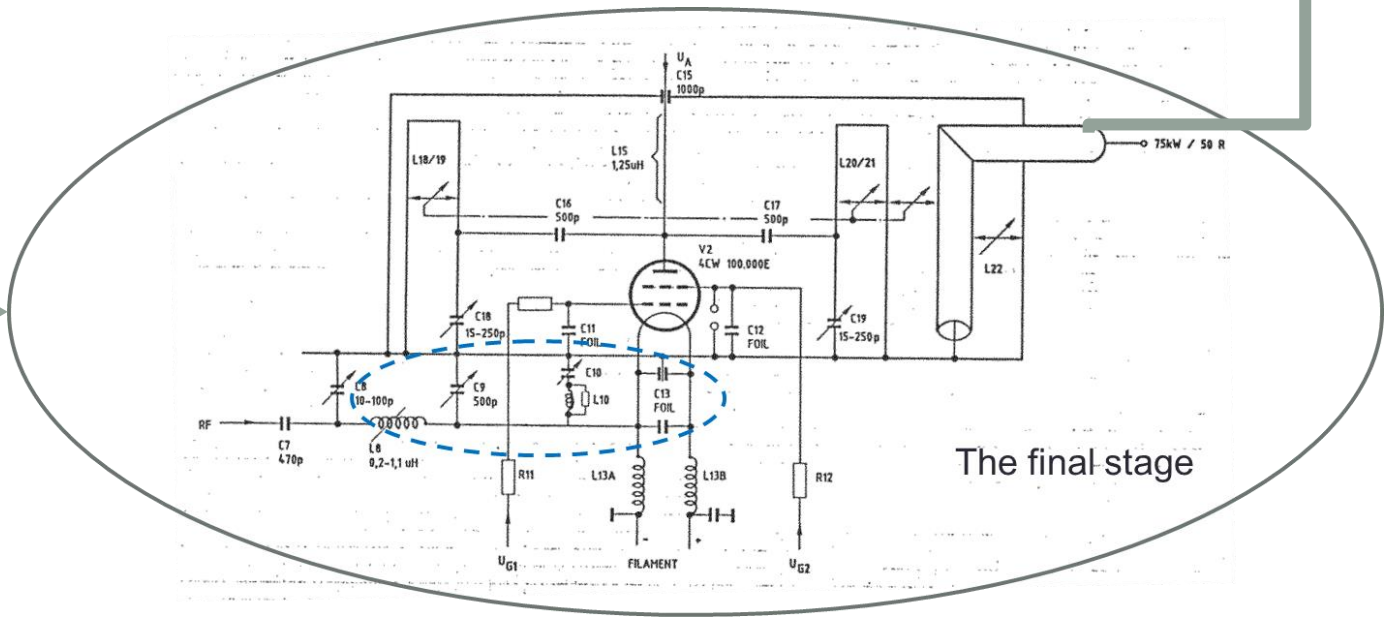
RF_{in}

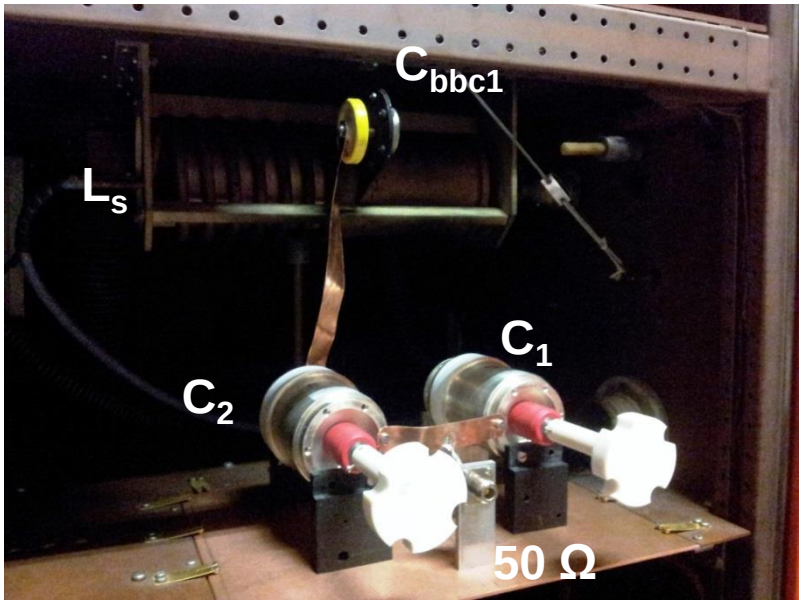
50Ω

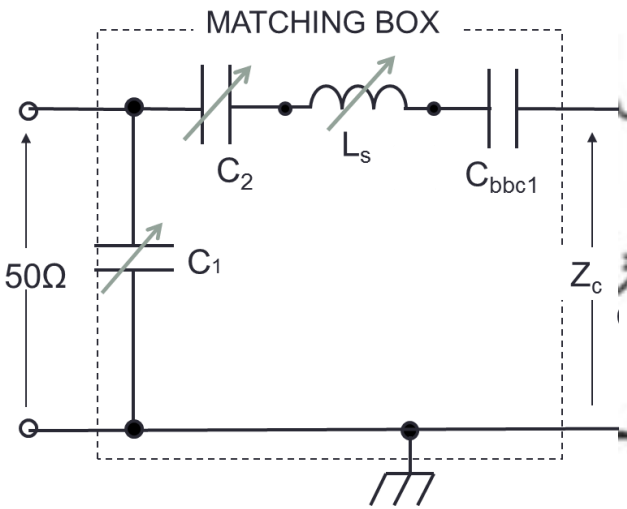


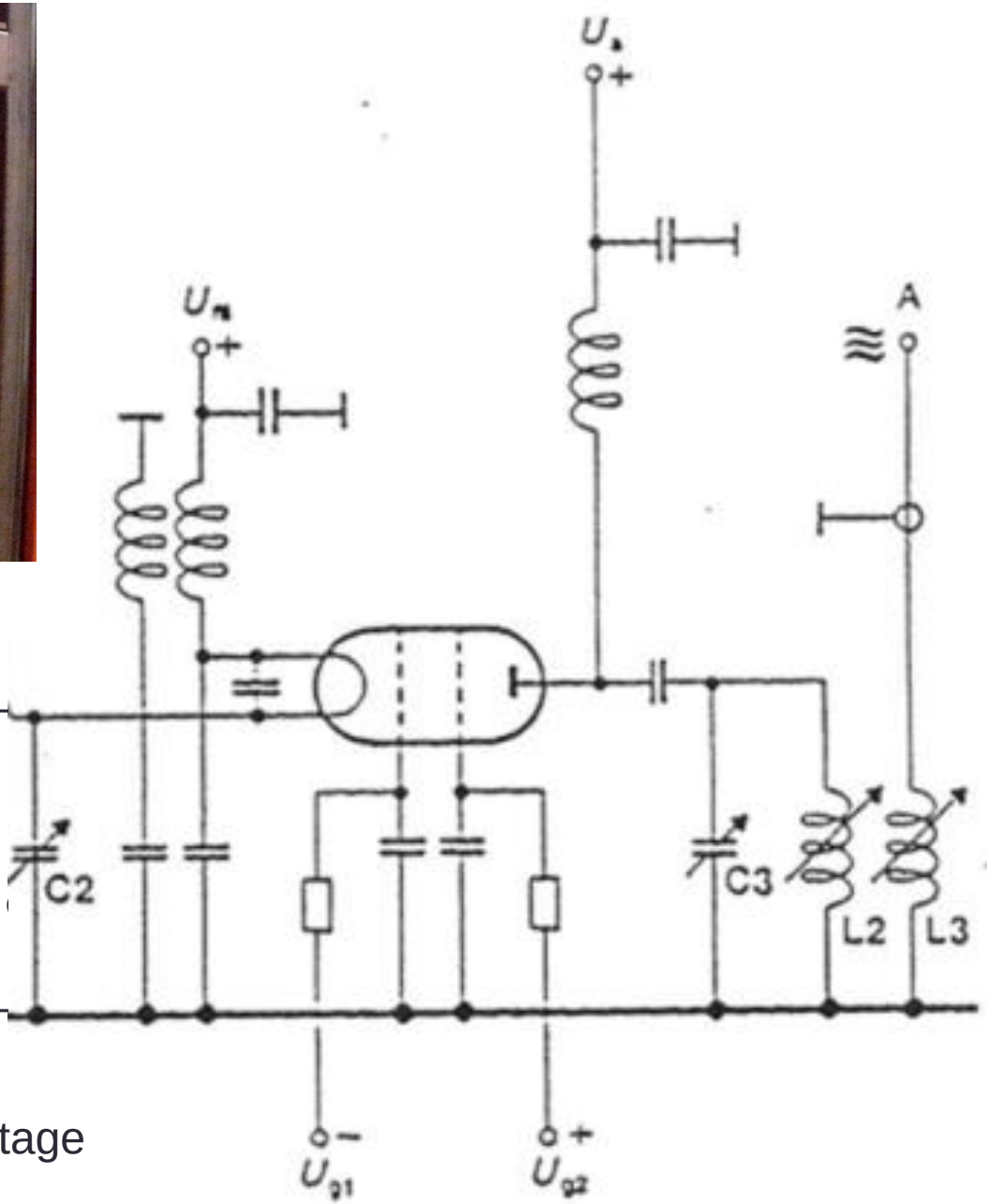
Cyclotron cavity

$Z_{in} = R \pm jX$

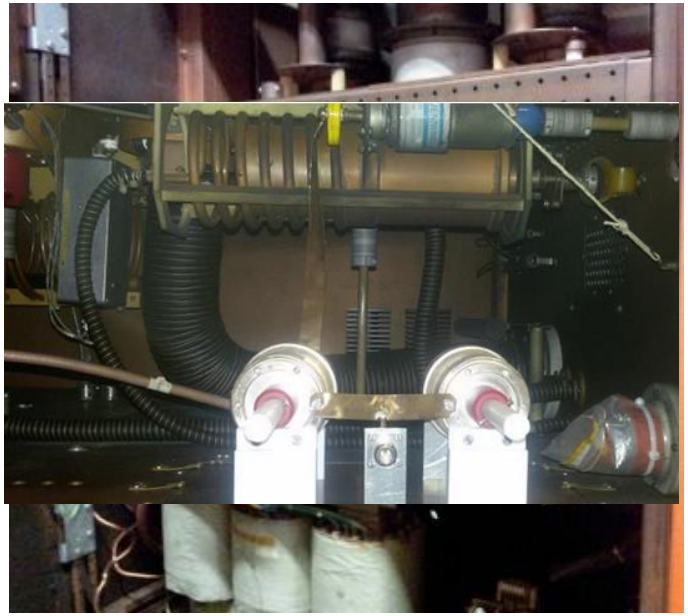


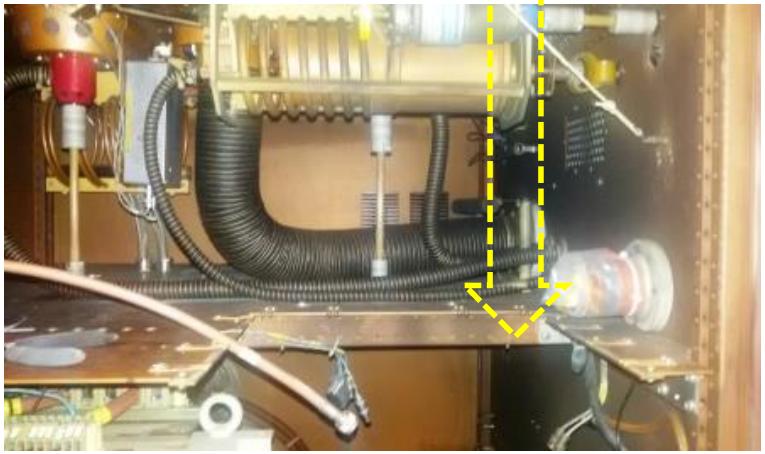






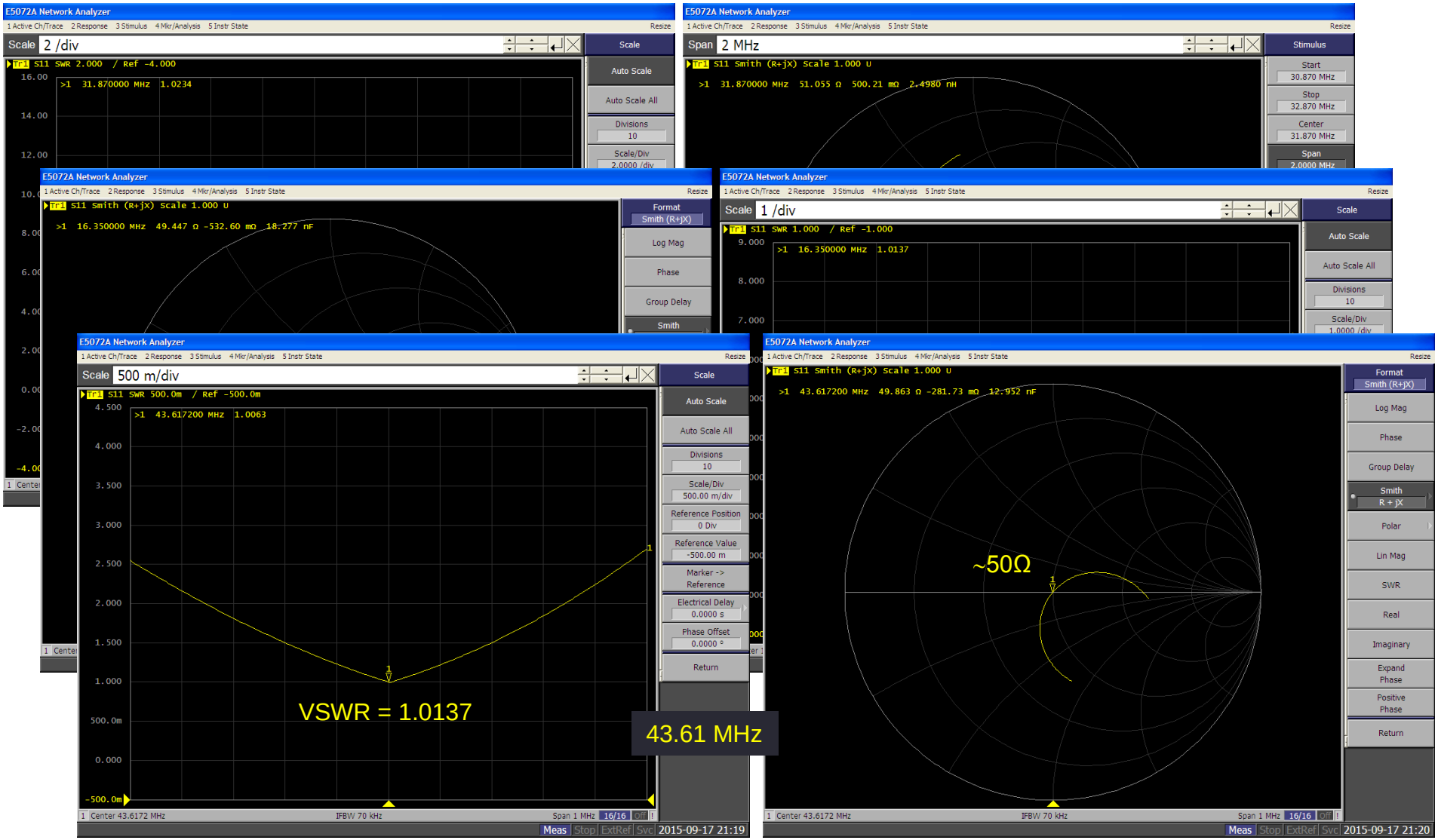
Inside the amplifier instead of 1st stage



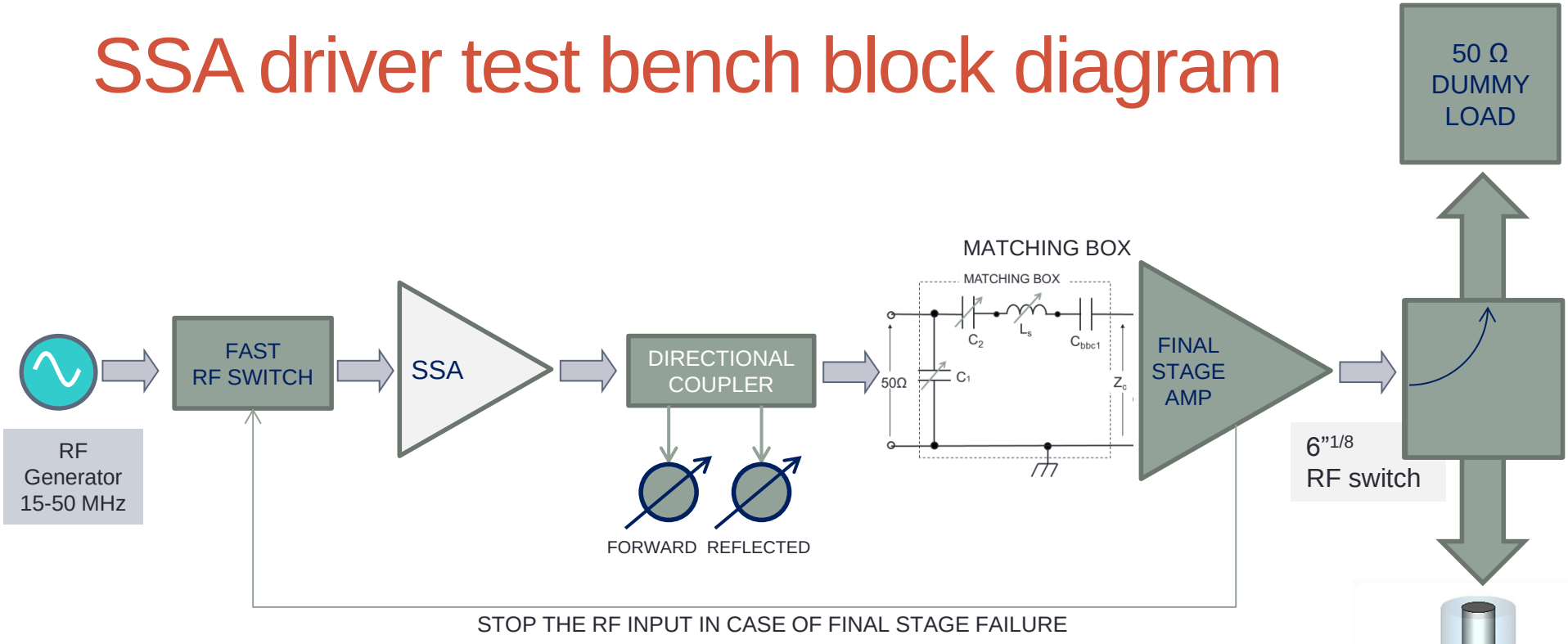


The matching box already installed instead of the 1st stage RS1054LSC in one of the 3 amplifiers

Matching measurements



SSA driver test bench block diagram



16 – 43 MHz

P_{IN}~ 200μV

From LLRF

AR 2500A225 Amplifier Research

2500W, 10 kHz–100 MHz

2500–1900W, 100 MHz–225 MHz

Gain 64 dB min

P_{SSA}~ 500W

FINAL
STAGE
AMP

Gain ~16 dB

P_{OUT} ~ 20kW

Cyclotron
Resonator

Courtesy of L.Piazza

Beams delivered with SSA as permanent driver of Cavity 3

36.8534 MHz

P_{IN}~ 158μV

From LLRF

AR 2500A225 Amplifier Research

2500W, 10 kHz–100 MHz

2500–1900W, 100 MHz–225 MHz

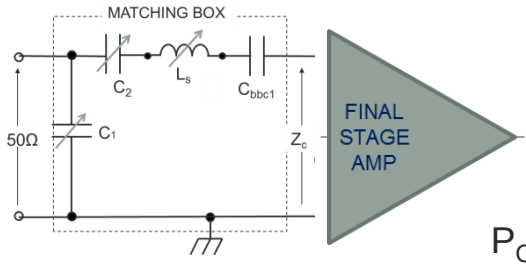
Gain 64 dB min

CLASS A - AB

SSA

P_{SSA}~ 400W

(~56 dBm)



Gain ~16 dB

P_{OUT} ~ 16kW

55 MeV/amu

16.35 MHz

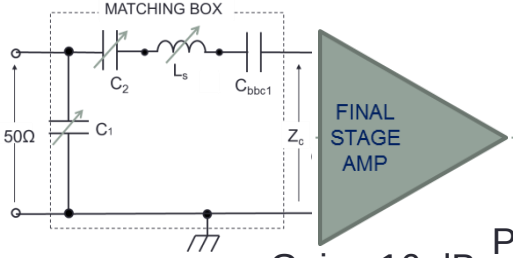
P_{IN}~ 400μV

From LLRF

SSA

P_{SSA}~ 160W

(~52 dBm)



Gain ~16 dB

P_{OUT} ~ 7 kW

10 MeV/amu

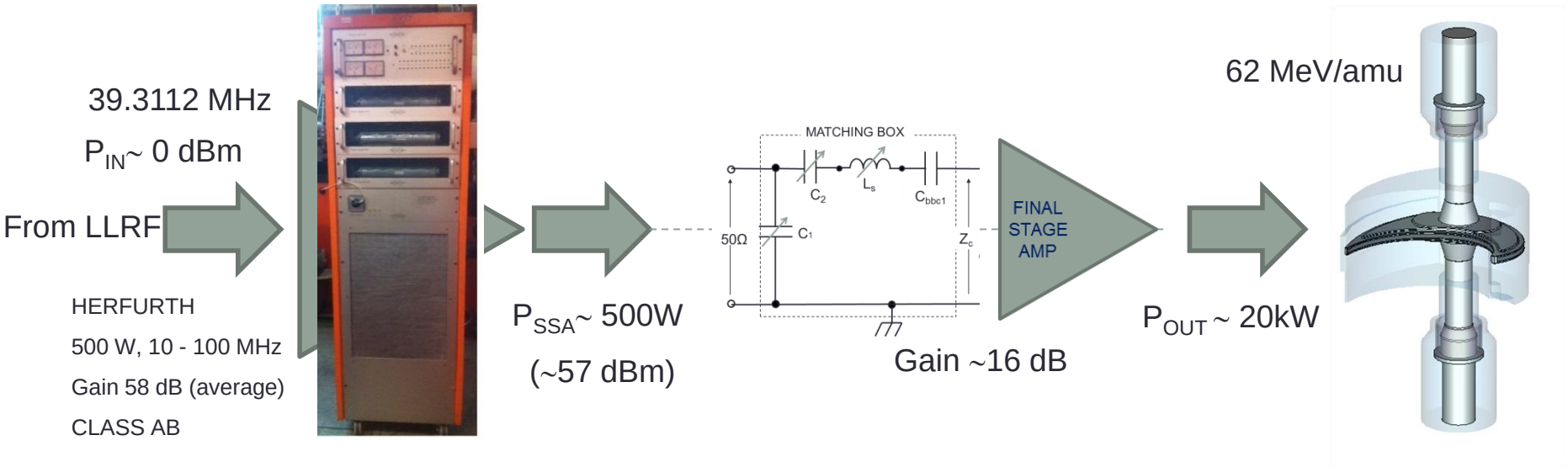
2071 EM POWER

300 W, 1 MHz–100 MHz

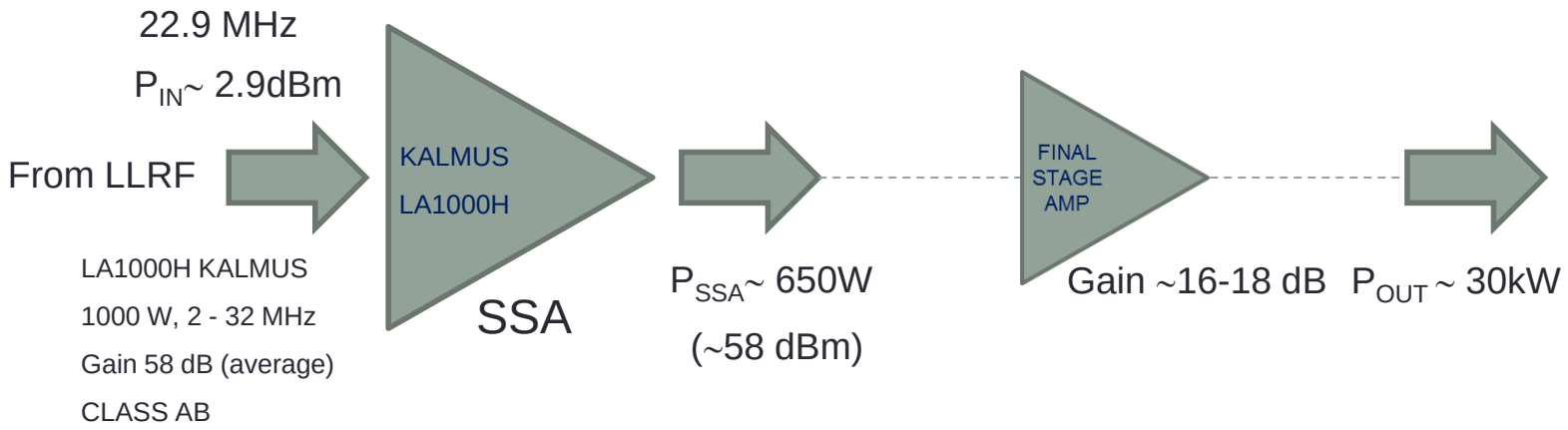
Gain 56 dB

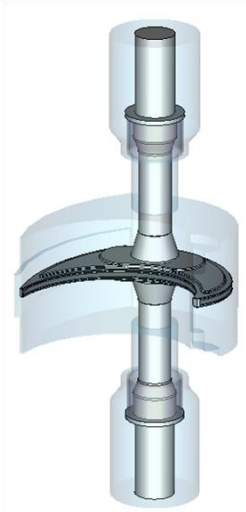
CLASS AB

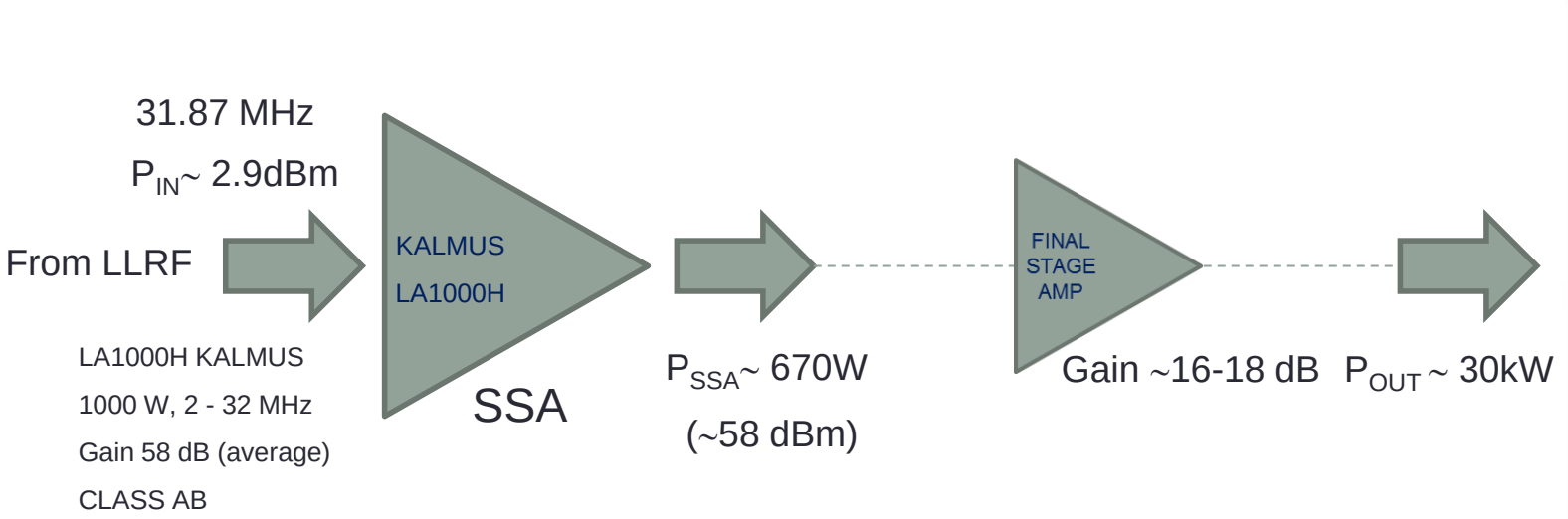
Beams delivered with SSA as permanent driver of Cavity 3

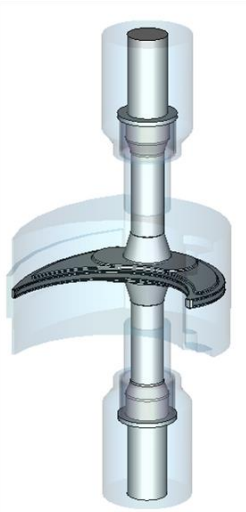


SSA as driver amplifier (preliminary test on Cavity 2)

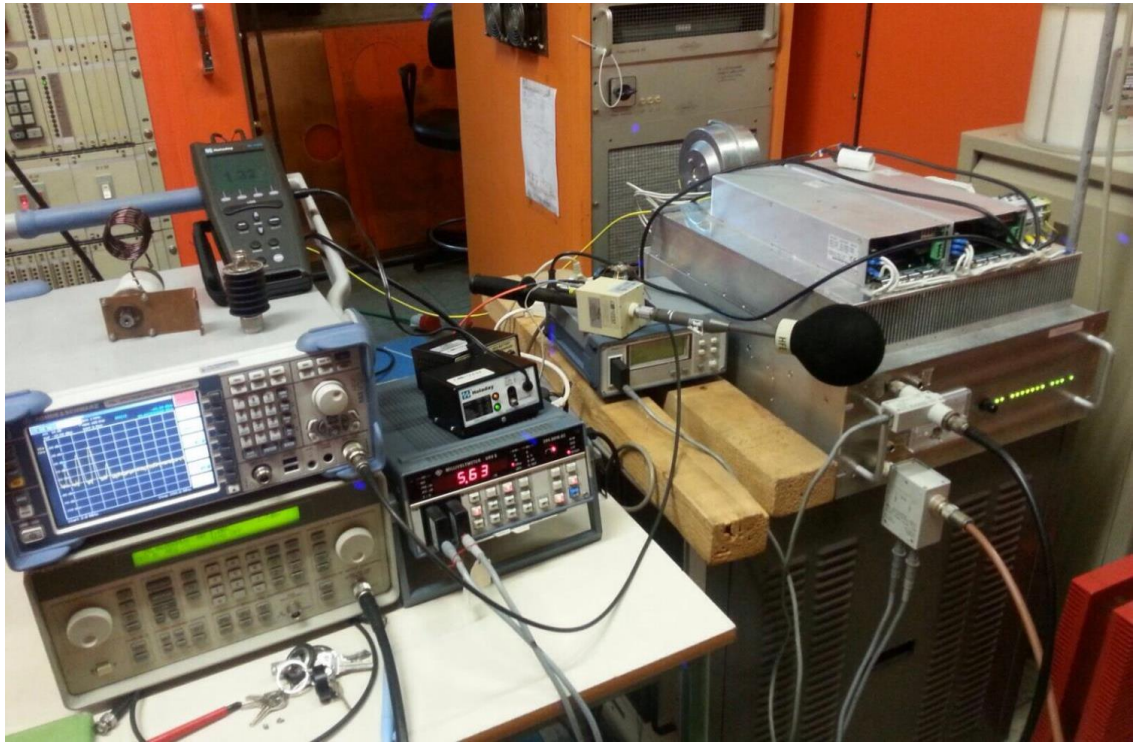








Test bench driver dB-Science



16 - 29 MHz

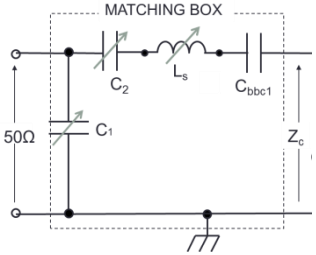
P_{IN}~ 0 dBm

RF in

dB Elettronica

P_{SSA}~ 500W

(~+57 dBm)



Gain ~16 dB

FINAL STAGE AMP

P_{OUT} ~ 20kW

DUMMY LOAD

dB prototype

1 kW, 2 - 30 MHz

Gain 57 dB (average)

DRIVER BASED ON NEW LDMOS FREESCALE

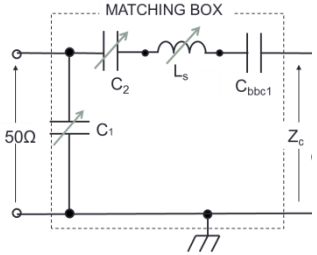
We got a pre assembled board and made a driver amplifier…

33.74 MHz
29.835 MHz
16.35 MHz
39.3112 MHz

LDMOS Transistor
>1 kW, 2-600 MHz

P_{IN}~ 0 dBm

From LLRF → 1W (~+30 dBm) → FREESCALE OR NXP → P_{SSA}~ 500W (~+57 dBm) → MATCHING BOX → FINAL STAGE AMP → P_{OUT} ~ 20kW



Gain ~16 dB

DUMMY LOAD

INFN/LNS prototype
1 kW, 1.8 - 54 MHz
Gain 27 dB (average)

Output Power ≥ 1kW

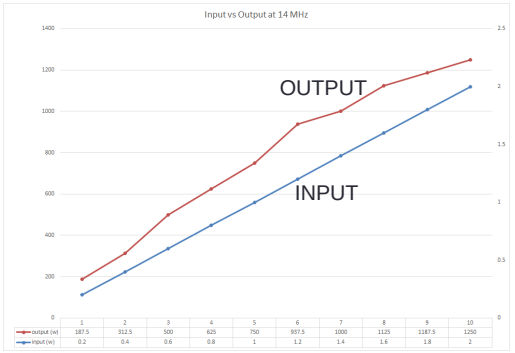
Flatness ± 1.5 dB

Gain ~ 27 dB

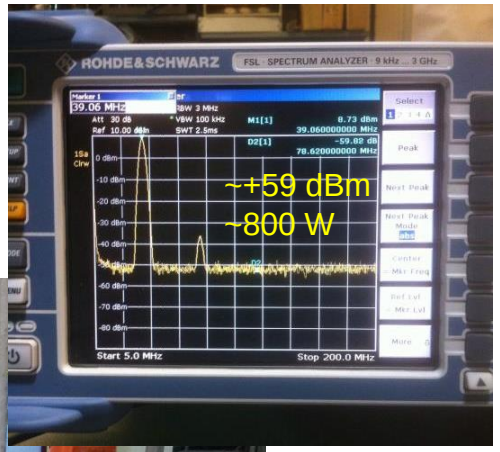
Mismatch max tested 2:1

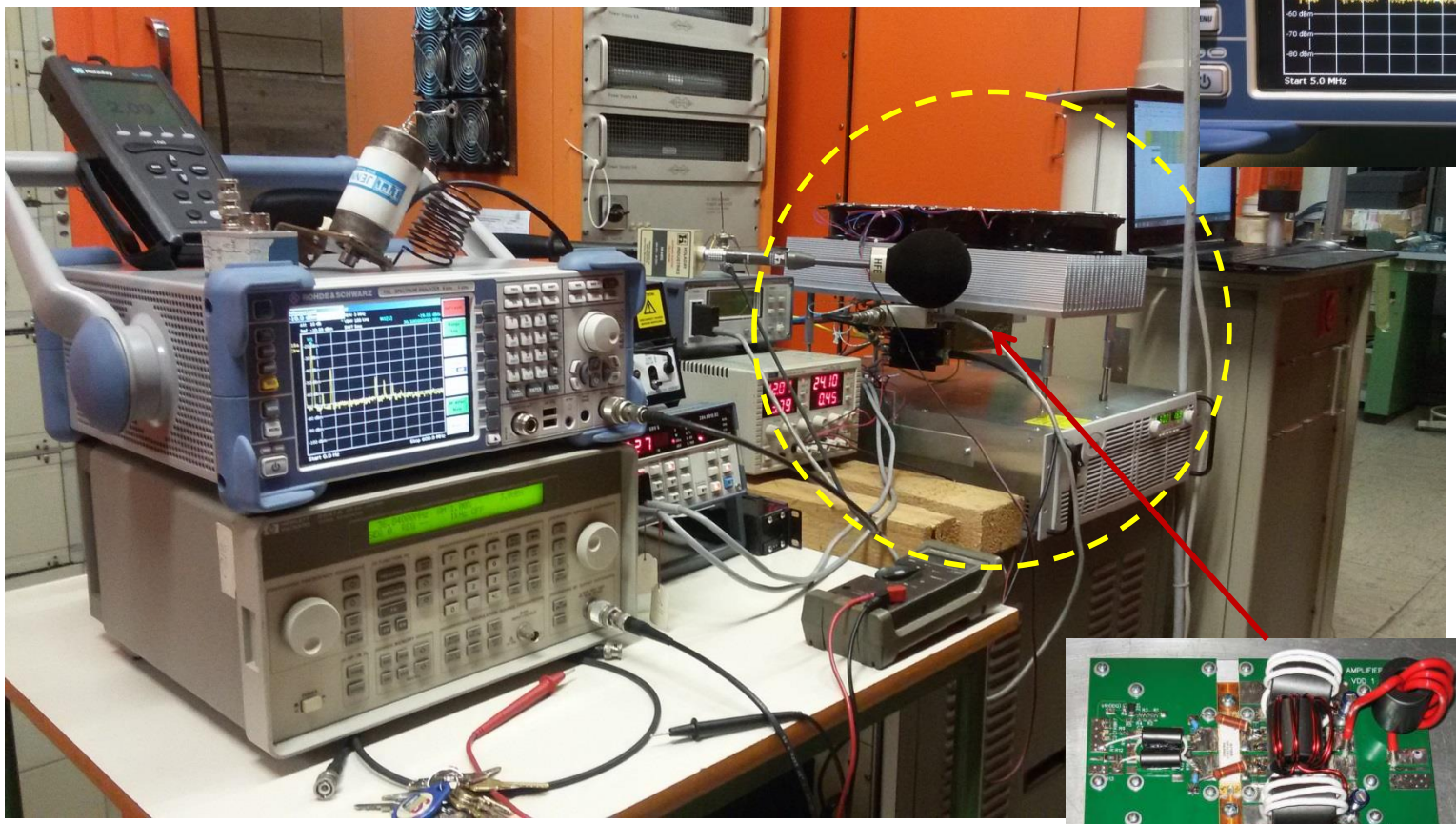
Frequency range 1.8 - 54 MHz

MRFE6VP61K25HR6 (FREESCALE)



Test bench LDMOS TEST





COMPONENTS

Freescale Semiconductor
Technical Data

Document Number: MRFE6VP61K25H
Rev. 4.1, 3/2014

RoHS

RF Power LDMOS Transistors

High Ruggedness N-Channel
Enhancement-Mode Lateral MOSFETs

These high ruggedness devices are designed for use in high VSWR industrial (including laser and plasma exciters), broadcast (analog and digital), aerospace and radio/land mobile applications. They are unmatched input and output designs allowing wide frequency range utilization, between 1.8 and 600 MHz.

- Typical Performance: V_{DD} = 50 Volts, I_{DQ} = 100 mA

Signal Type	P_{out} (W)	f (MHz)	G_{ps} (dB)	η_D (%)
Pulse (100 µsec, 20% Duty Cycle)	1250 Peak	230	24.0	74.0
CW	1250 CW	230	22.9	74.6

Application Circuits (1) — Typical Performance

Frequency (MHz)	Signal Type	P_{out} (W)	G_{ps} (dB)	η_D (%)
27	CW	1300	27	81
40	CW	1300	26	85
81.36	CW	1250	27	84
87.5–108	CW	1100	24	80
144–148	CW	1250	26	78
170–230	DVB-T	225	25	30
352	Pulse (200 µsec, 20% Duty Cycle)	1250	21.5	66
352	CW	1150	20.5	68
500	CW	1000	18	58

1. Contact your local Freescale sales office for additional information on specific circuit designs.

Load Mismatch/Ruggedness

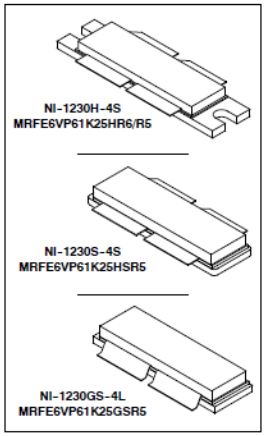
Frequency (MHz)	Signal Type	VSWR	P_{out} (W)	Test Voltage	Result
230	Pulse (100 µsec, 20% Duty Cycle)	> 65:1 at all Phase Angles	1500 Peak (3 dB Overdrive)	50	No Device Degradation

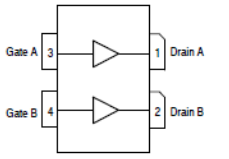
Features

- Unmatched Input and Output Allowing Wide Frequency Range Utilization
- Device can be used Single-Ended or in a Push-Pull Configuration
- Qualified Up to a Maximum of 50 V_{DD} Operation
- Characterized from 30 V to 50 V for Extended Power Range
- Suitable for Linear Application with Appropriate Biasing
- Integrated ESD Protection with Greater Negative Gate-Source Voltage Range for Improved Class C Operation
- Characterized with Series Equivalent Large-Signal Impedance Parameters
- In Tape and Reel. R6 Suffix = 150 Units, 56 mm Tape Width, 13-inch Reel. R5 Suffix = 50 Units, 56 mm Tape Width, 13-inch Reel.

MRFE6VP61K25HR6
MRFE6VP61K25HR5
MRFE6VP61K25HSR5
MRFE6VP61K25GSR5

1.8–600 MHz, 1250 W CW, 50 V
WIDEBAND
RF POWER LDMOS TRANSISTORS





(Top View)

Note: The backside of the package is the source terminal for the transistors.

Figure 1. Pin Connections

freescale

BLF188XR; BLF188XRS

Power LDMOS transistor

Rev. 5 — 12 November 2013 Product data sheet

1. Product profile

1.1 General description

A 1400 W extremely rugged LDMOS power transistor for broadcast and industrial applications in the HF to 600 MHz band.

Table 1. Application information

Test signal	f (MHz)	V_{DS} (V)	P_L (W)	G_p (dB)	η_D (%)
CW	2 to 30	50	1270	29.0	75
	27	50	1400	23.7	73
	41	50	1200	22.0	82
	60	48	1240	22.0	77
	72.5	50	1350	23.1	83
	81.4	50	1200	27.1	77.8
	88 to 108	50	1320	22.5	85
	108	50	1200	26.5	83
	200	50	1288	19.3	68.3
pulsed RF	81.4	50	1200	25.8	85
	81.4	50	1400	25.4	81
	108	50	1400	24.0	73
DVB-T	174 to 230	50	225	23.8	29

1.2 Features and benefits

- Easy power control
- Integrated ESD protection
- Excellent ruggedness
- High efficiency
- Excellent thermal stability
- Designed for broadband operation (HF to 600 MHz)
- Compliant to Directive 2002/95/EC, regarding Restriction of Hazardous Substances (RoHS)

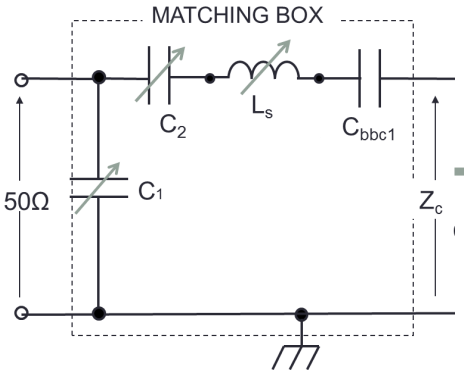
1.3 Applications

- Industrial, scientific and medical applications
- Broadcast transmitter applications

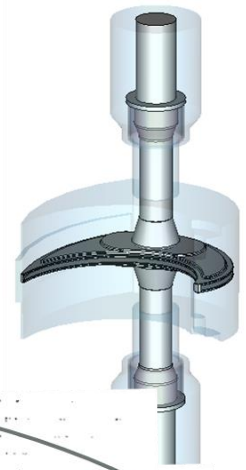
NXP

RF_{in}

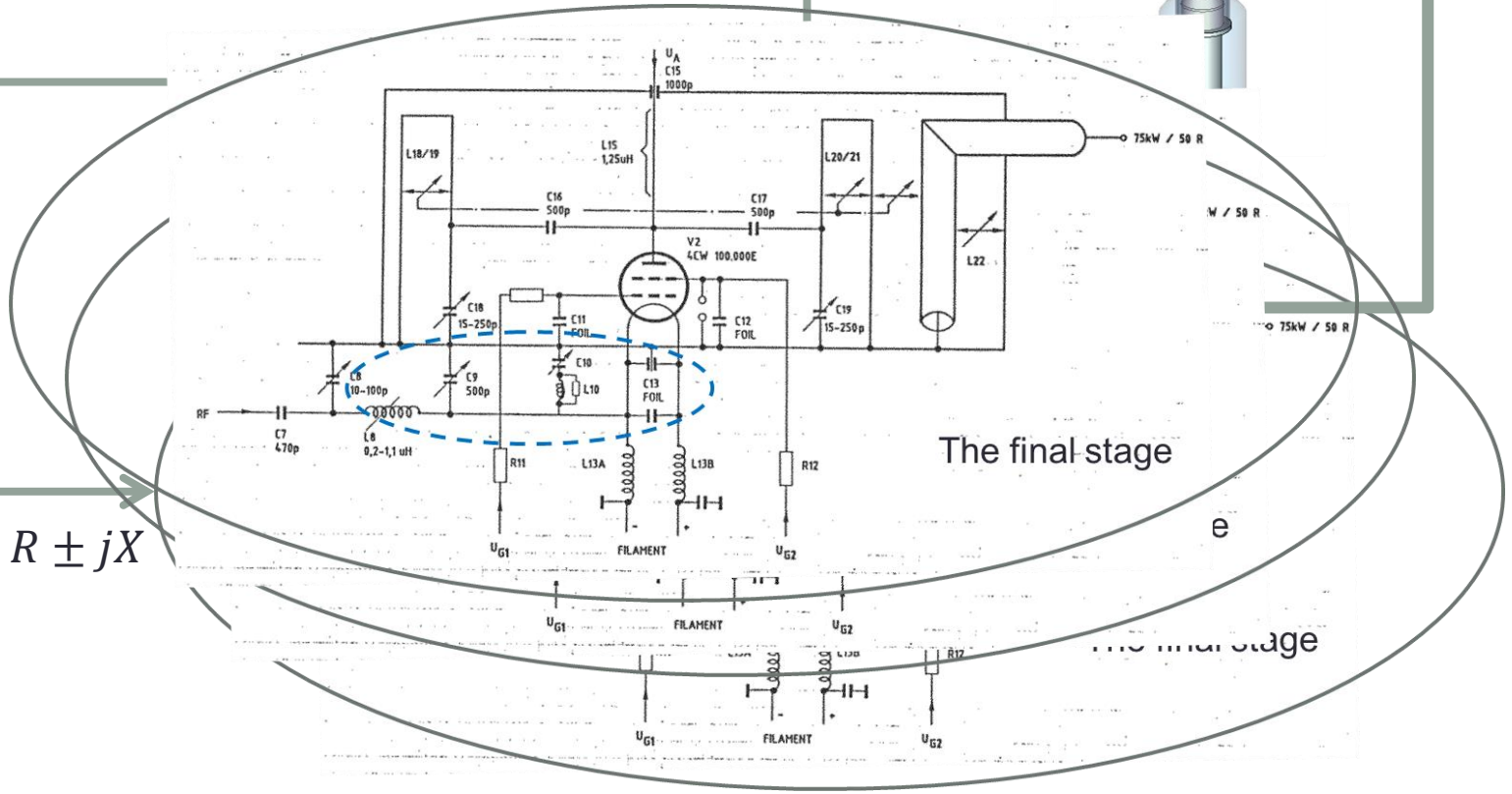
50Ω



Cyclotron cavity



$Z_{in} = R \pm jX$



Conclusions

- The whole frequency range is achieved (15 – 50 MHz);
- Mismatch up to 2.0:1 was tested too (30%);
- The matching network works very well with lot of final 1st stage configuration (tetrode, mosfet, bjt, etc) of the SSA drivers;
- Enough power, 20-30 kW, at the output of the final tetrode, was achieved;
- Automatic tuning of the matching network, in the near future;
- Better integration of the 1st stage with the amplifier;

- Gained lot of know how, useful in the next phase, to prepare the line guide for a proper 1st stage (custom and/or commercial).

Thank you for your kind attention

Working Group

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1.INFN-LNS – Catania, Italy

2. Warsaw University, Warsaw, Poland

References:

- THALES RS1054LSC, data sheet;
- THALES TH298, data sheet;
- EIMAC 4CX3500, data sheet;
- MRFE6VP61K25HR6 (FREESCALE), data sheet;
- BLF188XR (NXP), data sheet;
- http://www.w6pql.com/ (James Klitzing – Custom Radio Equipment CA-USA)
- Integrated Electronic: analog and digital circuits and system, Millman-Halkias; Mc Graw-Hill (New York)
- Electronic and Radio Engineering, Terman, Mc Graw-Hill (New York);
- Manuale di elettronica e telecomunicazioni, Biondo – Sacchi, Hoepli.