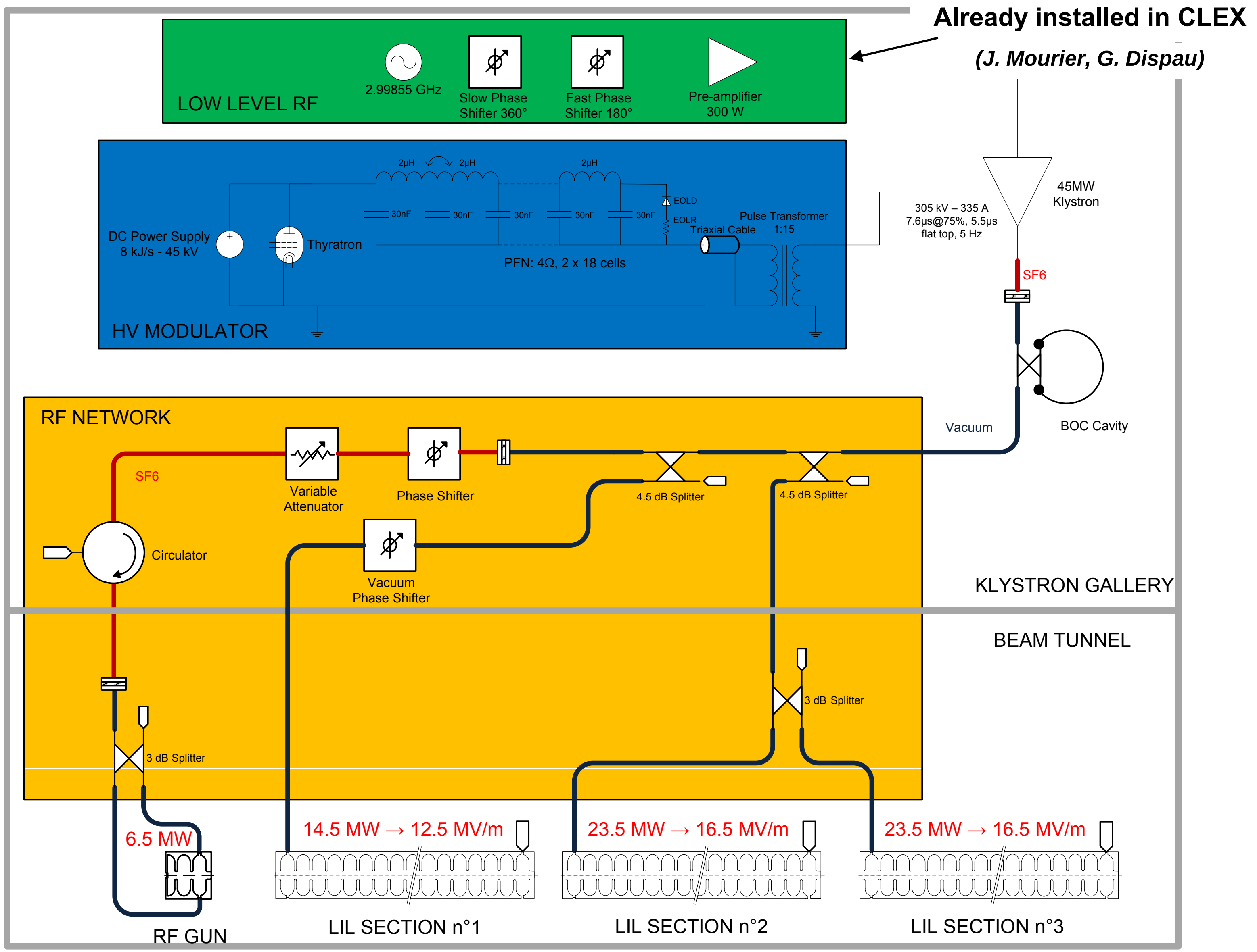
High Power RF for CALIFES

- General Layout of the RF system
- High Voltage Modulator
- 3D Layout of RF Network
- RF Power Phase Shifter and 4.5 dB Power Splitter
- Transient behaviour of gun and LIL sections

General Layout of the CALIFES RF System



Already installed in CLEX

(J. Mourier, G. Dispau)

TH2100C Klystron

- Highest S-band peak power klystron procured by Thales: 45 MW RF power during 5.5 µs
- Five integrated cavities klystron, vertical position
- Electromagnetic beam confinement by solenoid
- Collector and body water-cooled
- Output waveguide pressurized by SF6 at 4 bars (absolute pressure)

Parameters	Specifications	Units
RF Frequency	2998.5	MHz
Peak RF Power	45	MW
RF Gain	54	dB
Efficiency	44	%
RF Pulse Length	5.5	µs
Nominal Klystron Voltage	305	kV
Nominal Klystron Current	335	A
High Voltage Pulse Length @ 75%	7.6	µs
Pulse repetition rate	5	Hz
Average Collector Power	3.6	kW
Peak RF Drive Power	400	W
Total height	1.7	m
Weight	70	kg

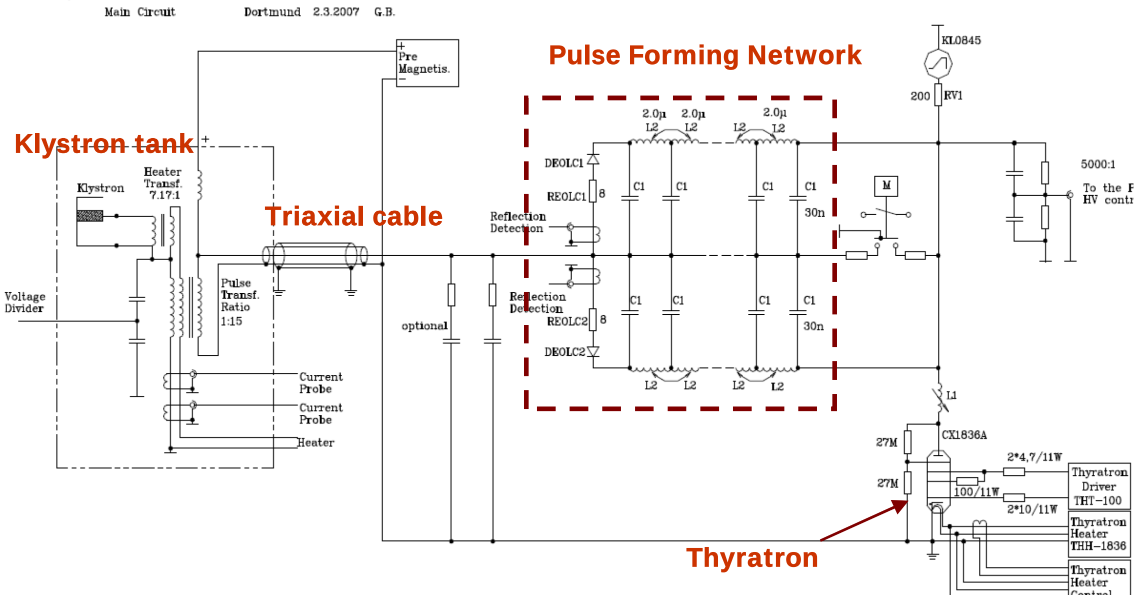
Delivery time for klystron and solenoid: 04.04.08 (CERN)

High voltage modulator

- **Procured by Puls-Plasmatechnik GmbH (Germany)**
- Capacitor charging unit 45 kV / 8 kJ/s from PPT/Poynting
- Thyratron CX1836A from EEV for high voltage switch
- Pulse Forming Network (PFN): 4Ω impedance, 2 lines in parallel, 2 x 18 cells (30nF/2µH each)
  - Inductance = single layer coil + aluminium core
  - mutual coupling between the inductances

Better approximation of a rectangular pulse shape (Guillemin type E network [1])

- Pulse transformer ratio 1:15 and tank with x-y-z frame from Stangenes
- Associated power supplies (magnet, heater, ion pump)
- Transport system to remove the klystron in the maintenance area
- Control system based on a PLC SIEMENS S7 300, with ethernet interface and "fetch and write" protocol for remote communication



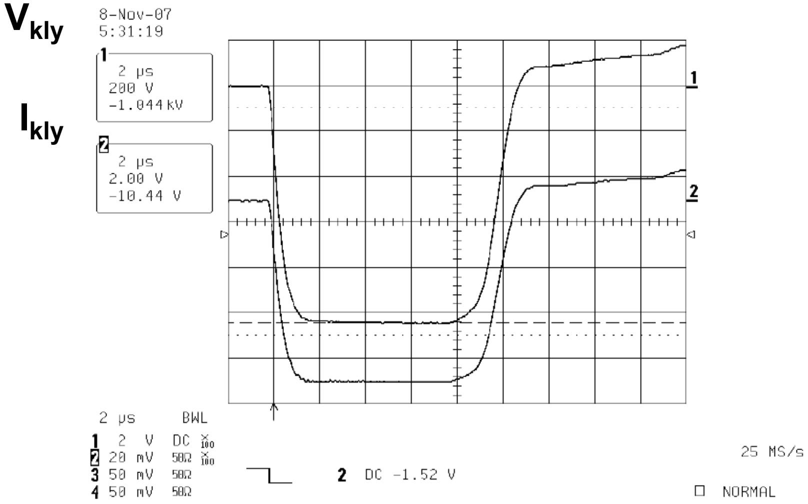
Parameters	Specifications	Units
Peak voltage	320	kV
Peak current	360	A
Pulse length (flat top)	5.5 min	µs
Pulse repetition rate	5	Hz
Inverse voltage (out of the pulse)	70 max	kV
Pulse voltage ripple	± 0.25 max	%
Pulse to pulse stability	± 0.1 max	%
Rise time 10 – 90 %	1 max	µs
Fall time 90 – 10 %	2 max	µs
Pulse width at 75 %	7.6 max	µs

[1] Glasoe and Lebacqz: « Pulse Generators », MIT Radiation Lab Series, vol. 5, McGraw-Hill Book company, New York, 1948

Factory test of the modulator

Done the 8-9th of November 2007 with CEA and CERN (S. Curt, G. McMonagle):

- Very good results for the pulse quality
  - measured at low voltage (250V) after the pulse transformer on a 900 Ω dummy load
  - flat top = 6 µs and ripple = +/- 0.23 %
  - rise time = 0.95 µs, fall time = 1.6 µs, FWHM = 9.65 µs, Width at 75% = 8.97 µs
- Pulse to pulse stability OK
  - measured value = 0.1 %, at 43 kV – 5.5 kA on 5.4Ω dummy load before pulse transformer at 0.3 Hz because of temperature drift of the load
- Pulse length too long
  - from 8.97µs to 7.6 µs at 75% of height because of klystron acceptance
  - remove one or two capacitances on each line
- Reverse voltage too high
  - measured value = 24%
  - specified value 70kV/305kV = 23%



Pulse quality Low level (250V) PFN , absolute value

Installation of the modulator in CLEX

- Delivery at CERN (week 47)
- Mechanical installation (week 48 and 49)
  - – racks and tank installed and connected
  - – water cooling and line voltage installed by CERN
  - – installation of a spare TH2100C klystron S/N 094011 with solenoid and PPT lead shielding
  - – Test of the transportation of the tank+klystron+lead shielding to the maintenance area OK

- Control system
  - – local control tested and explained to CERN
  - – remote control: discussion on the connection and structuring the data
- Calibration
  - – setting and calibration of all the auxiliary Power Supplies (PS) with the PLC values
  - – problem with ion pump PS: defect on the HV cable → replaced by a CERN PS
- Tests
  - – machine and person interlocks OK
  - – Tests of the klystron in diode mode with loads on RF ports
  - – High voltage up to 38kV / 2 Hz PFN voltage which corresponds to 250 kV – 280 A on the klystron
  - – inverse voltage < 3% : OK
  - – pulse length = 7.67 μs at 75%: OK
  - – flat top = 5.5 to 5.7 μs: OK

S. Curt, JL. Jannin, J. Marques, G. Rossat, G. Yvon

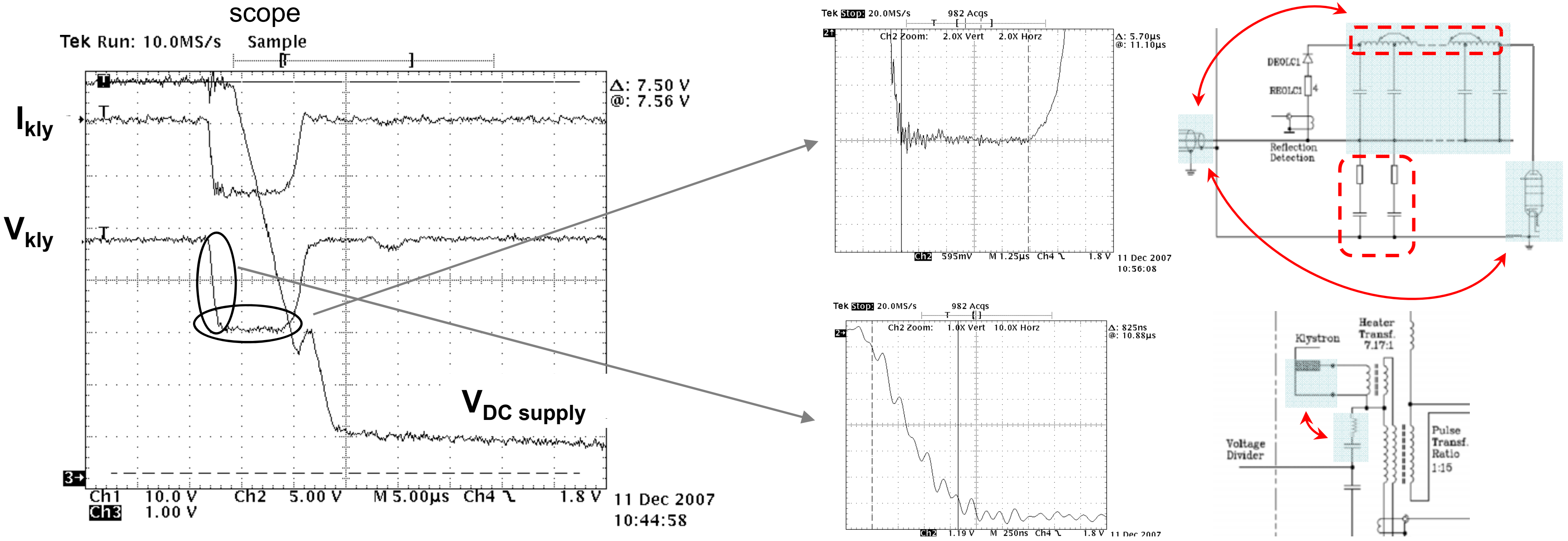
Modulator: Pulse quality problem

Pulse quality problem : ripple on flat top too high = +/- 4 % instead of +/- 0.25%

- long wave on the flat top
- high frequency noise at the beginning of the voltage pulse

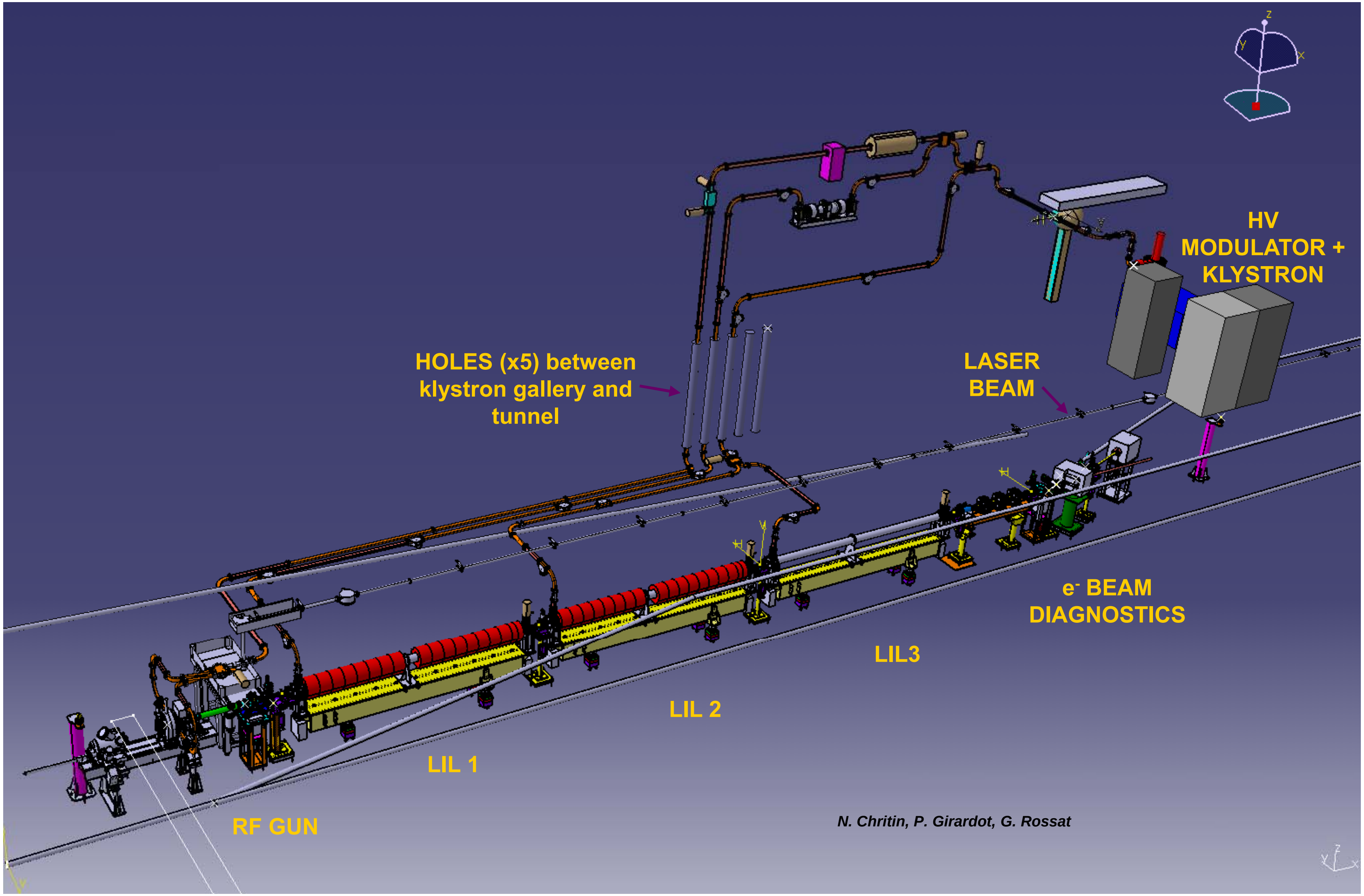
Expertise & solutions:

- – for the long wave ripple: mismatch between PFN or thyratron and triaxial cable
  - → tune the PFN and/or add a RC series combination
- – for the HF noise: measurement problem with Voltage Divider (VD) :
  - •can be due to fast oscillation between the load (klystron) and the resonator composed of the capacitance of the VD and a parasitic self
- – other possibilities: parasitic current between mass, antenna effect with last PFN inductance, unstable scope

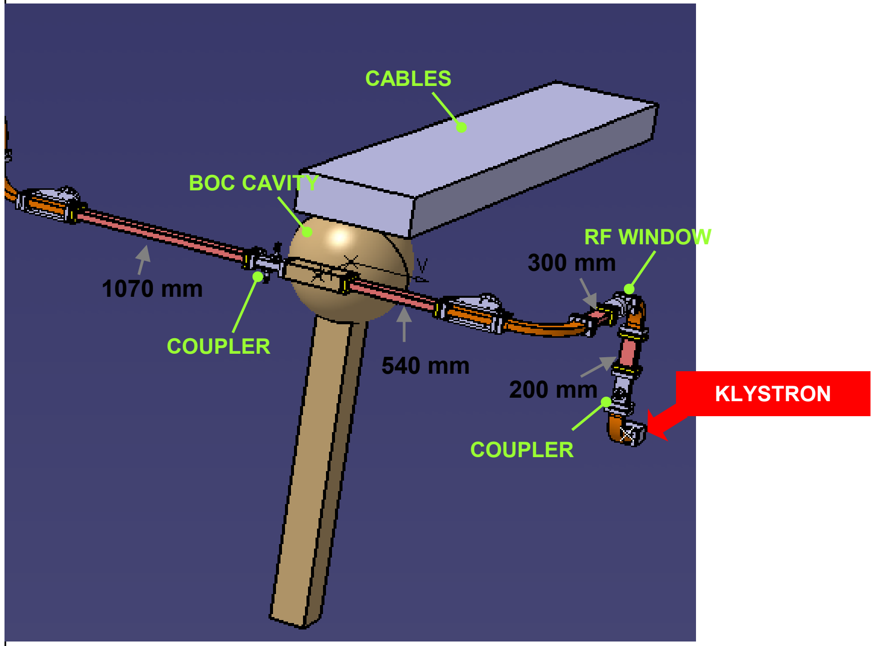


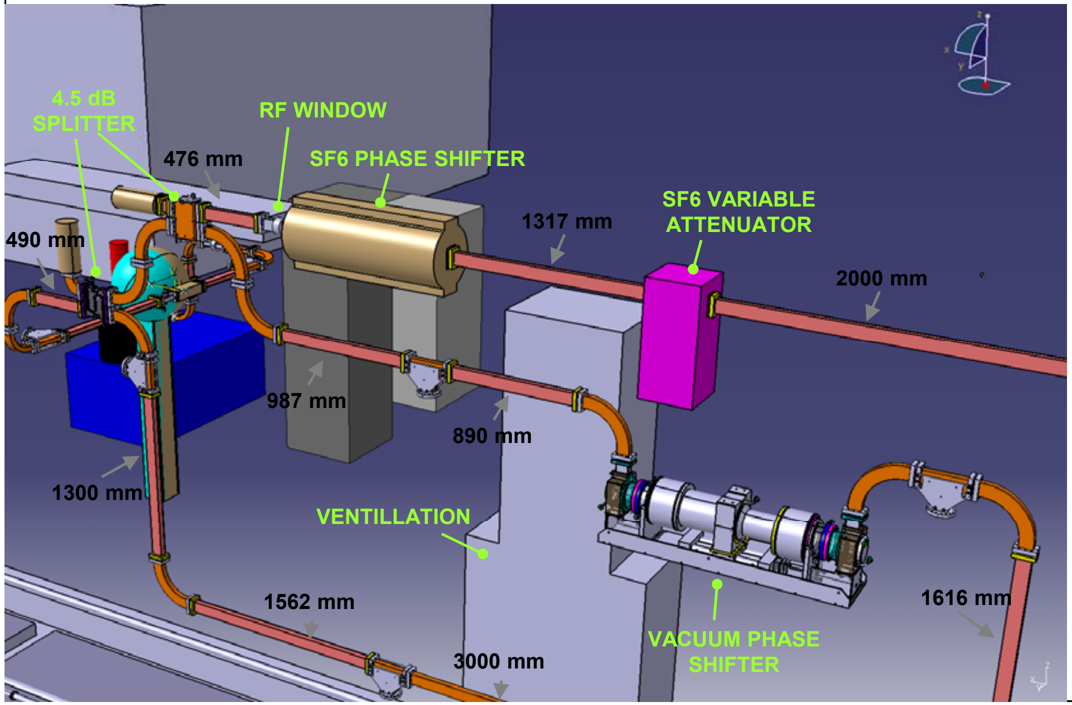
- ➢ Start with RF if possible: phase measurement = best way to check the ripple
- ➢ Next possibility to start and test the modulator : <u>mid March 2008</u> → PPT is confident to reach the specifications

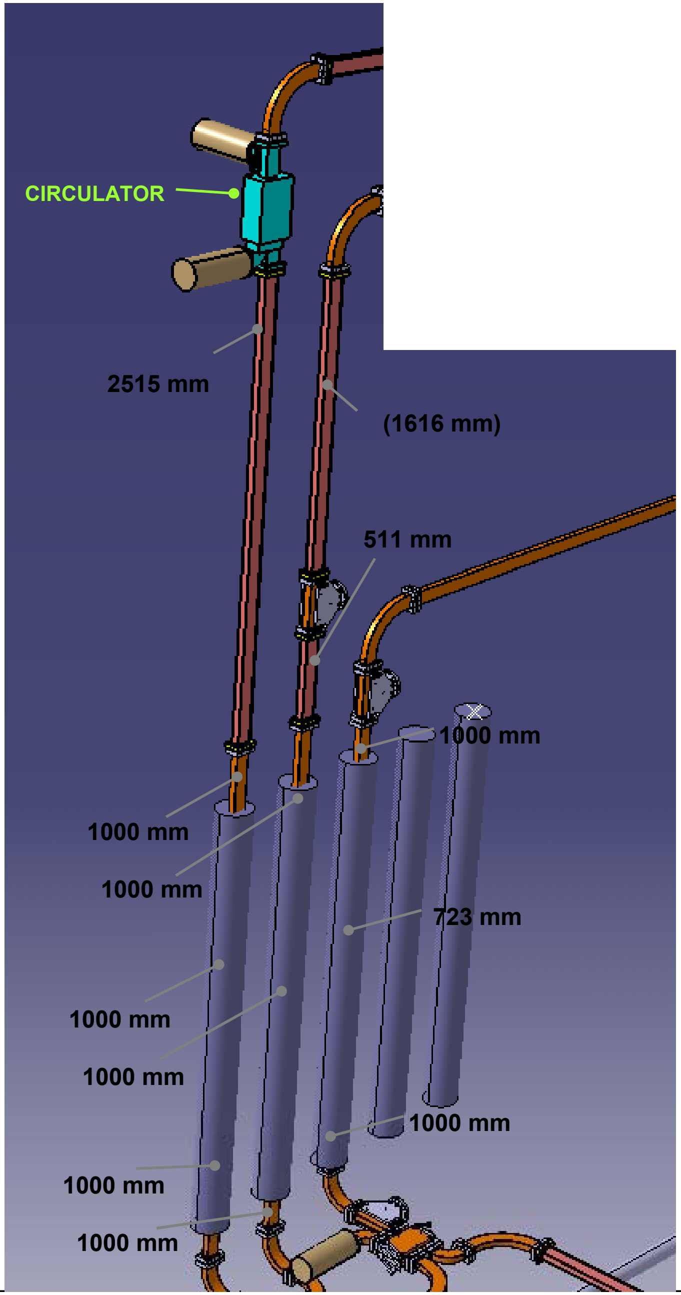
RF Network layout

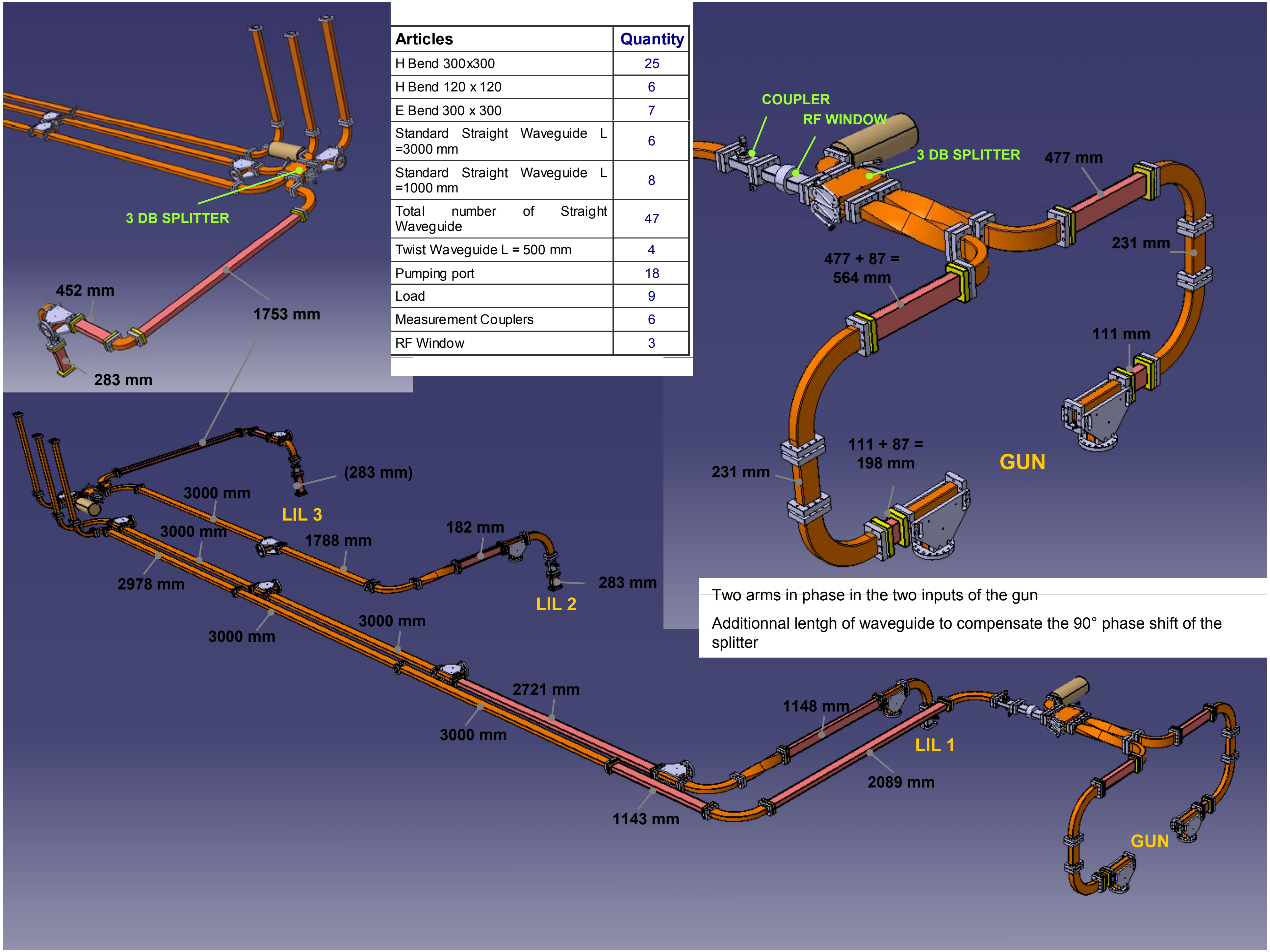


N. Chritin, P. Girardot, G. Rossat


CABLES
BOC CAVITY
RF WINDOW
300 mm
1070 mm
COUPLER
540 mm
200 mm
KLYSTRON
COUPLER


4.5 dB SPLITTER
RF WINDOW
476 mm
SF6 PHASE SHIFTER
490 mm
1317 mm
SF6 VARIABLE ATTENUATOR
2000 mm
987 mm
890 mm
1300 mm
VENTILLATION
1562 mm
3000 mm
VACUUM PHASE SHIFTER
1616 mm


CIRCULATOR
2515 mm
(1616 mm)
511 mm
1000 mm
1000 mm
1000 mm
723 mm
1000 mm
1000 mm
1000 mm
1000 mm
1000 mm



Articles	Quantity
H Bend 300x300	25
H Bend 120 x 120	6
E Bend 300 x 300	7
Standard Straight Waveguide L =3000 mm	6
Standard Straight Waveguide L =1000 mm	8
Total number of Straight Waveguide	47
Twist Waveguide L = 500 mm	4
Pumping port	18
Load	9
Measurement Couplers	6
RF Window	3

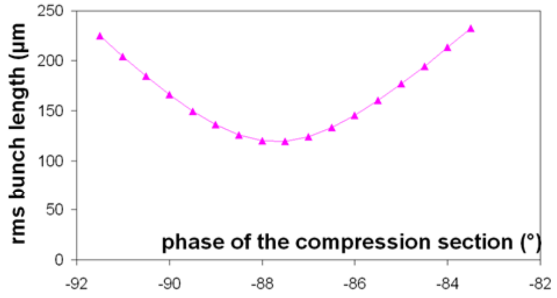
Two arms in phase in the two inputs of the gun

Additionnal lentgh of waveguide to compensate the 90° phase shift of the splitter

Power Phase Shifter on the Bunching Section

- a variation of 1° of the RF phase in the bunching section induce a variation of 20% of the rms bunch length σ_Z

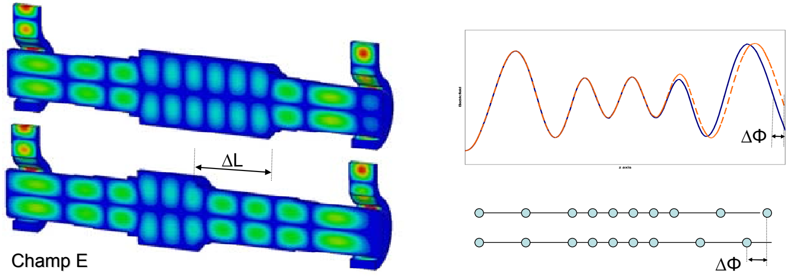
Parmela simulation in single bunch



- Main specifications of the phase shifter

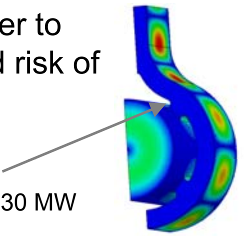
Parameters	**Specifications**
Frequence	3 GHz
Puissance RF crête	25 MW
Impulsion	1.5 µs, 5 Hz
Course max	200 °
Precision	0.5 °
Stabilité	0.1 °
Bande passante $\lvert S_{11}\rvert$	< 27 MHz @ -30 dB

- Principle: phase shift by variation of guided wavelength



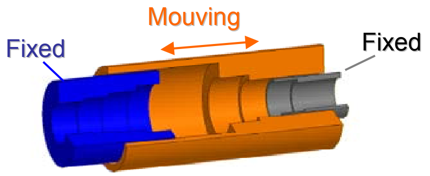
Based on A. Grudiev and SLAC concept

- $TE_{10}^{\square}$ - TE_{01}^{O} mode converter to avoid surface electric field and risk of breakdown

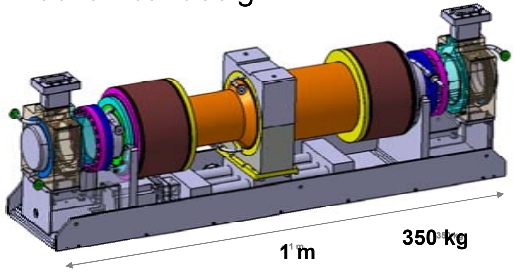


E max = 8.1 MV/m for 30 MW

- Mechanically feasible by three circular waveguides

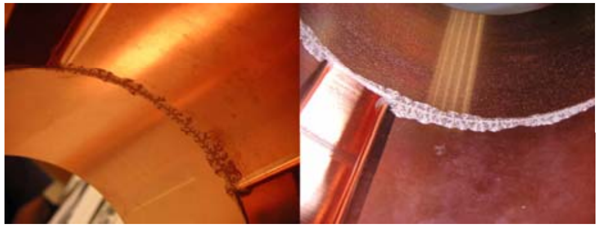


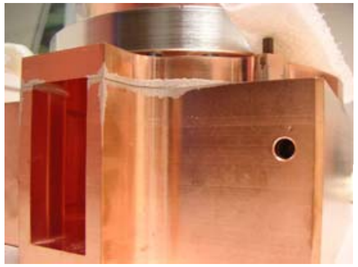
- Mechanical design



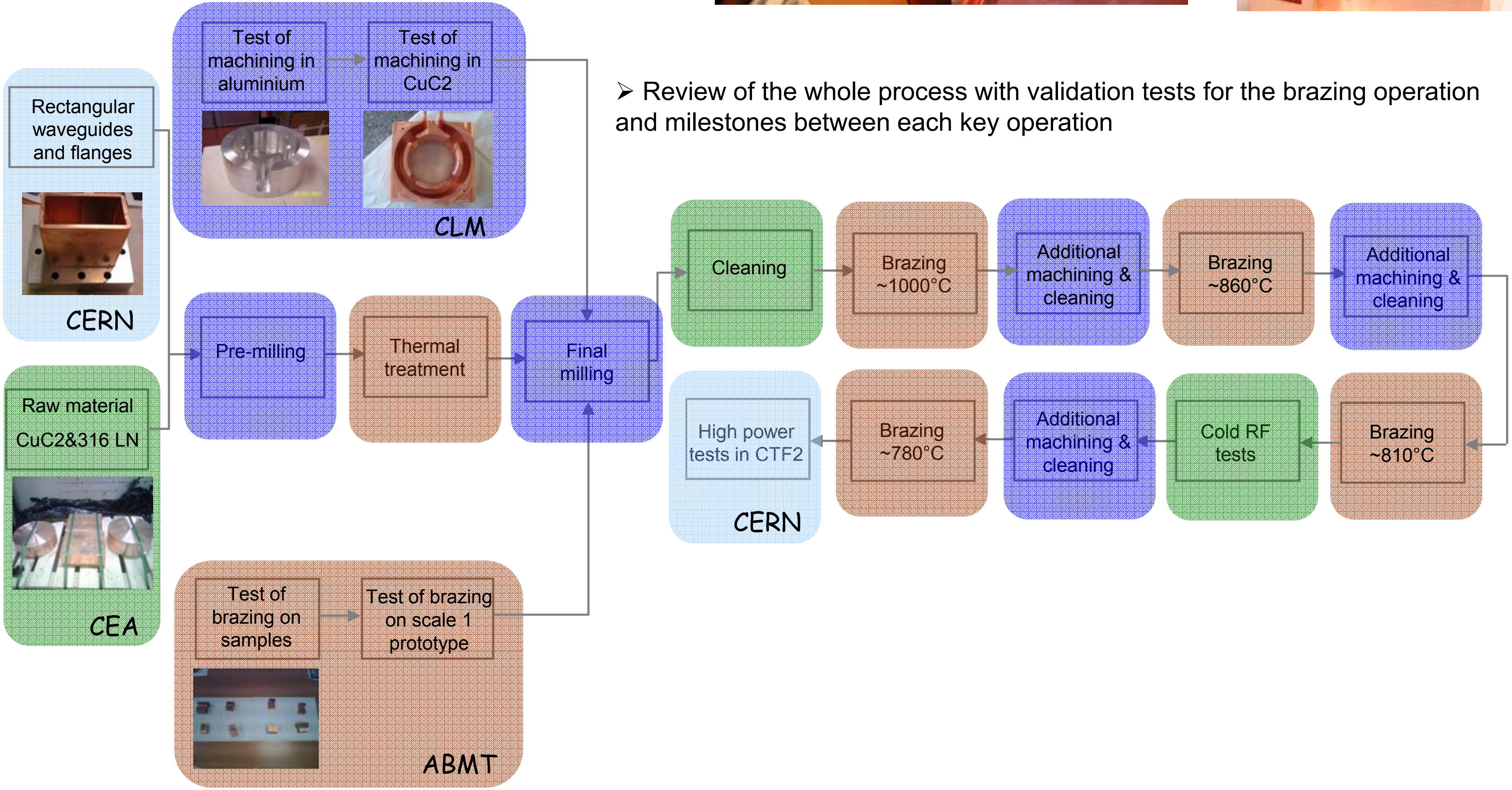
Fabrication of mode converter

- First try of fabrication : milling operation OK but leakage after brazing: bad behavior of the brazing alloy





- Review of the whole process with validation tests for the brazing operation and milestones between each key operation



CERN

Rectangular waveguides and flanges

CEA

Raw material CuC2&316 LN

CLM

Test of machining in aluminium → Test of machining in CuC2

ABMT

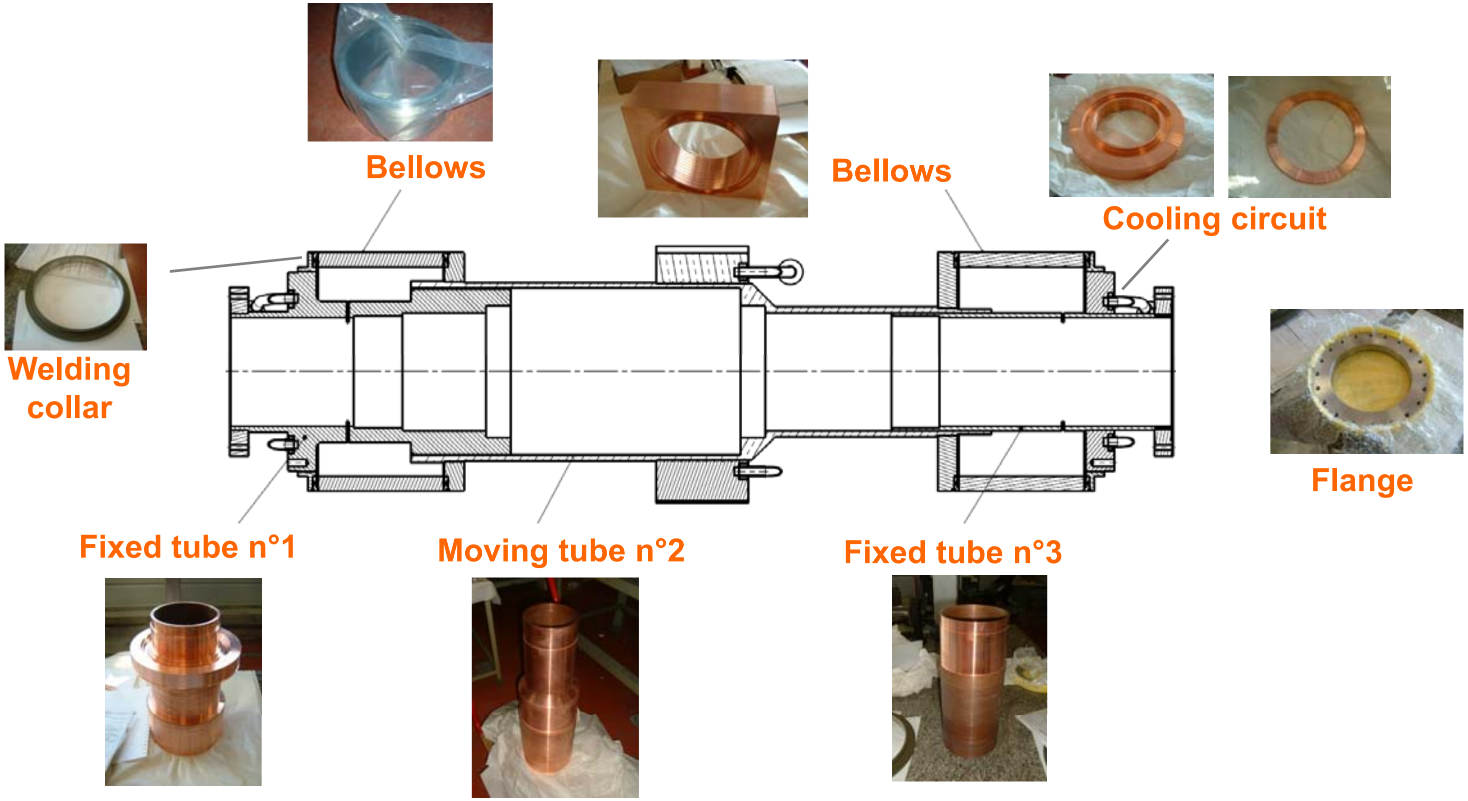
Test of brazing on samples → Test of brazing on scale 1 prototype

Pre-milling → Thermal treatment → Final milling → Cleaning → Brazing ~1000°C → Additional machining & cleaning → Brazing ~860°C → Additional machining & cleaning → Brazing ~810°C → Cold RF tests → Additional machining & cleaning → Brazing ~780°C → High power tests in CTF2

CERN

Fabrication of sliding circular waveguides

- Turning operations made by CLM in two steps
  - Pre-machining
  - Thermal treatment at 250 °C for CuC2 and 950°C for 316L
  - Final machining



- Brazing operation at CERN
- Final mounting and welding of bellows

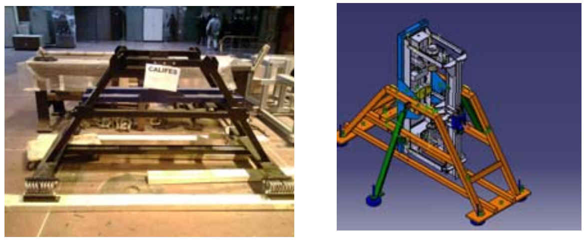
Delivery time :Sept. 2008, commissioning Oct. 2008

More about power phase shifter…

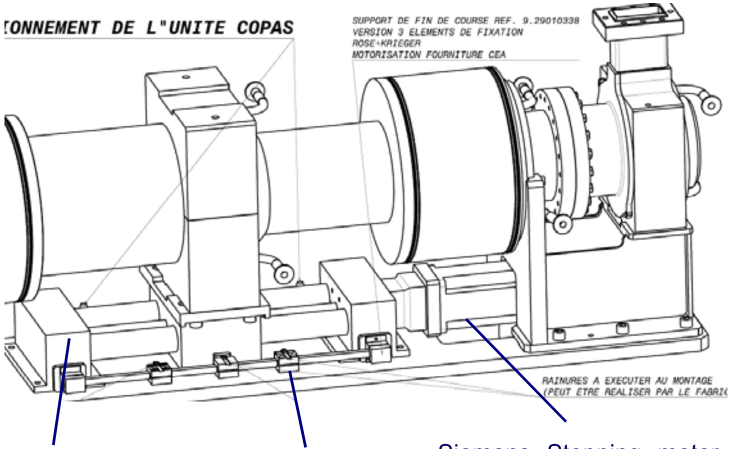
Cradle for lifting and handling

Holding tool of fixed tubes

Frame for transportation in vertical position



Motor driven phase shifter

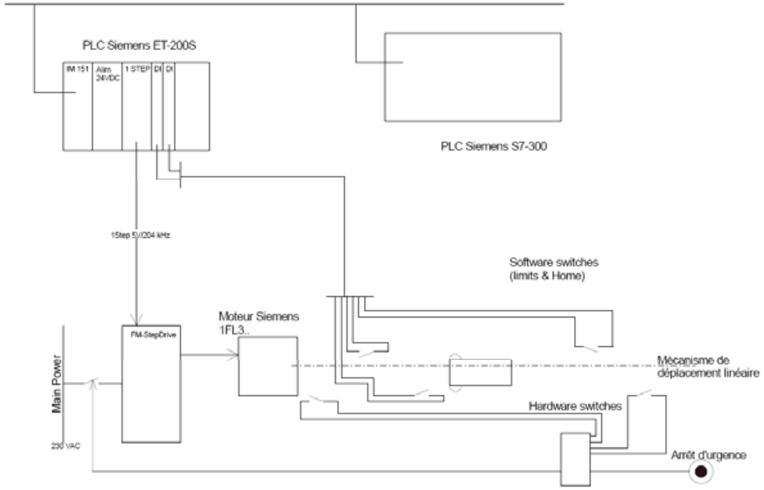


Rose & Kriger Linear unit, 4 mm per turn, accurary 0.2 mm

Security switch

Siemens Stepping motor, 4 Nm, 1000 steps per turn, 1 à 2 kHz

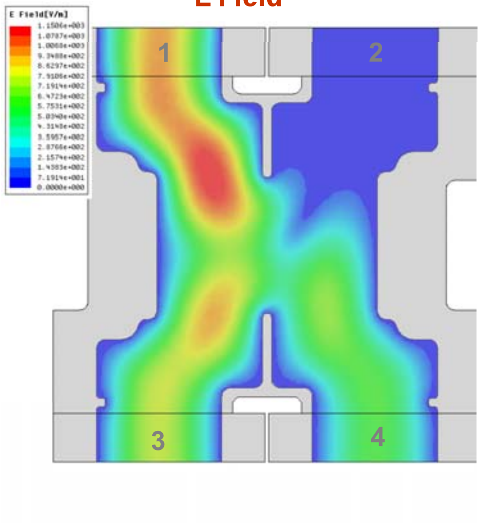
Control command synoptic



4.5 dB Power Splitter

- ➢ One 4.5 dB power splitter is not available in the RF Network and is not procured by the industry
- ➢ RF Simulations and mechanical design made by CEA and fabrication made by CERN

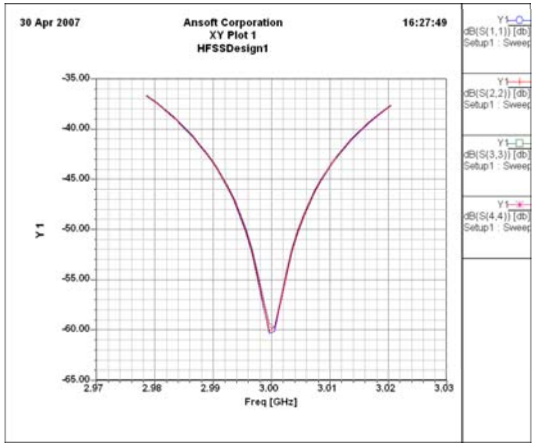
E Field



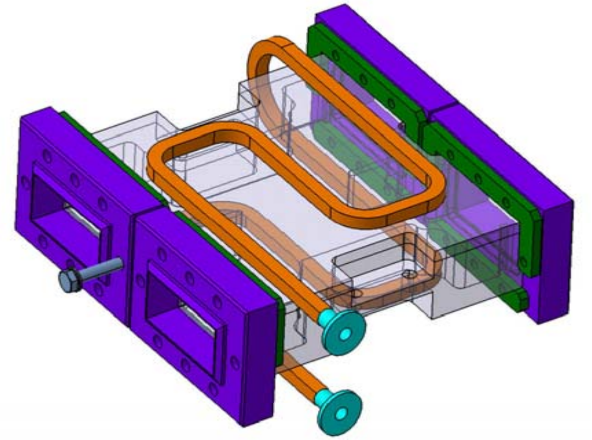
Main characteristics

Parameters	**Specifications**	**Units**
RF Frequency	2998.5	MHz
Max. E field for 90MW input power	11	MV/m
S11 parameter at +/- 20 MHz	< -37	dB
S13 parameter at 2998.5 MHz	-1.9	dB
S14 parameter at 2998.5 MHz	-4.5	dB
Phase shift between port 3 and 4	90	deg
RF Flange	WR284 LIL type	
Total length	250	mm

Bandwidth

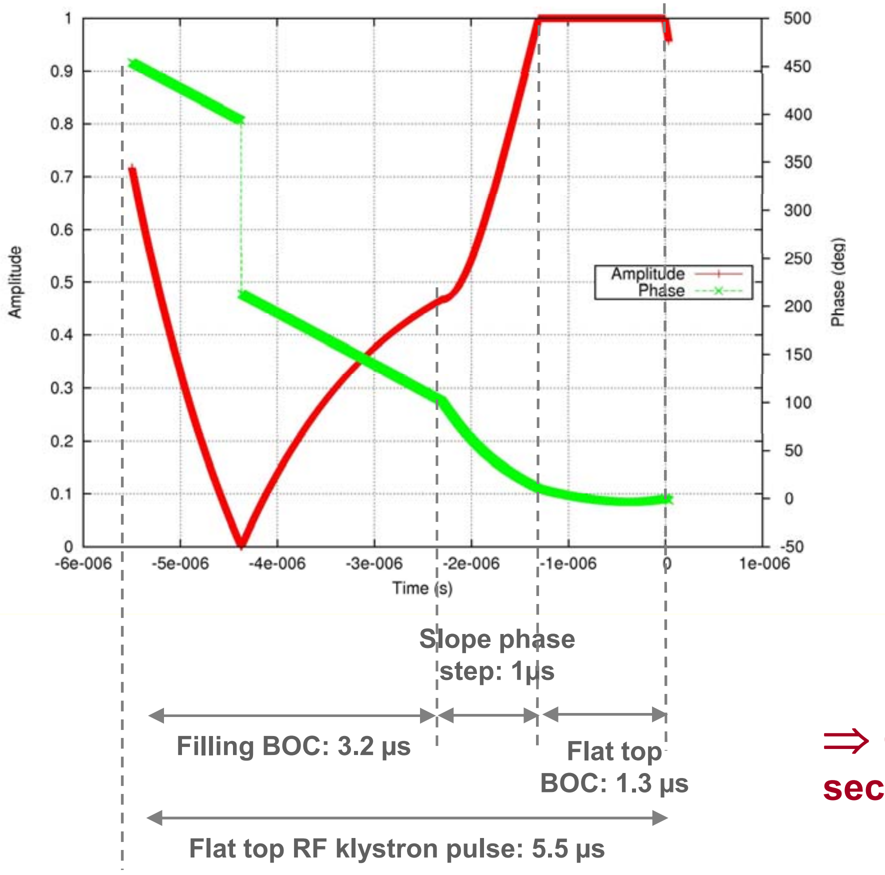


Mechanical design



Transient simulations: filling of LIL section with RF pulse from BOC

- Simulation of the temporal response of the BOC and the TW section for field set up:
    - solve envelope differential equation by Runge-Kutta integration



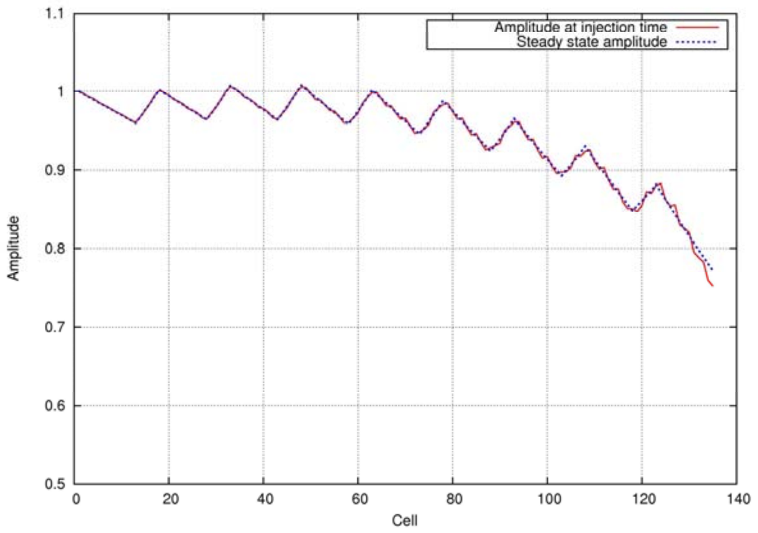
Slope phase step: 1µs

Filling BOC: 3.2 µs

Flat top BOC: 1.3 µs

Flat top RF klystron pulse: 5.5 µs

Specific code developed (A. Mosnier)



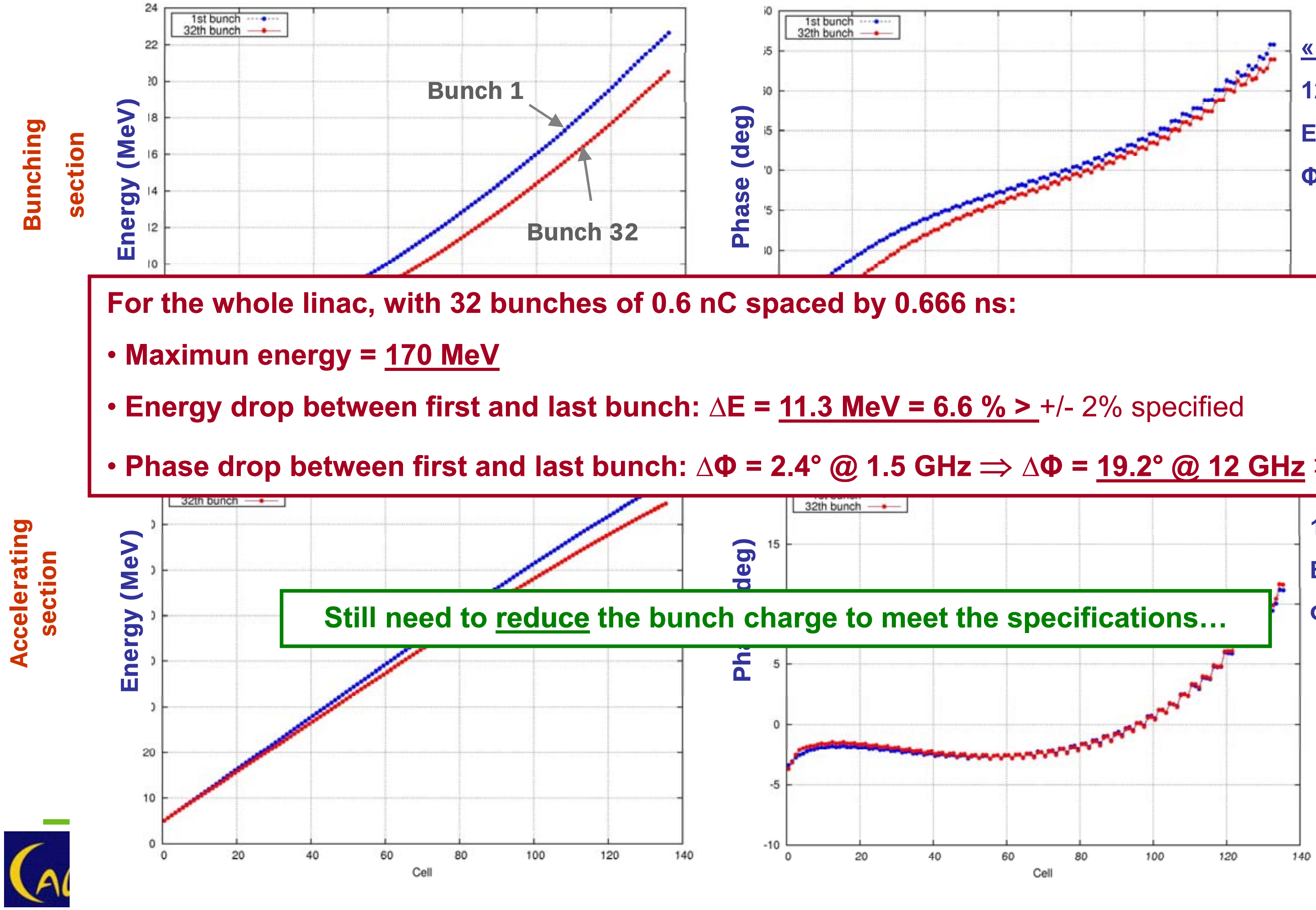
⇒ Quasi steady state field reached in LIL sections

- Phase step of 1 rad and linear variation from 1 to π rad
- Power multiplication factor = 1.95 → 45 MW x 1.95 = 87.7 MW at the output of the BOC cavity
- Drive frequency: 2.99855 GHz + 150 kHz for constant phase during BOC flat top

Transient simulations: effect of beam loading in multibunch operation

- The train of (short) bunch is assumed as a sequence of δ-function current pulses
- The transient beam loading is calculated by introducing amplitude and phase jumps in the cell excitation at each bunch traversal through the cell n
- The propagation of these induced waves through the structure (with dispersive effects) between the bunch time intervals are calculated

E_{inj} = 5 MeV, 32 bunches, Qb = 0.6 nC, Bunch spacing = 0.666 ns



<u>« out-of-phase » acceleration:</u>

12.8 MV/m (14.1 MW) and Φ=-88°:

E_{max} =22.6 MeV, ΔE=2.1 MeV

Φ=-54.2 °, ΔΦ =1.9 ° @ 1.5 GHz

⇒ 15.2 ° @ 12 GHz

For the whole linac, with 32 bunches of 0.6 nC spaced by 0.666 ns:

- **Maximun energy = <u>170 MeV</u>**
- **Energy drop between first and last bunch: ΔE = <u>11.3 MeV = 6.6 % ></u>** +/- 2% specified
- **Phase drop between first and last bunch: ΔΦ = 2.4° @ 1.5 GHz ⇒ ΔΦ = <u>19.2° @ 12 GHz</u>** > 10° specified

<u>on</u>

16.5 MV/m (23.4 MW) and Φ=-3°:

E_{max} =79 MeV, ΔE=4.6 MeV

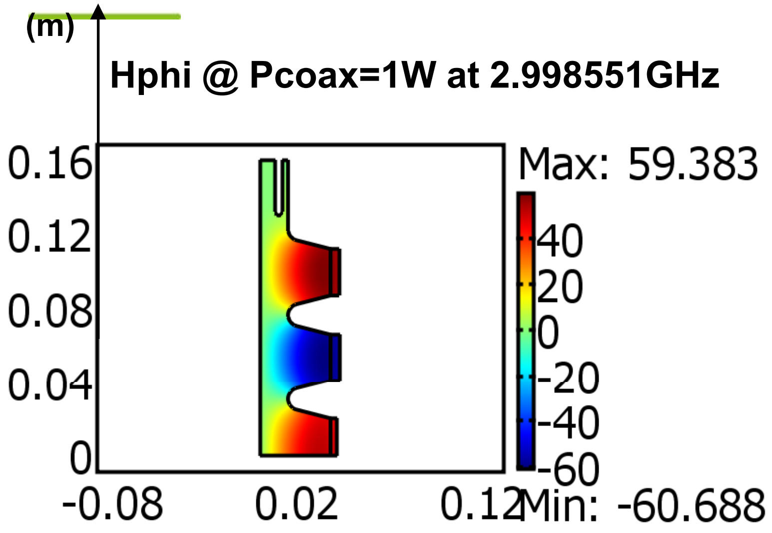
Φ=11.1 °, ΔΦ =0.5 ° @ 1.5 GHz

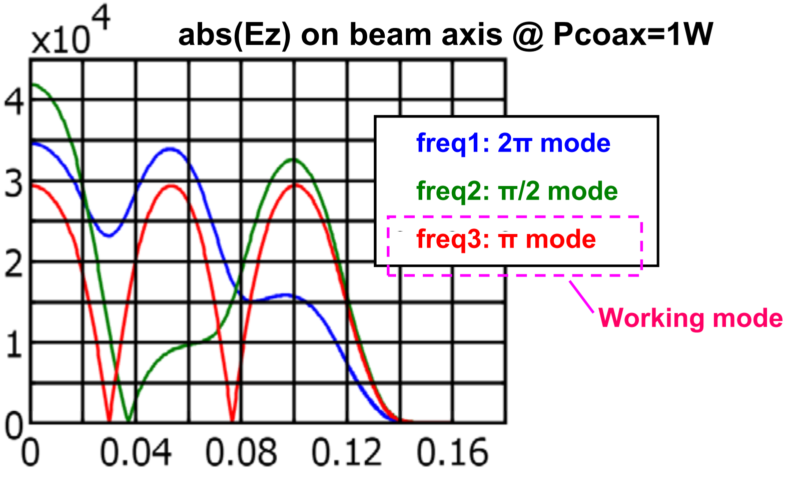
⇒ 4 ° @ 12 GHz

Still need to <u>reduce</u> the bunch charge to meet the specifications…

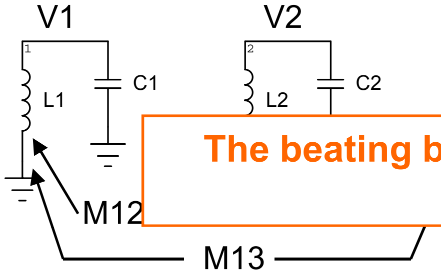
Transient simulations: Filling of Gun with RF Pulse from BOC

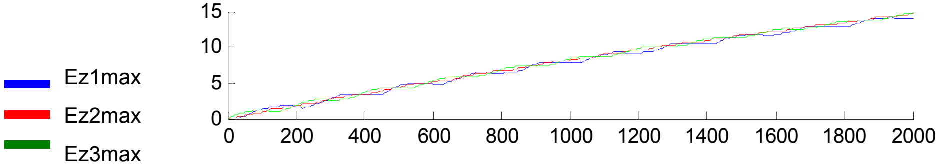
- Simulation of the temporal response the gun for field set up for the first monopole bandpass modes (π/2, π, 2π)
  - reach steady state? … Mix between modes?...
  - COMSOL eigenfrequency analysis coupled with equivalent circuit : solve envelope differential equation by Runge-Kutta integration *(M. Desmons-CEA)*





Equivalent circuit for shorter computed time

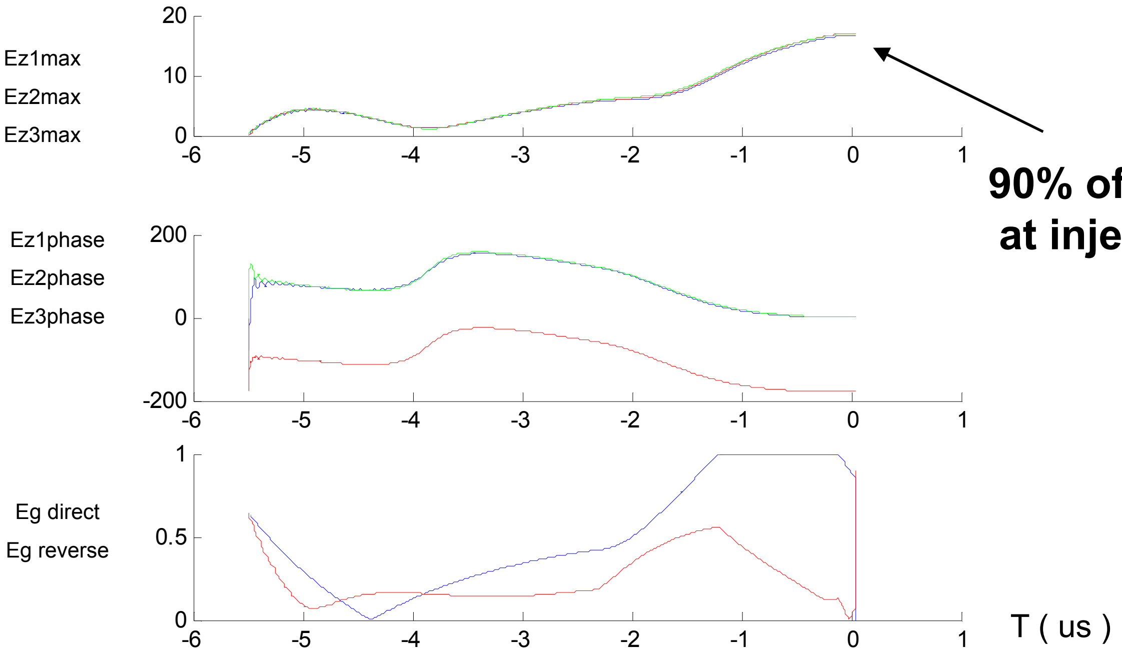




The beating between the 3 modes becomes very low after 2000 of RF period = 0.66 µs

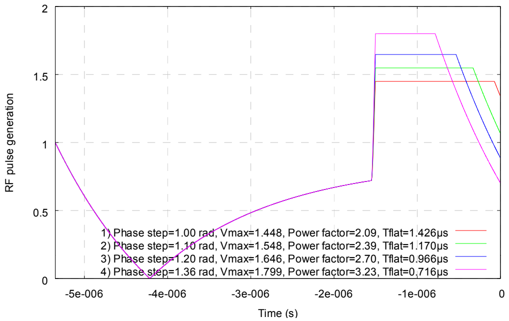
(m)

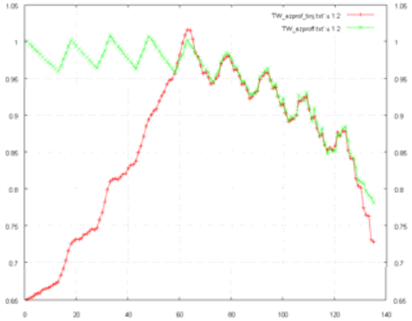
Response of the gun to a BOC RF pulse



90% of max. field at injection time

- ➢ Recall: in the 32 bunches mode, the train length is only 32 x 0.66ns = 21 ns !
- ➢ Possibility to increase the peak power (and so the gradient) in LIL sections by doing a **partial filling** of the structure





→ **to be studied this year**

Particle-In-Cell Simulations

- Finite Difference Time Domain (FDTD) code developed at CEA Saclay *(R. Duperrier)*
- Solve Maxwell equations in a given structure: calculate the fields induced by the beam in addition with the applied field (standing or travelling wave fields, static fields)
- Take into account the transient beam loading, the space charge forces, the intra-bunch and long range Wakefields
- Compute the energy loss, the energy/phase spread and the emittance degradation
- Can simulate the gun and the LIL sections
- Cluster available at CEA Saclay for parallelized calculation

Transverse Electric Field Ex (V/m) in the RF Gun at 0.5 nC

⇒ Energy dispersion in the gun : ~ 2 ‰ (1)

- **Wakefield simulation in the LIL sections → to be done this year**

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(1) R. Duperrier, Compression de paquets pour CTF3, Journées Accélérateurs de la SFP, Roscoff 2005

Conclusion

- HV modulator partially tested and accepted at factory, installed and started in CLEX
  - Pulse quality to be improved : to be done by PPT in end March / April (not the critical path for schedule)
- 3D layout of RF Network done
  - Still a lot of procurement to do
- Power phase shifter
  - copper pieces machined (milling and turning operations OK)
  - Brazing problem : new procedure of fabrication with validation steps (brazing tests on a scale-one prototype)
- new results of beam dynamic simulations for multi-bunch operation with updated CLIC parameters
- Suite of specific codes developed to compute the transient behavior of the RF accelerator cavities
  - useful for commissioning and higher performances evaluation of CALIFES

Very good collaboration with CERN team !

Thank you for your attention …