FROM RESEARCH TO INDUSTRY

New Klystron Concept

CLIC Seminar

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May 16, 2014

OUTLINE

- Context and objectives
- New klystron concept
- Simulation codes
- Klystron development plan

- **Context and objectives**
- New klystron concept
- Simulation codes
- Klystron development plan

WP12
Innovative RF Technologies
2013 - 2017

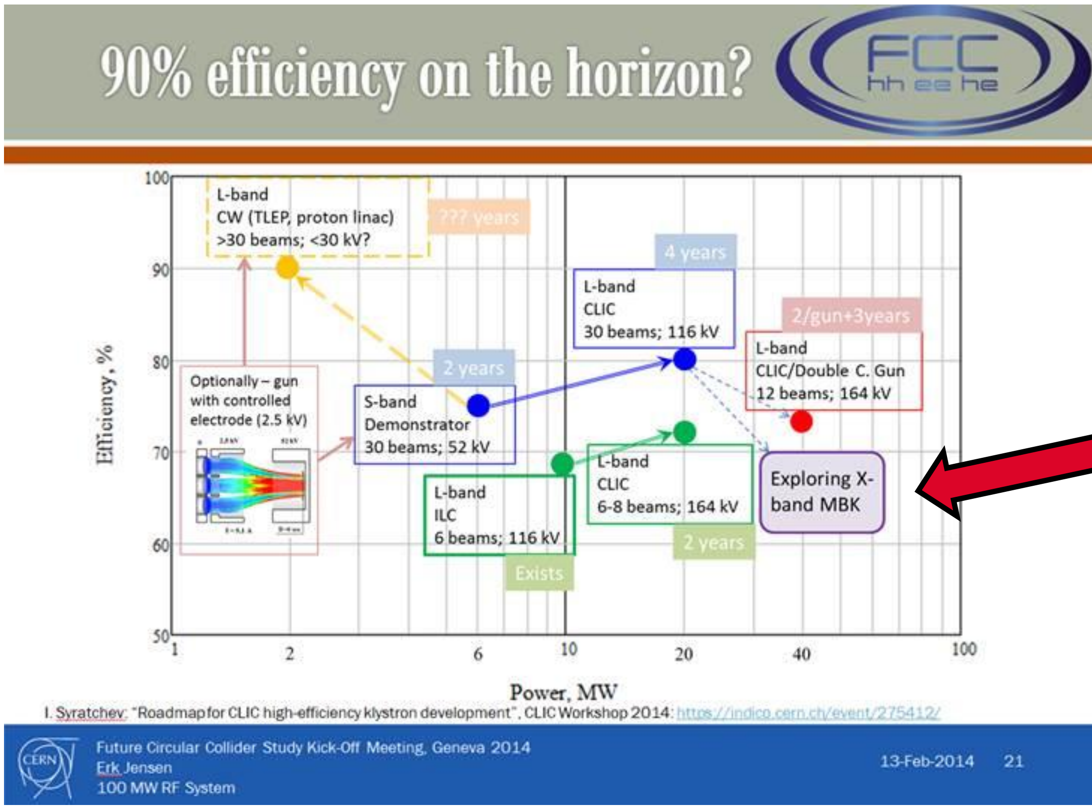
« In this sub-task, CEA will develop and search for innovative concepts of X band RF power sources and components. The objective is to propose ***affordable and reliable*** *solutions for future testing capabilities for the CLIC accelerating structures. The task includes the design and the fabrication of prototype RF devices to demonstrate the feasibility of the new concepts proposed. »*

- ***Juliette PLOUIN: CEA project leader for this sub-task***
- ***Budget available to build a (small) part of the RF power source or component***

☞ **Fully oriented towards an R&D activity**

A STRONG MOTIVATION WITH A MORE GENERAL INTEREST

- Some important projects (XFEL, ESS, CLIC-drive beam, FCC…) search for “green technologies” and so require **ultra-high efficiency RF sources**
- Modulators are now close to 90% efficiency. Microwave tubes are almost the only weak point in the energy consumption chain



- A road map to reach the 90% efficiency horizon have been established by Igor at different frequencies
- Our Eucard2 task is well in agreement with this road map

- This project is also an occasion to acquire knowledge and experience on RF sources “in-lab design” and why not “in-lab fabrication” in Europe (like what is done at SLAC or on HV modulator at CERN for example)

QUICK BRAINSTORMING FOR AN INNOVATIVE CONCEPT

- **Microwave vacuum tubes for X band and high peak power**
  - **O type tubes**
    - Carcinotron
    - Travelling wave tube
    - Klystron
      - Single beam klystron
      - Multibeam klystron
      - Sheet beam klystron
      - Hollow beam klystron
  - **Gyro devices**
    - Gyroklystron
  - **M type tubes**
    - Locked Magnetron
  - **Gridded tubes**
    - IOT

"affordable and reliable"
=
reduced surface fields (DC and RF)

"high efficiency"
=
Optimal beam / RF interaction

WHAT IS A KLYSTRON?

It is a vacuum microwave electron tube amplifier where:

- The input cavity prebunch slightly a DC beam provided by an electron gun
- The intermediate cavities develop an RF voltage induced by the beam loading (image charges). These induced voltage intensify the bunching process.
- The beam is strongly decelerated in the output cavity and a high RF power is created
- The decelerated beam is collected in a collector
- The beam is focused by an axial magnetic field (solenoid)

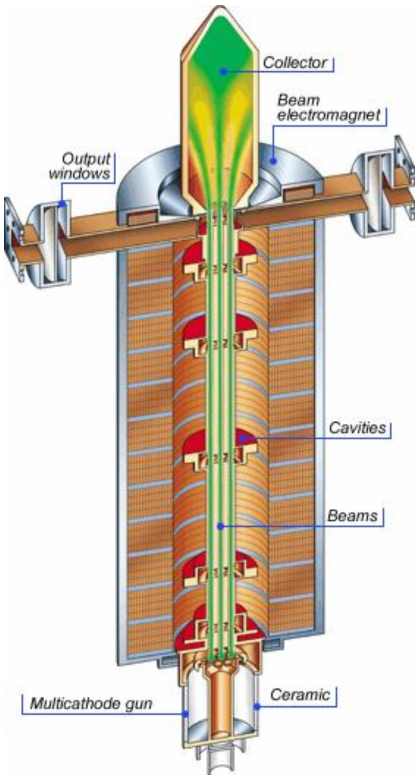
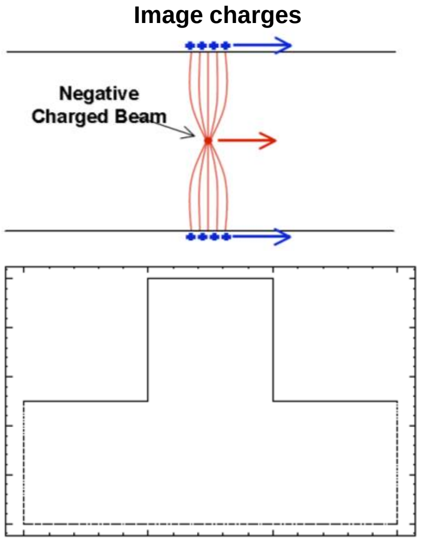
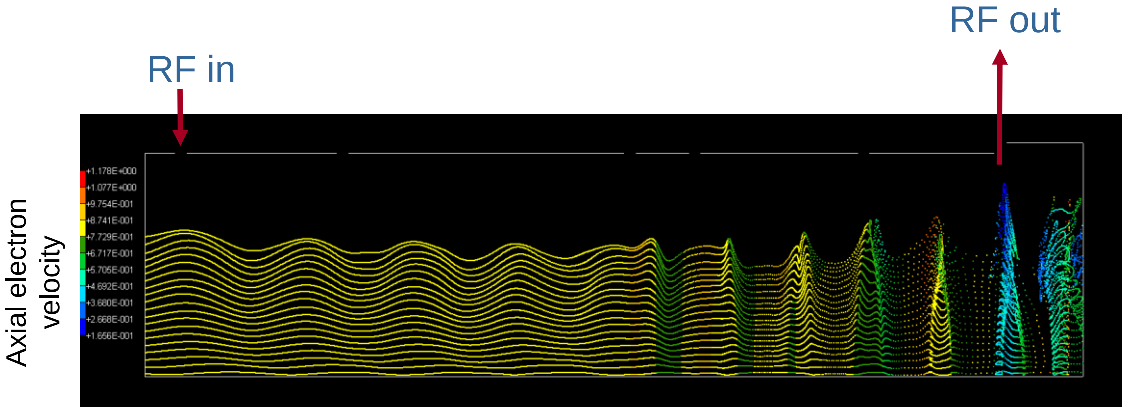


Image: courtesy of Thales Electron Devices

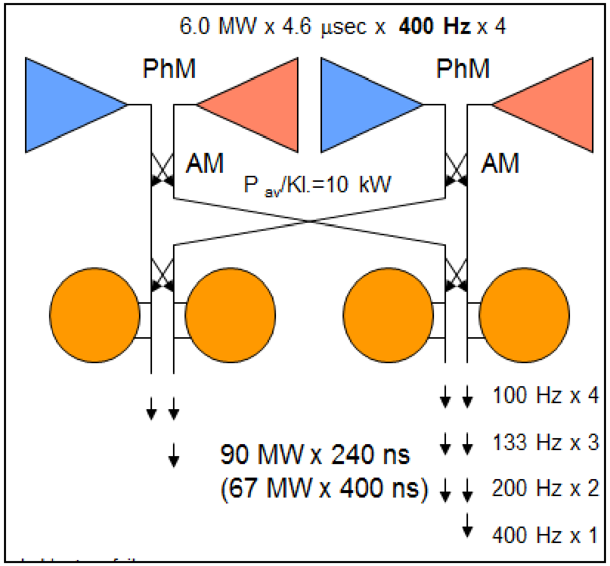




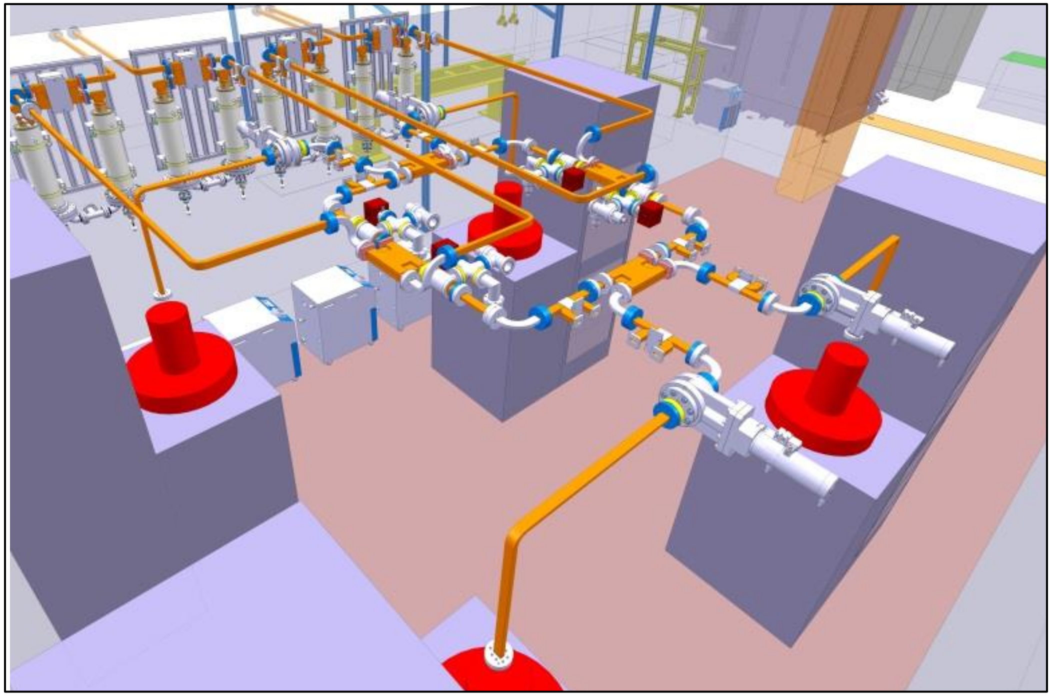
S. Berger - Thales, XB2008 workshop, Cockcroft Institute, UK

XBOX3 AT CERN

- XBOX3 will use four Medium Power X-band klystrons recombined and compressed to produce a 50 MW power level
- This smart concept is well adapted to the reliability and affordability we are looking for and it will constitute the basis of our study



I. Syratchev, G. McMonagle, N. Catalan Lasheras



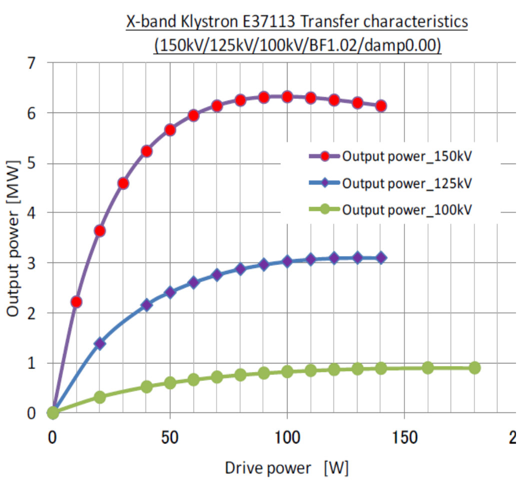
- Medium power x-band RF sources have also a wider interest in FEL and medical applications

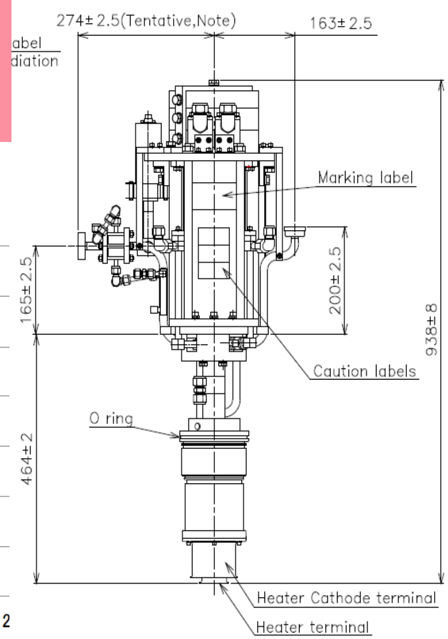
XBOX 3 AT CERN

- CERN is ordering commercial products for XBOX3 (4 units of each)
- No particular R&D is required and delivery time is short

TOSHIBA klystrons parameters

Peak power: 6 MW
Beam Voltage: 150 kV
Beam current: 90 A
Average power: 12.4 kW
Efficiency: 47.5%





SCANDINOVA Modulator parameters

Peak RF power: 8.0 MW
Pulsed voltage: 175 kV
Pulse current: 115 A
Average power: 50 kW
Pulse length (flat): 5 μsec
Rep. rate: 400 Hz

A VERY CHALLENGING OBJECTIVE

Our proposal is to study and design a 12 GHz single beam klystron able to deliver a peak power of 10 to 12 MW with a pulse duration of 4.5 μs.

It should be compatible with the Scandinova modulator ordered for XBOX3 in order to do fully qualify the klystron at CERN.

A possible operating point could be:

- Vk = 170 kV
- Ik = 100 A -> μP = 1.4 μA/V$^{1.5}$
- efficiency > 70 % -> Pout = 12 MW

A new klystron concept is required

If these challenging performances are achieved, the 6 MW Toshiba klystron could be replaced by our 12 MW klystron and would **double the testing capability of XBOX3**

A classical solenoid based focusing system would be considered for this first step.

The klystron should be designed to operate at a pulse repetition rate of 400 Hz minimum and - why not -, up to 1 kHz, a highly interesting repetition frequency for future FEL projects

- Context and objectives
- **New klystron concept**
- Simulation codes
- Klystron development plan

THE CLASSICAL WAY TO DESIGN A KLYSTRON

- One or two cavities around central frequency to ensure the bandwidth
- Two or three bunching cavities at higher frequency, located at approximately a quarter of the reduced plasma wavelength λ_q

$$\lambda p = 0.036 \frac{V^{0.75} \cdot b}{I^{0.5}}$$ with b beam radius

$$\lambda q = \lambda p / F$$

<ins>Exemple</ins>:
Vk=170 kV, Ik = 85 A
b = 1.8 mm, a = 3.5 mm
λp = 59 mm
γ_e .b = 0.61 rad
F = 0.35
λq = 168.5, λq/4 = 42 mm

→ At Ik = 1.5 x 85 A = 136 A, λq/4 is decreased to ~ 33 mm

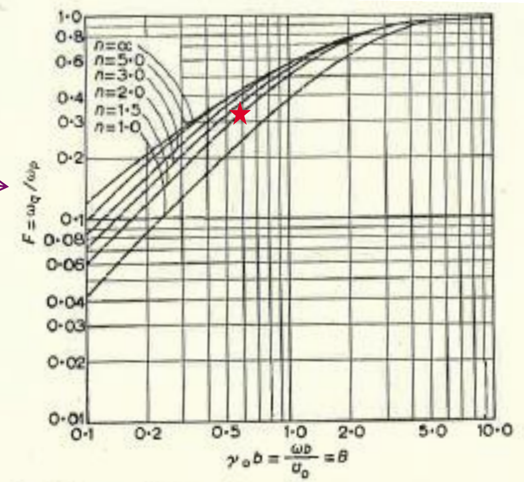


Fig. 3. Space-charge reduction factors for cylindrical beams in cylindrical tunnels.

Fig. 3† shows a plot of F_1 as a function of B, for various values of $n = a/b$, as a parameter. F_1 lies between 0 and 1 and, at any

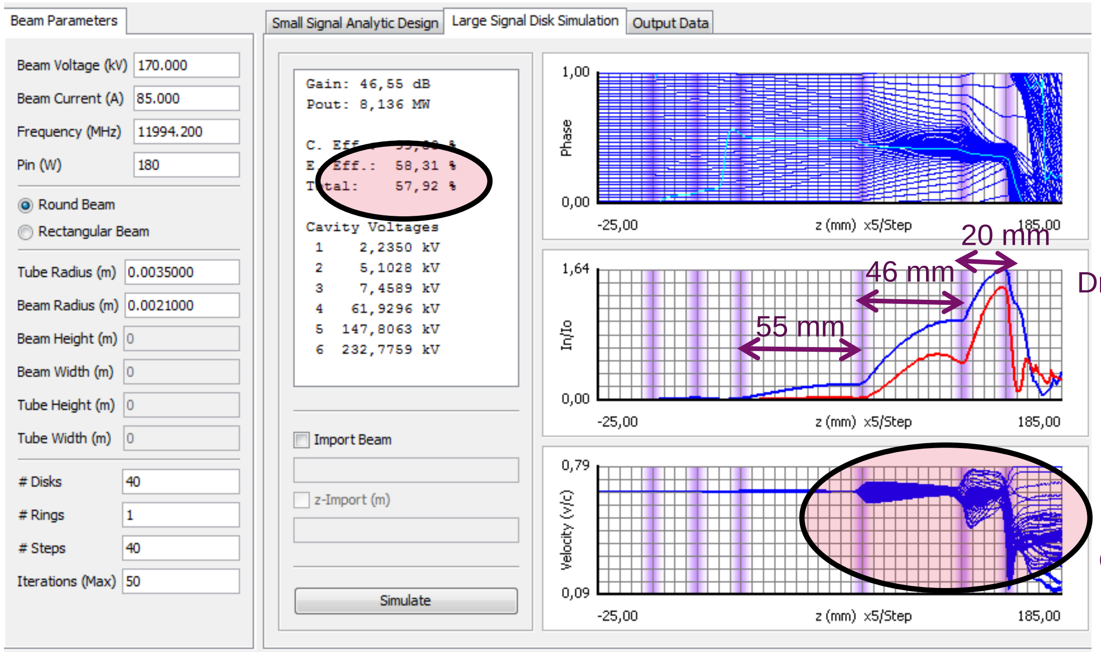
Beck, « Space Charge Wave », 1958, p.106

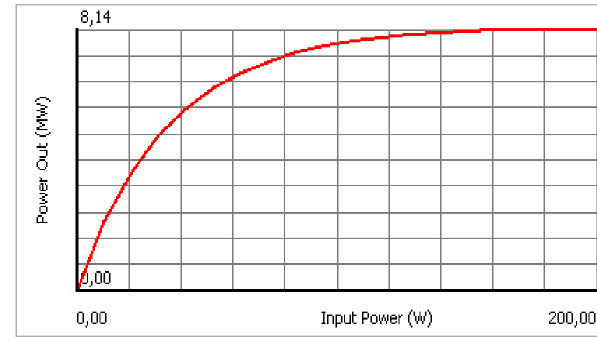
- Maximize the modulated current I1/I0

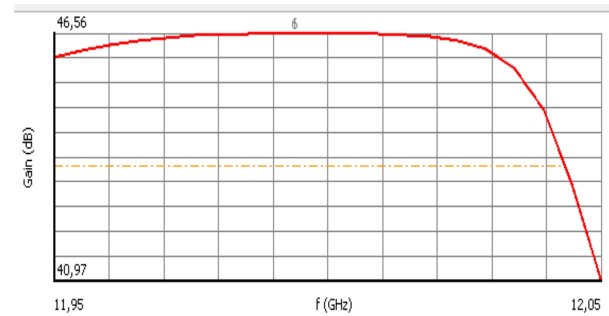
- Sometimes a 2nd harmonic is added to reduce the length of the interaction structure

A CLASSICAL 6 CAVITIES KLYSTRON

- Quick design with AJDISK (SLAC 1D code)







Cavity Parameters

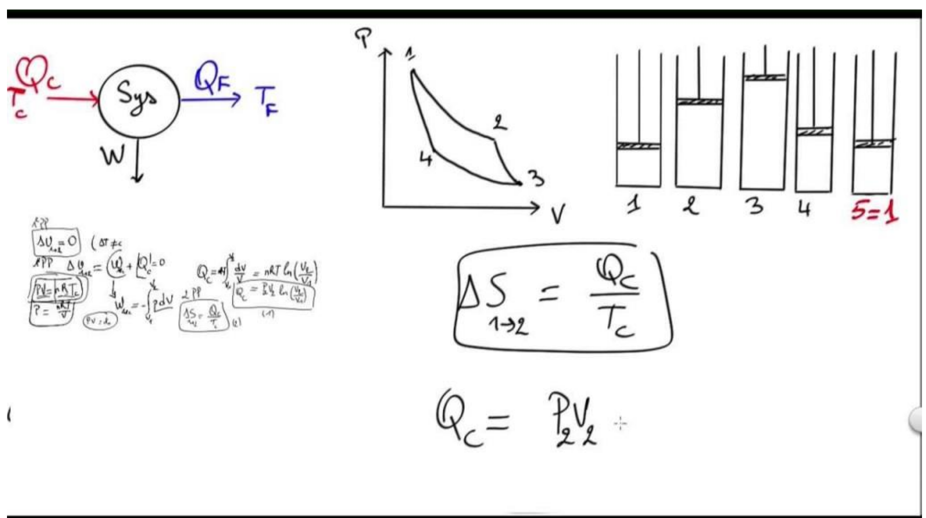
Cavity ID, Unused	R/Q (ohms)	M or SF7 Grid File, z(m)	Qe	Qo	f (MHz)	z (m)
1	88	0.74	500	5500	11994.200	0
2	88	0.74	95000	5500	11850.000	0.02000
3	88	0.74	95000	5500	23988.400	0.03000
4	88	0.74	95000	5500	12060.000	0.04000
5	88	0.74	95000	5500	12100.000	0.09500
6	90	0.74	95000	5500	12220.000	0.14100
7	90	0.74	37	5500	11994.200	0.16100

- Limit of the method: induce large velocity dispersion and so limit the interaction efficiency (except for very low perveance and/or advanced optimization method – cf Baikov, Guzolov et al.)

THE ADIABATIC CONCEPT

- A system is called adiabatic when the external forces vary more slowly than the interaction forces in the system. The dynamics of the system is then a **succession of equilibrium states** and the entropy does not increase.

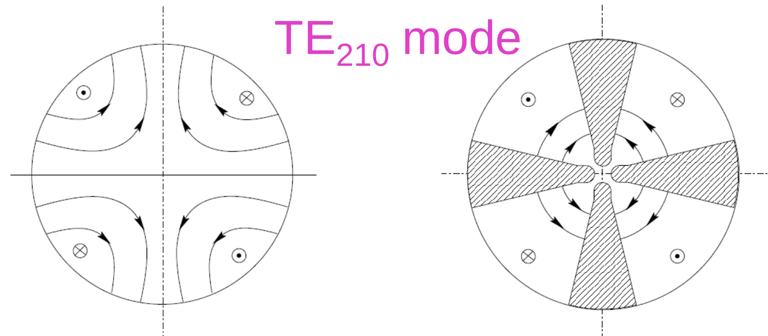
<u>Example in thermodynamic:</u> adiabatic if no heat exchange with the external medium: the piston velocity must be smaller than the speed of sound in the gas

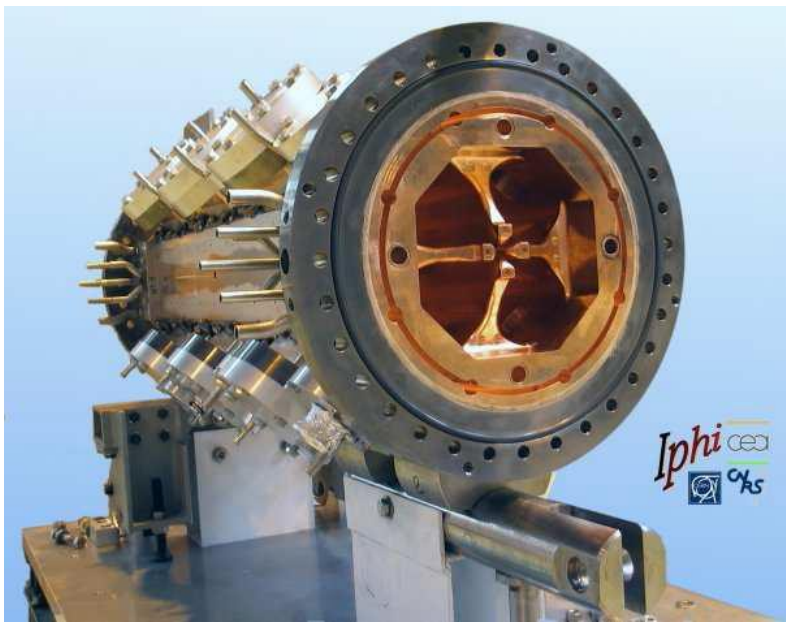


- In our case, the external forces are the beam induced bunching forces and the interaction forces are the space charge forces.

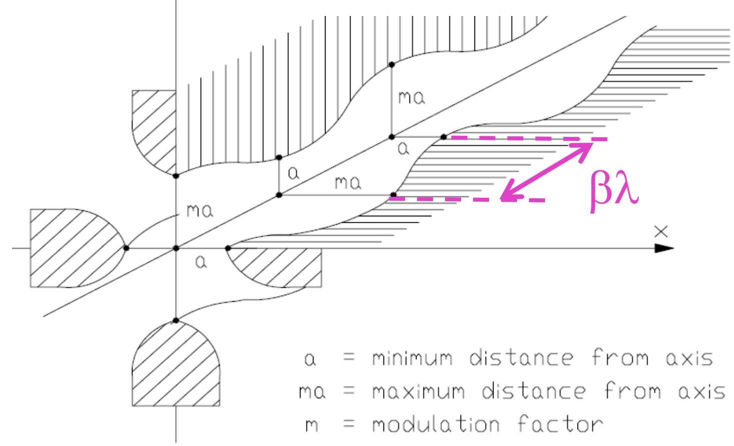
A PARALLEL WITH RFQs FOR PROTON LINAC

An RFQ cavity is used in proton linac injector to <u>bunch</u>, focus and accelerate a continuous beam from few tens of keV to few MeV.
It allows a beam transport in space charge regime (high intensity beams is possible) with very low beam losses.





longitudinal modulation on the electrodes creates a longitudinal component in the TE mode that bunch and accelerate the beam

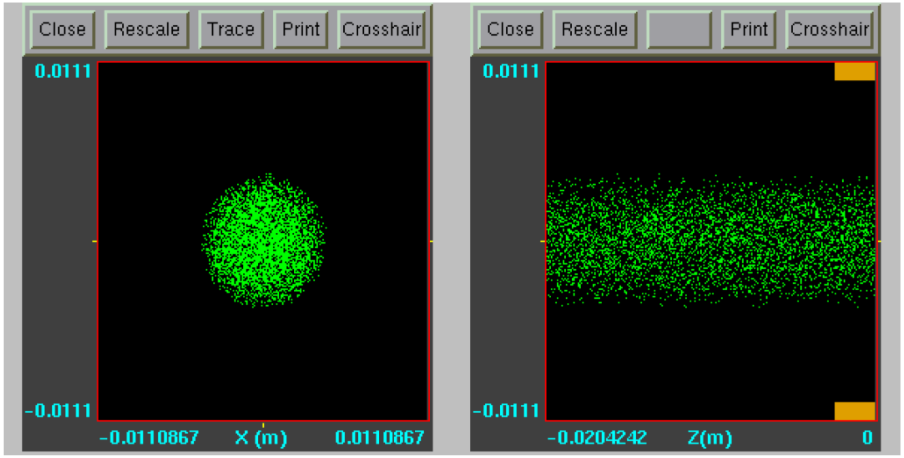


In the IPHI RFQ (3 MeV, 6m, 352 MHz), around 350 cells are used to bunch the beam

PHASE SPACE DISTRIBUTION IN AN RFQ

The bunching process in an RFQ is adiabatic (« gentle » buncher)

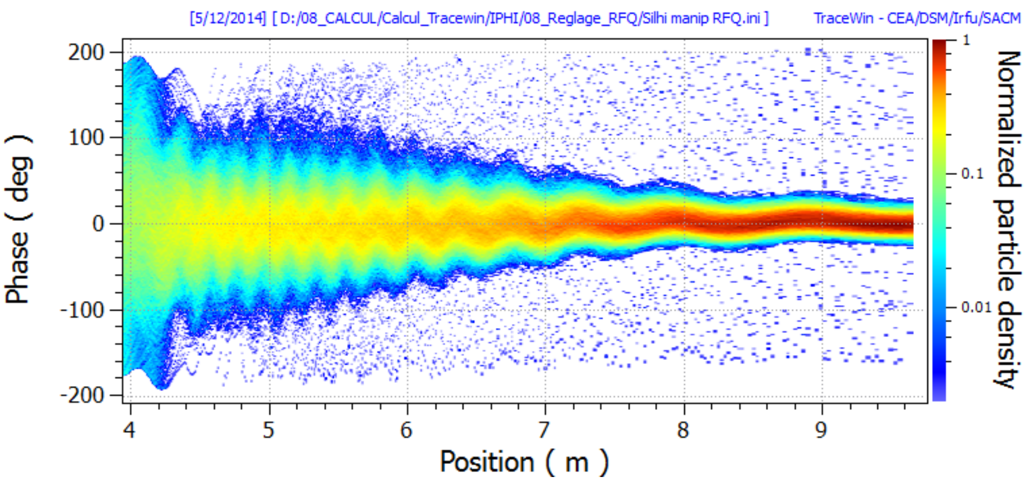
The RFQ preserve the beam quality, has a high capture (~90%) compare to a discrete bunching model (50%)



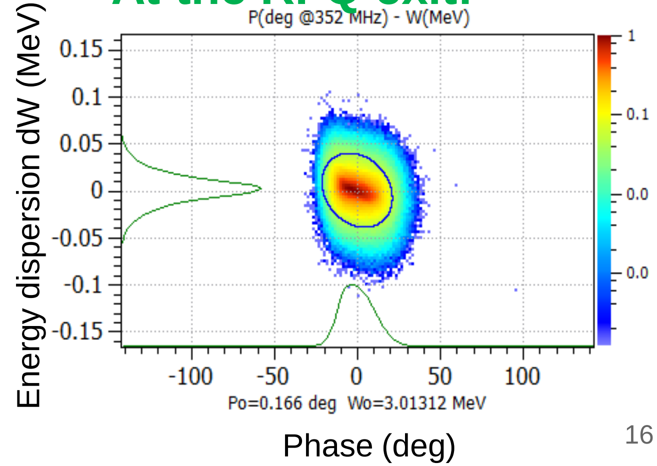
TOUTATIS code (CEA, R. Duperrier)

RFQ_Anim.avi

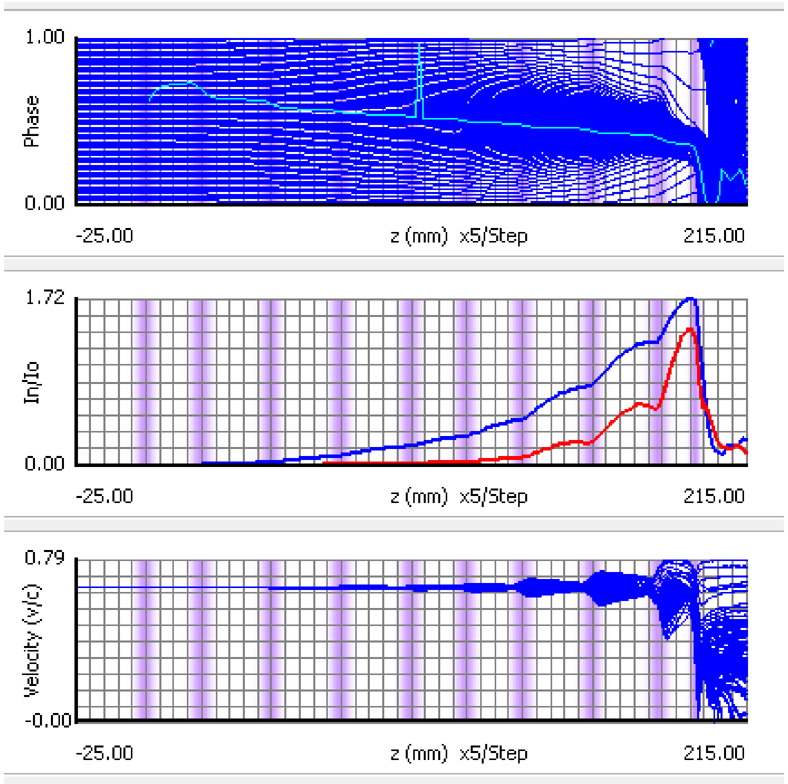
Along the 6m RFQ:



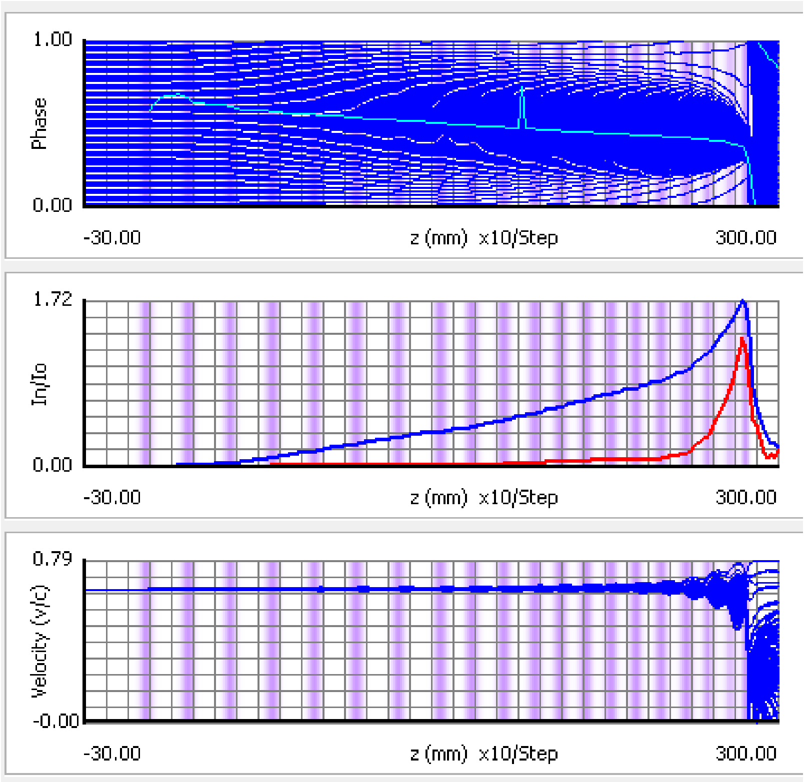
At the RFQ exit:



INCREASING THE NUMBER OF CAVITIES IN A KLYSTRON



10 cavities
Efficiency 67.2 %
Length 197 mm



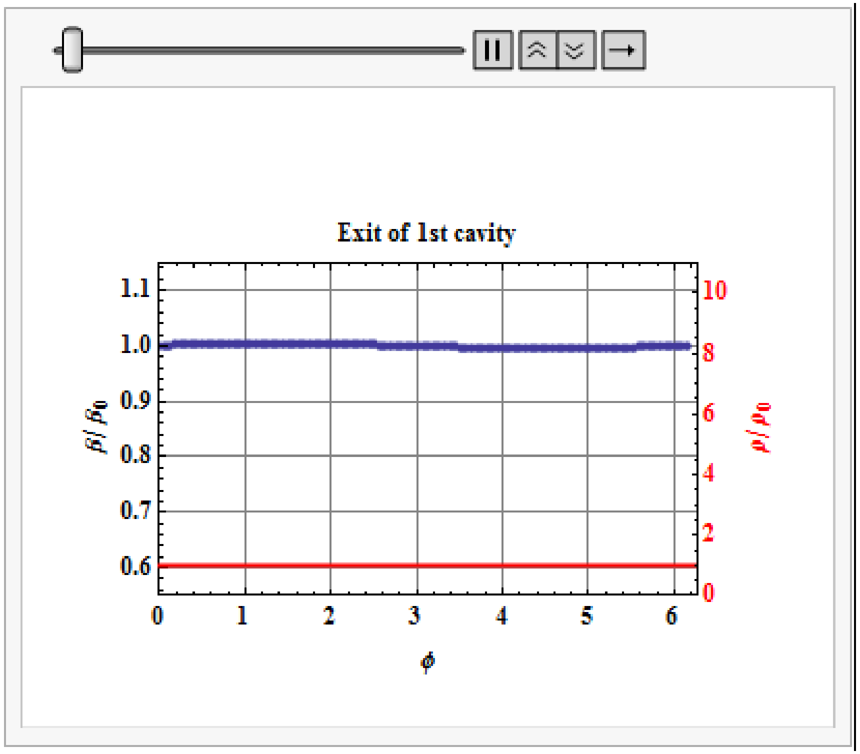
20 cavities
Efficiency 78 %
Length 285 mm

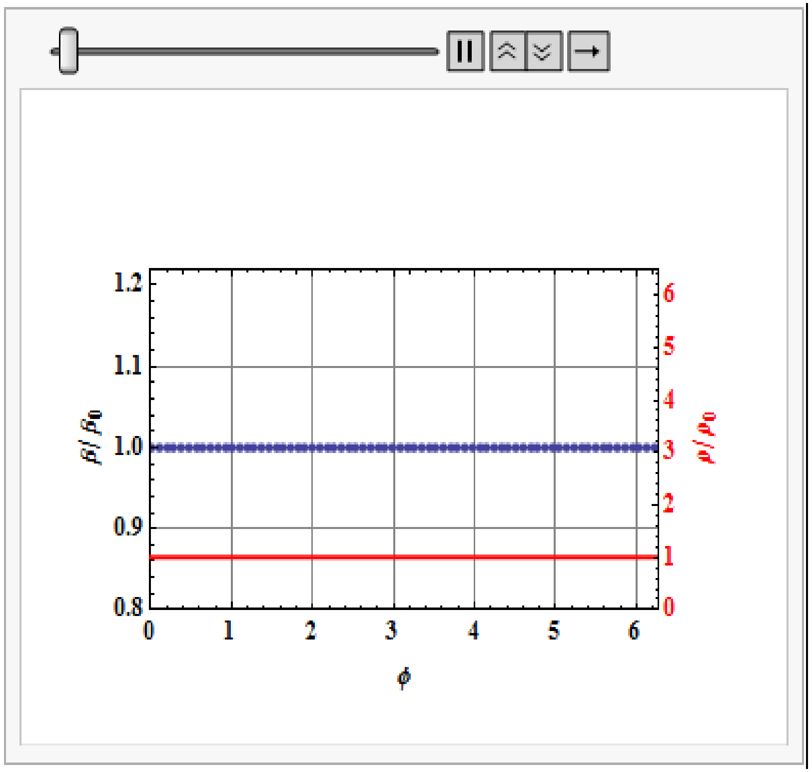
- The idea is also to maintain a classical perveance value of 1.4 $\mu A/V^{1.5}$ (170 kV – 100 A) : high current leads to shorter plasma wavelengths (and so shorter structures)
- In the design proposed, the cavities are weakly coupled to the beam (low R/Q) and largely detuned to avoid strong bunching

ANIMATION FROM AJDISK RESULTS (CHIARA MARRELLI)

5 cavities – 1 GHz optimized by C. Marrelli
μPerveance = 0.21
$P_{out} \approx 2.3$ MW
Efficiency 78. %

20 cavities – 12 GHz optimized by F. Peauger
μPerveance = 1.4
$P_{out} \approx 12.5$ MW
Efficiency 78 %

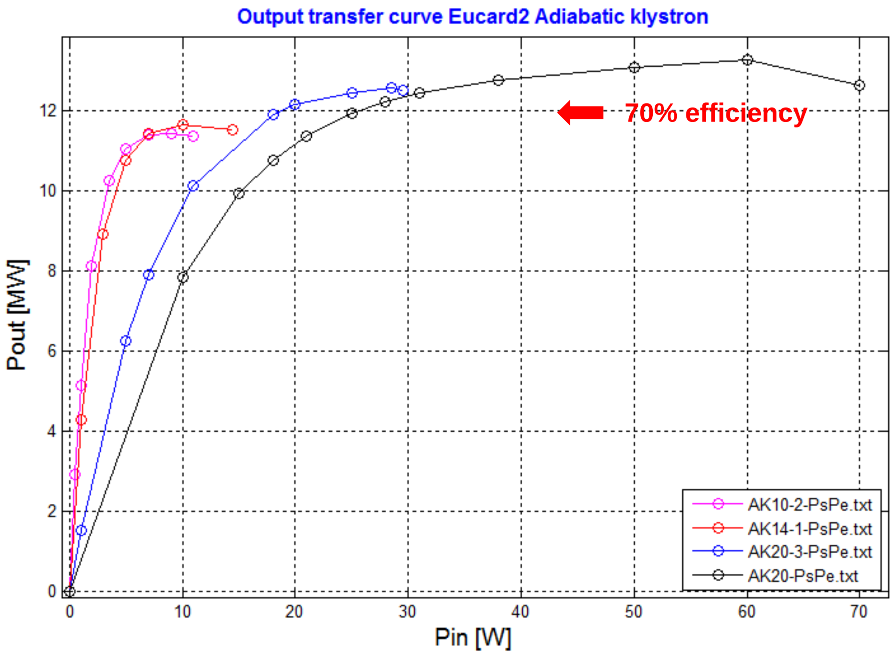


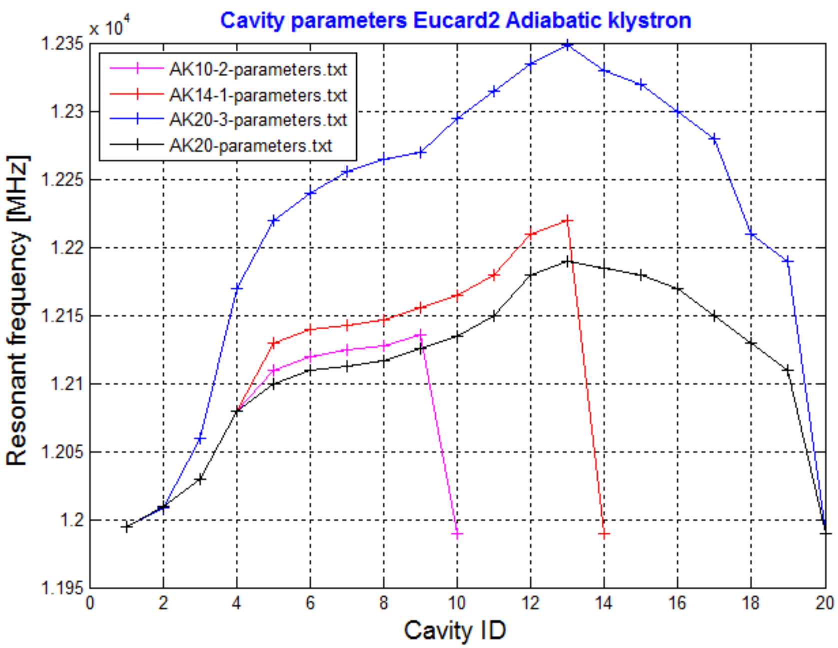


EXPECTED PERFORMANCES WITH 4 DIFFERENT DESIGNS

Name	Numbers of cavities	R/Q [Ohm]	TTF	Efficiency	Overall length [mm]
AK10-2	10	20 to 50	0.683	**67.2 %**	197
AK14-1	14	20	0.683	**68.5 %**	221
AK20-3	20	27.4	0.688	**74 %**	285
AK20	20	12	0.72	**78 %**	285

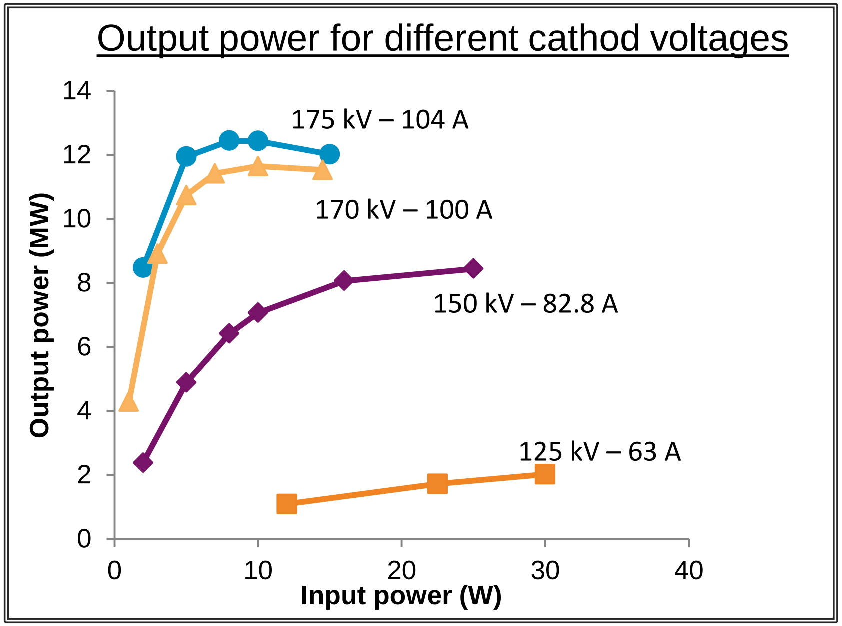
- At that time AJDISK was limited to 20 cavities.
- Now the limit is higher (many thanks to Aaron JENSEN(SLAC)), but the structures appeared to be more or less unstable for more that 22 cavities

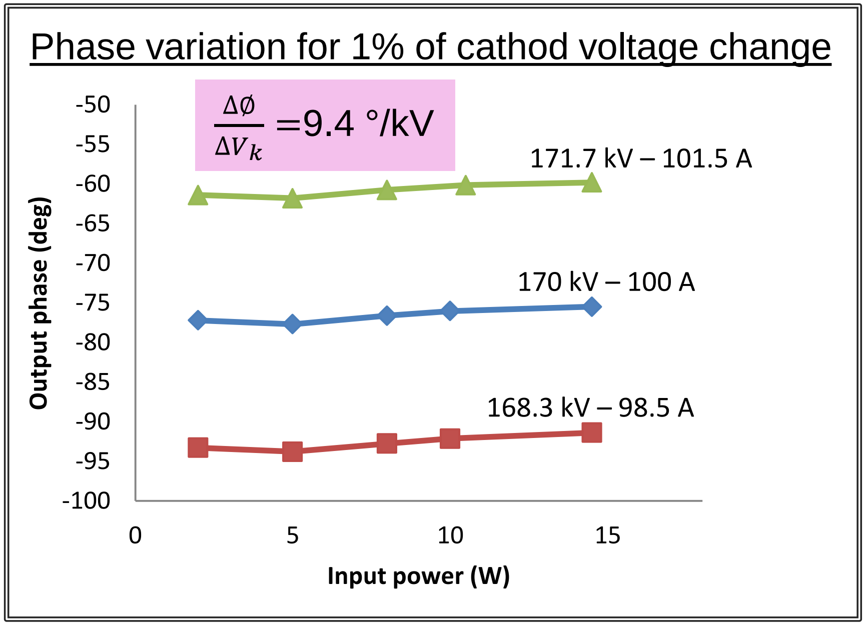


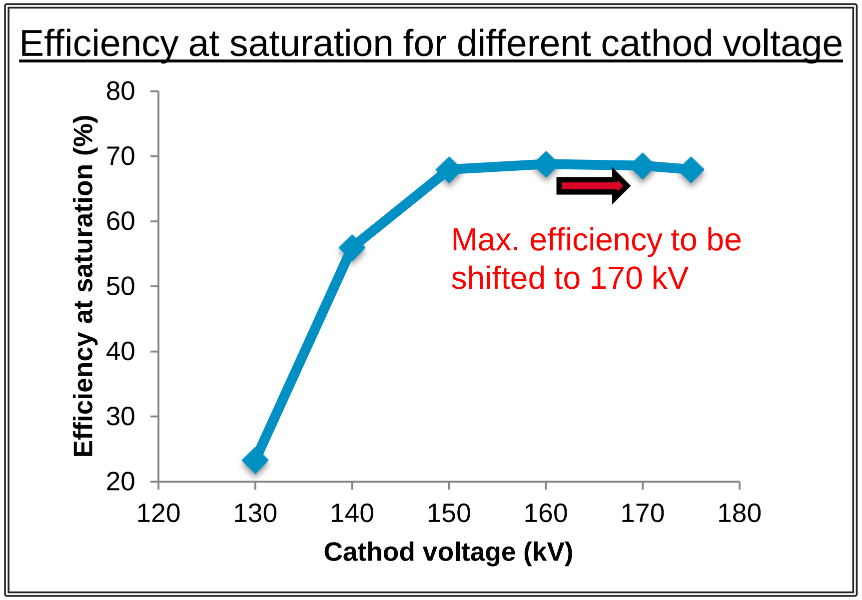


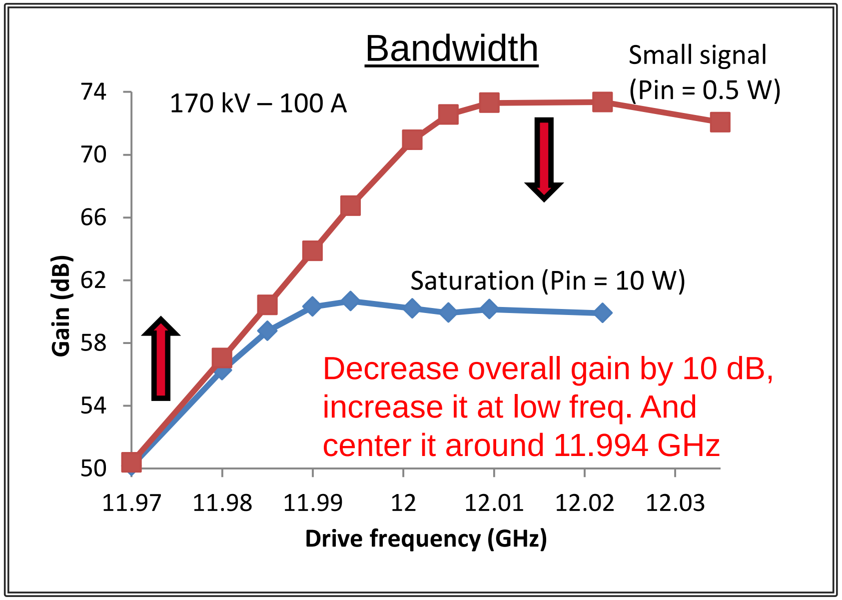
- These design have been manually optimized and could be certainly fully improved by an automatic procedure.

EXPECTED DETAILED PERFORMANCES 14 CAVITIES STRUCTURE



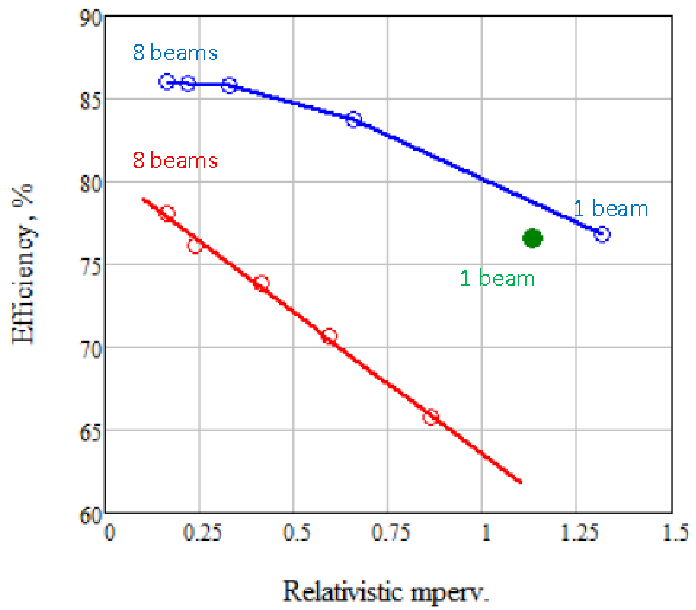


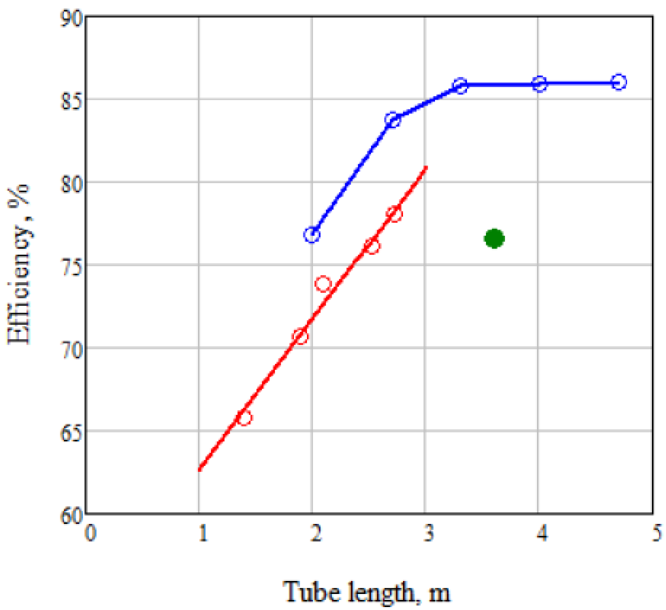




GLOBAL COMPARISON WITH OTHER METHOD (IGOR SYRATCHEV)

Red line: 20 MW, 8 beams MBK originally simulated by Chiara. The perveance was changed by changing both the current and voltage (fixed number of beams).
Blue line: 20 MW, 180 kV MBK simulated by Andrey ('global' optimum through the adiabatic bunching). The perveance was change by changing the number of beams (fixed voltage).
Green dot: 100 A, 170 kV kladistron by Franck (13 MW). The tube length is simply the frequency scaling from 12 GHz to 1 GHz

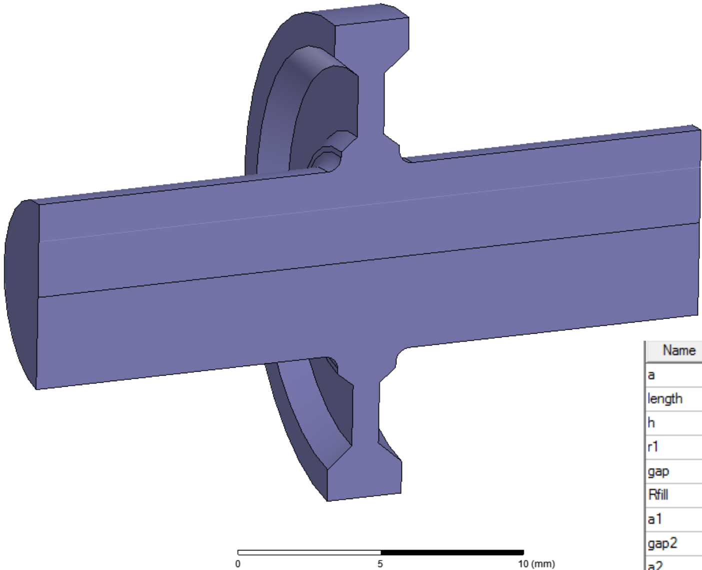




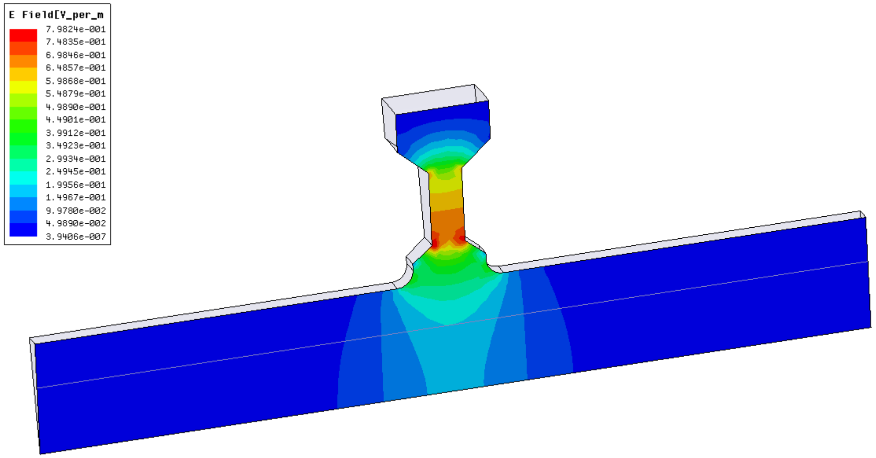
Because the simulations were done for different parameters (I and V), the relativistic perveance was used to compare the results:

$$\mu P = \frac{I}{\left(\left[1 + \frac{V}{2U_e}\right] V\right)^{3/2}}$$

BUNCHING CAVITY DESIGN



Name	Value	Unit
a	3.5	mm
length	25	mm
h	2.8	mm
r1	9	mm
gap	3.2	mm
Rfill	0.5	mm
a1	4.2	mm
gap2	1	mm
a2	4.7	mm
a3	7	mm
a4	7.8	mm

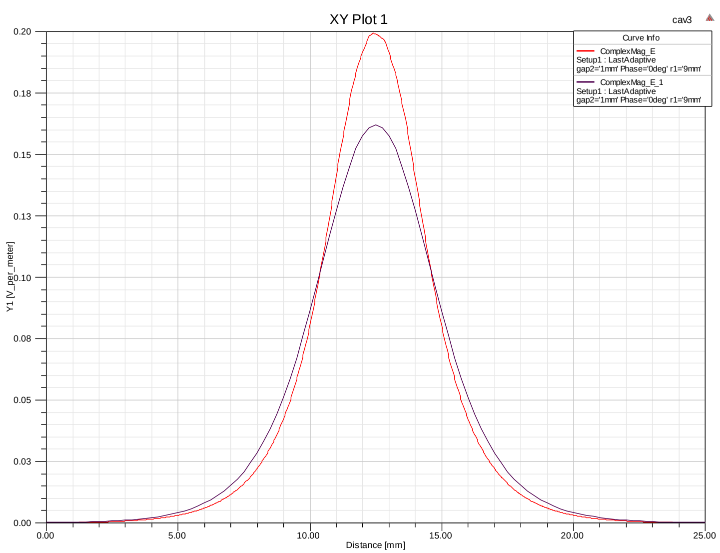


$$\frac{R}{Q} = \frac{\left[\int E_z(z)dz \right]^2}{2\omega U} \qquad M = \frac{\int E_z(z) e^{j\frac{\omega}{\beta \cdot C} z} dz}{\int_{-L/2}^{L/2} E_z(z)dz}$$

Eigenmode

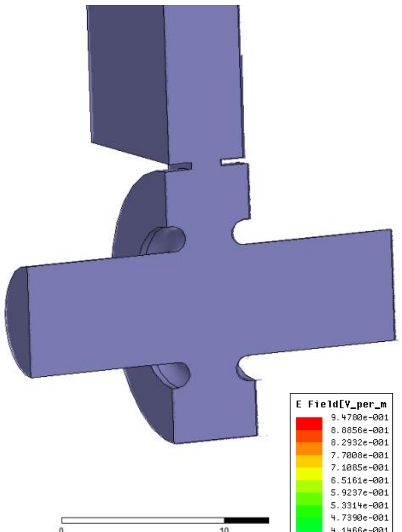
F = 11.9108 GHz,
Q = 2039 with copper

Utot = 2.5735E-19 J
R/Q = 23.9 ohm
M = 0.6127

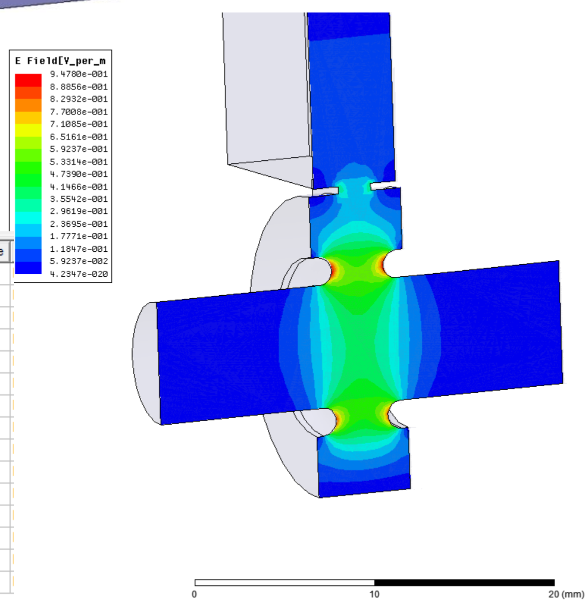


INPUT / OUTPUT CAVITY DESIGN

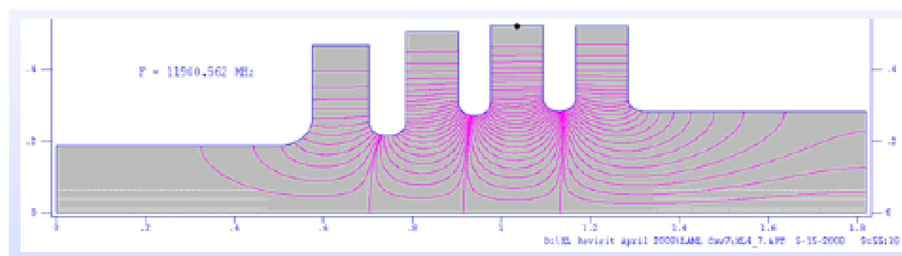
Input cavity
Qx = 460



Name	Value	Unit	Evaluated Value
a	3.5	mm	3.5mm
length	25	mm	25mm
h	5.68	mm	5.68mm
r1	8.6	mm	8.6mm
gap	3.2	mm	3.2mm
bec	(h-gap)/2		1.24mm
r2	5.1	mm	5.1mm
Rfill	0.8	mm	0.8mm
airis	7	mm	7mm
biris	2	mm	2mm
Dguide	9	mm	9mm
Lguide	20	mm	20mm
eps	3	mm	3mm
aguide	22.86	mm	22.86mm
bguide	5.08	mm	5.08mm



Output cavity: many possibilities:
- Same as input cavities but with Qx = 20 (change of the iris dimensions)
- Multicell output cavity: SW or TW
- Other ideas ? (Igor) (backward wave, recirculation, …)



SLAC XL5 output cavity (4 cells, π mode)

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- **Simulation codes**
- Klystron development plan

BEAM / RF INTERACTION SIMULATION TOOLS

AJDISK
(SLAC)
1D
free

Preliminary design

?
Frequency domain
2D

Design consolidation

MAGIC
PIC time domain
2D/3D

CST
PIC time domain
3D

WARP
(LBNL)
PIC time domain
2D/3D
Free, open source
Cluster

Full verification of the performances and oscillation study

TRACEWIN
(CEA)
Tracking
2D/3D
Cluster

Emittance growth, matching, halo and error studies (new use for klystron!)

- Remaining budget from the French exceptionnal contribution to CERN will allow us to buy one MAGIC licence
- Collaboration with THALES would be extremely helpfull to benchmark with their homemade codes

THE WARP CODE

Warp*: PIC modeling of beams, accelerators, plasmas

Lawrence Berkeley National Laboratory, CA, USA

Warp

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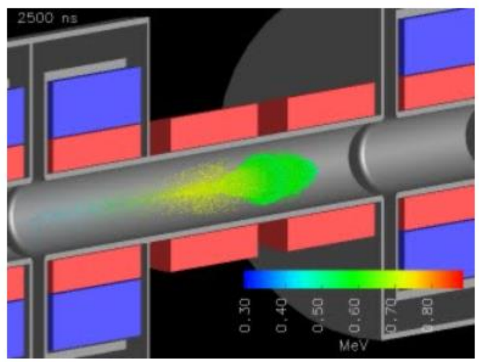
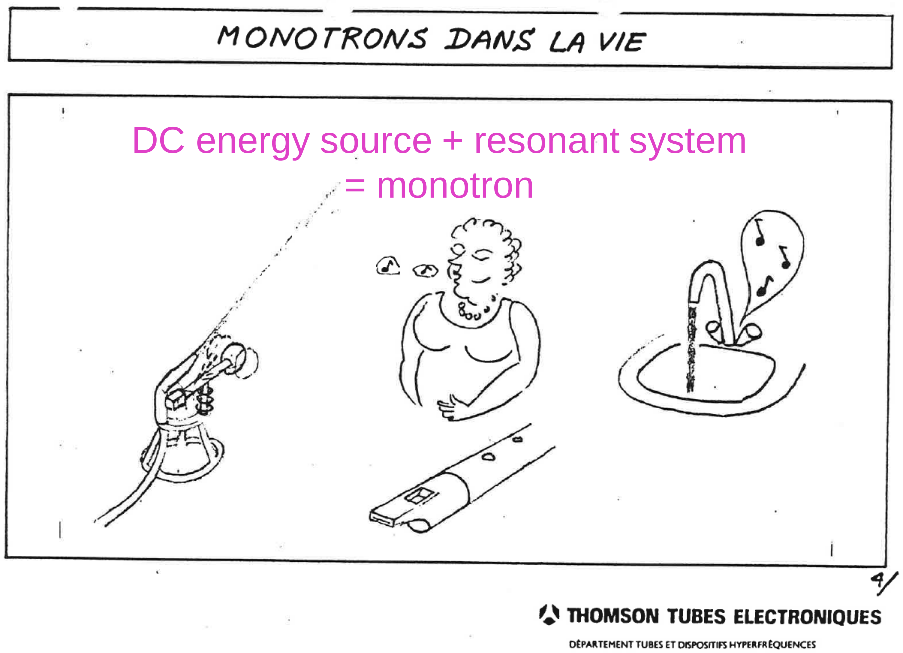
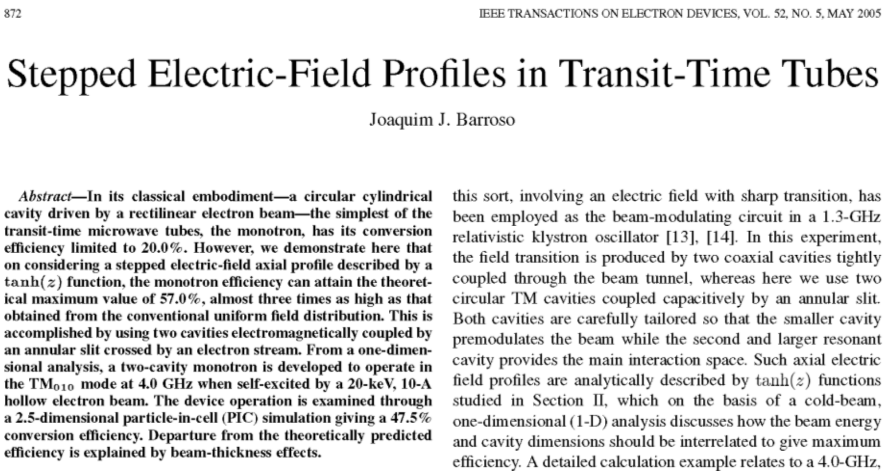


Warp is a particle-in-cell code designed to simulate high current particle beams. It has a variety of integrated physics models and extensive diagnostics. The code is setup around the interactive python interpreter with dynamically loaded compiled code modules. This allows flexible problem descriptions in python scripts which can exploit the full versatility of python and compiled packages as well as allowing interactive steering of runs. There are many diagnostics built in, mostly written in python, and which are documented in-line. A user can develop additional elaborate diagnostics as needed for specific applications. Warp has a hierarchy of multi-species models ranging from full 3D, transverse slice x-y (including p_z), and axisymmetric r-z (including p_{theta}), as well as simple envelope

SIMULATING A MONOTRON CASE WITH WARP

- Monotron oscillator = most simple microwave tube configuration
- A well know phenomena (most of the time not desired) in the microwave tube community




872 IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 52, NO. 5, MAY 2005

Stepped Electric-Field Profiles in Transit-Time Tubes

Joaquim J. Barroso

Abstract—In its classical embodiment—a circular cylindrical cavity driven by a rectilinear electron beam—the simplest of the transit-time microwave tubes, the monotron, has its conversion efficiency limited to 20.0%. However, we demonstrate here that on considering a stepped electric-field axial profile described by a $\tanh(z)$ function, the monotron efficiency can attain the theoretical maximum value of 57.0%, almost three times as high as that obtained from the conventional uniform field distribution. This is accomplished by using two cavities electromagnetically coupled by an annular slit crossed by an electron stream. From a one-dimensional analysis, a two-cavity monotron is developed to operate in the TM_{010} mode at 4.0 GHz when self-excited by a 20-keV, 10-A hollow electron beam. The device operation is examined through a 2.5-dimensional particle-in-cell (PIC) simulation giving a 47.5% conversion efficiency. Departure from the theoretically predicted efficiency is explained by beam-thickness effects.

this sort, involving an electric field with sharp transition, has been employed as the beam-modulating circuit in a 1.3-GHz relativistic klystron oscillator [13], [14]. In this experiment, the field transition is produced by two coaxial cavities tightly coupled through the beam tunnel, whereas here we use two circular TM cavities coupled capacitively by an annular slit. Both cavities are carefully tailored so that the smaller cavity premodulates the beam while the second and larger resonant cavity provides the main interaction space. Such axial electric field profiles are analytically described by $\tanh(z)$ functions studied in Section II, which on the basis of a cold-beam, one-dimensional (1-D) analysis discusses how the beam energy and cavity dimensions should be interrelated to give maximum efficiency. A detailed calculation example relates to a 4.0-GHz,

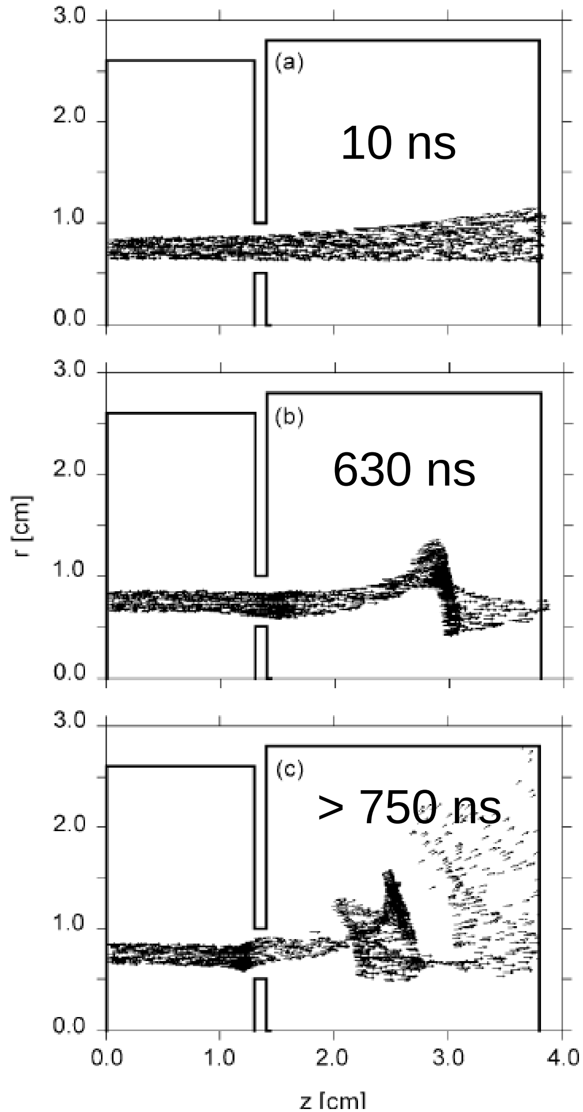
- Objective: validate WARP on its ability to simulate the beam/RF interaction where Barroso publication: 20 kV – 10 A, annular beam, two-steps cavity 4.1 GHz
- 1D analytical treatment is possible and 2D PIC results is compared

MONOTRON CASE

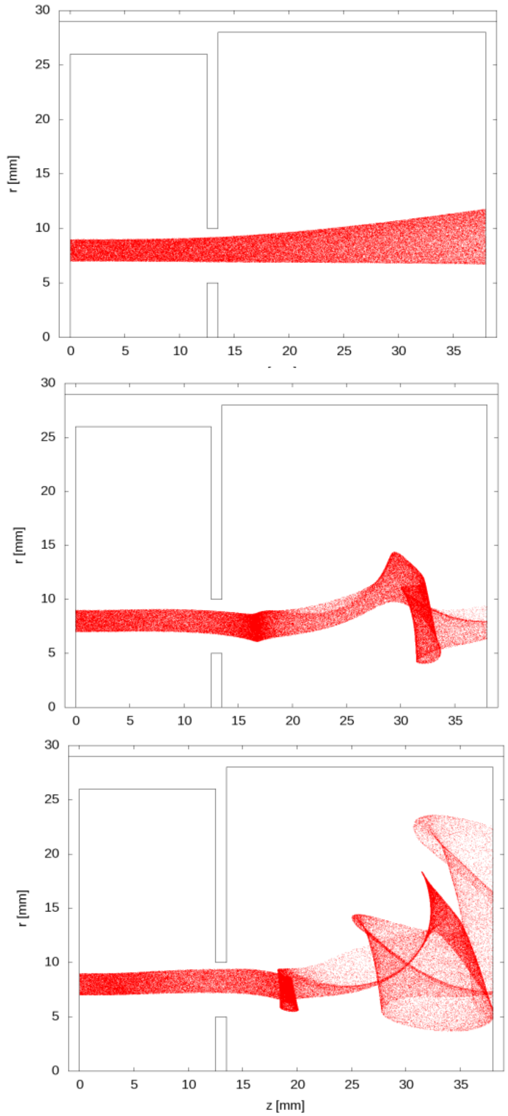
- Without focusing magnetic field Bz

Simulations performed by
Antoine Chancé - CEA

Barroso publication



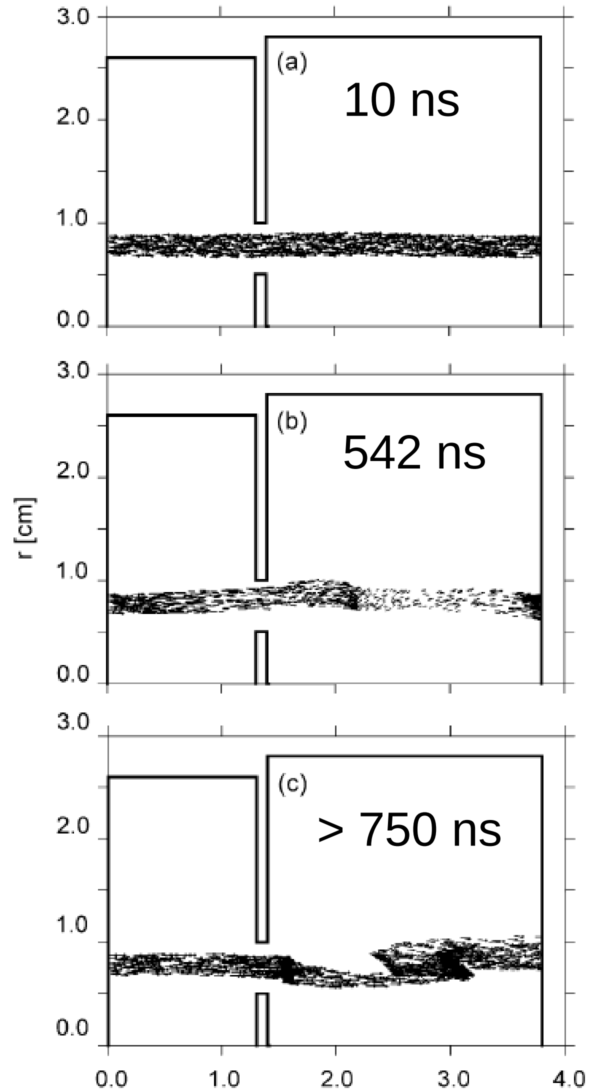
WARP simulation



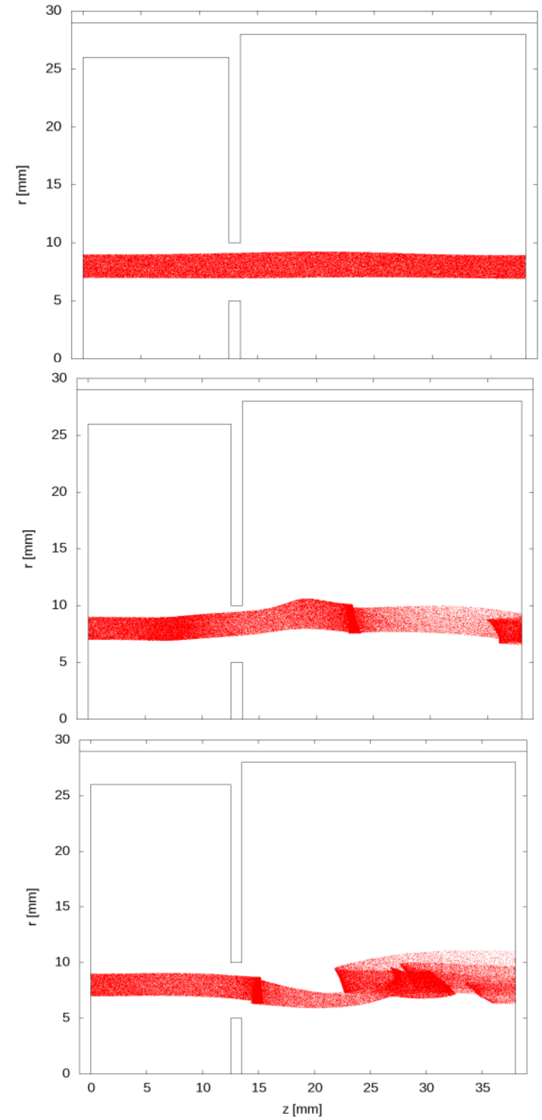
MONOTRON CASE

- With focusing magnetic field Bz

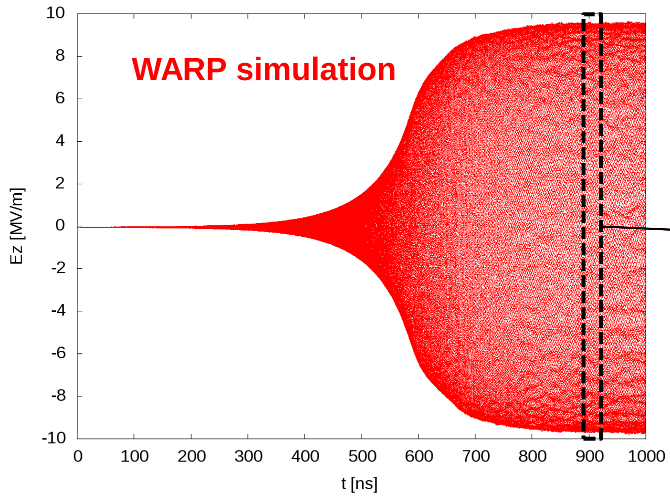
Barroso publication

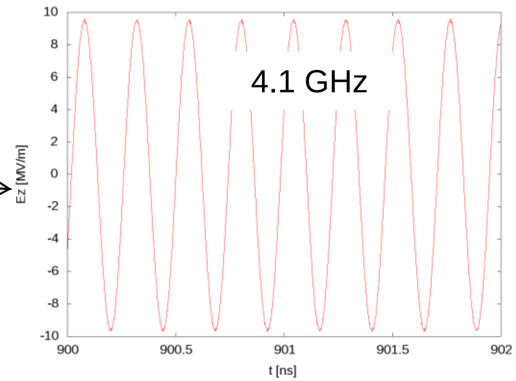


WARP simulation

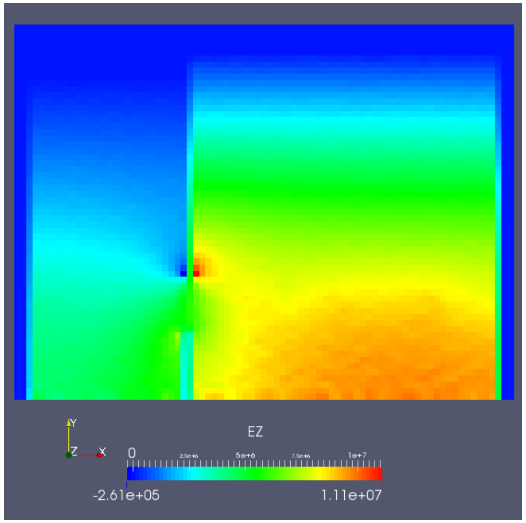


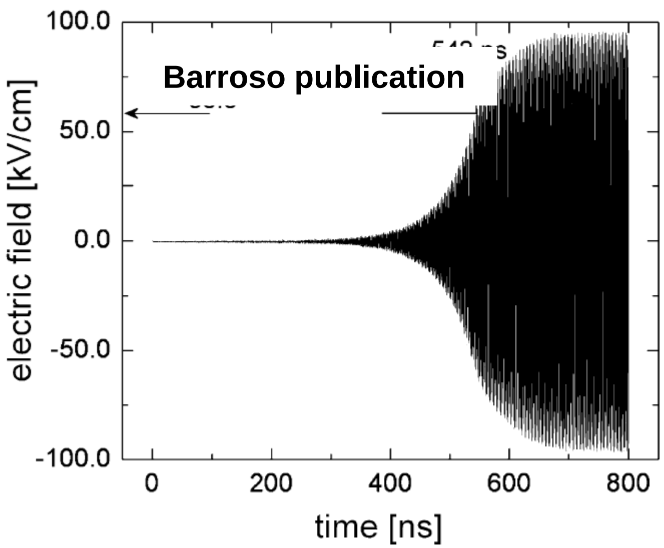
MONOTRON CASE

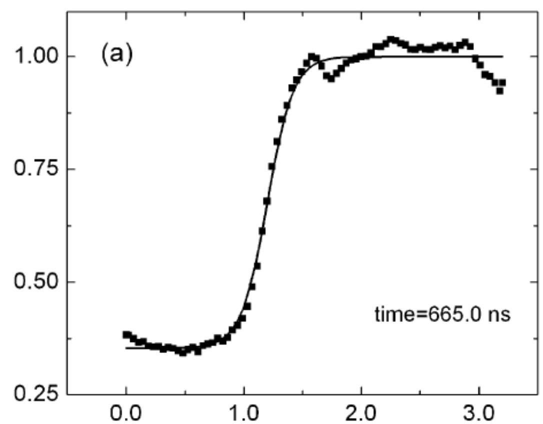


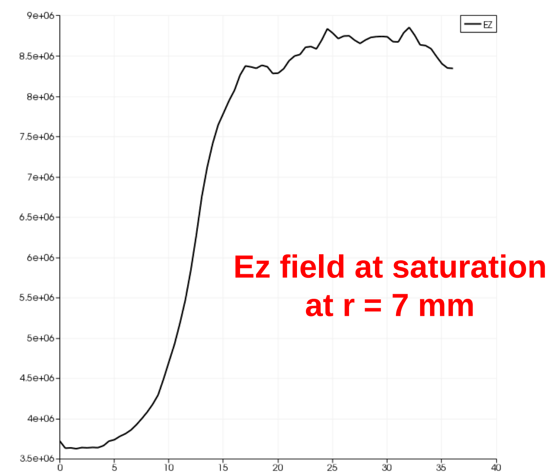


Ez field at saturation





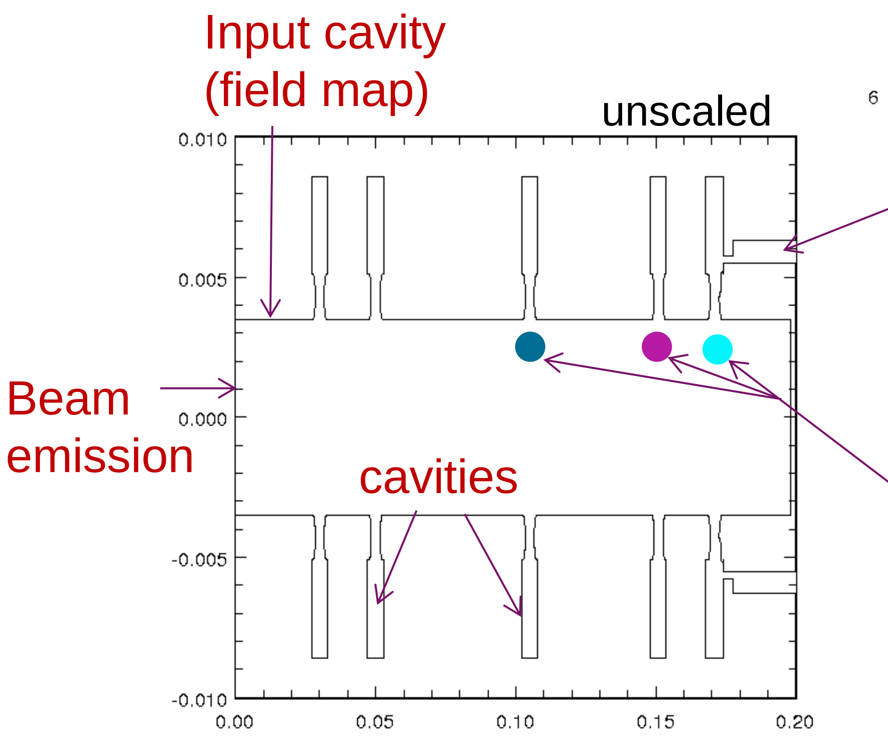


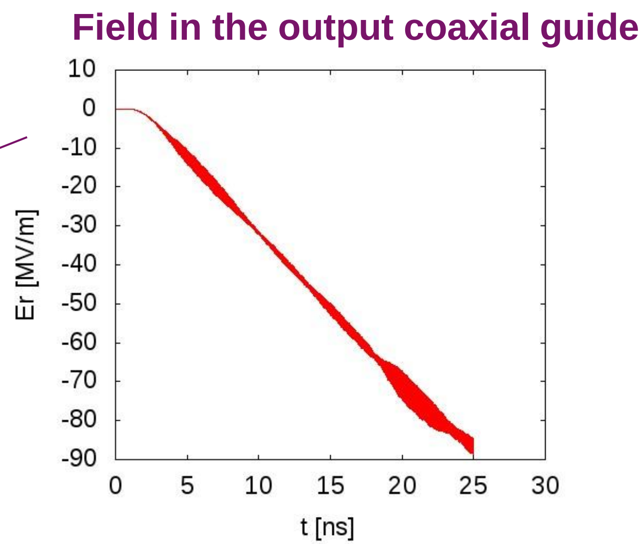


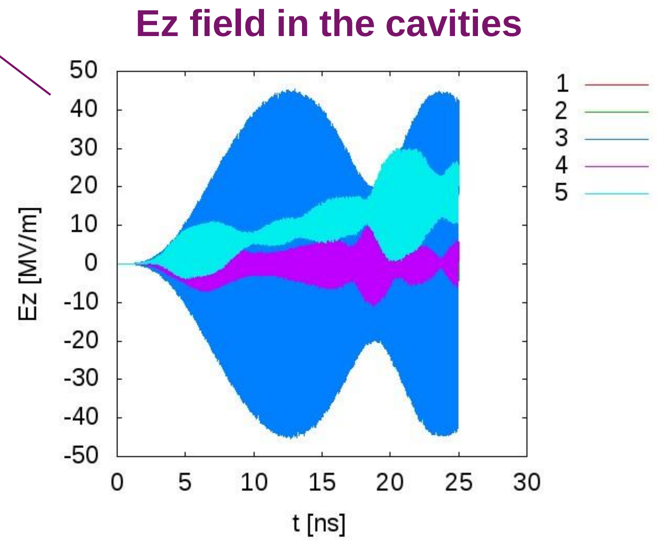
☞ **The WARP code is valid for simulating all kind of vacuum microwave tubes**

SIMULATING THE 6 CAVITIES KLYSTRON WITH WARP

- Second validation step: simulation of a full « classical klystron »
- We take the 6 cavities klystron designed and shown previously







Difficulties:

- Oscillation/beating is probably due to the frequencies difference from one cavity to the other
- Creation of a DC field component due to coaxial output configuration

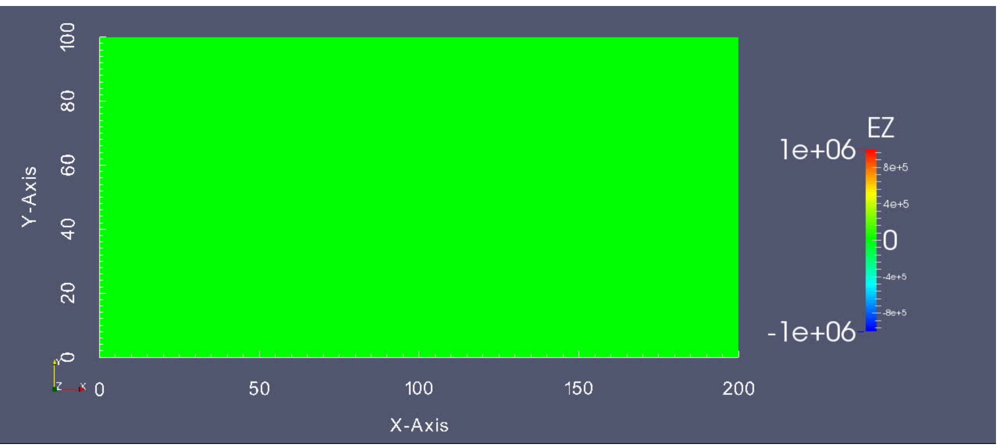
CAVITIES FILLING UP AND ELECTRON VELOCITY

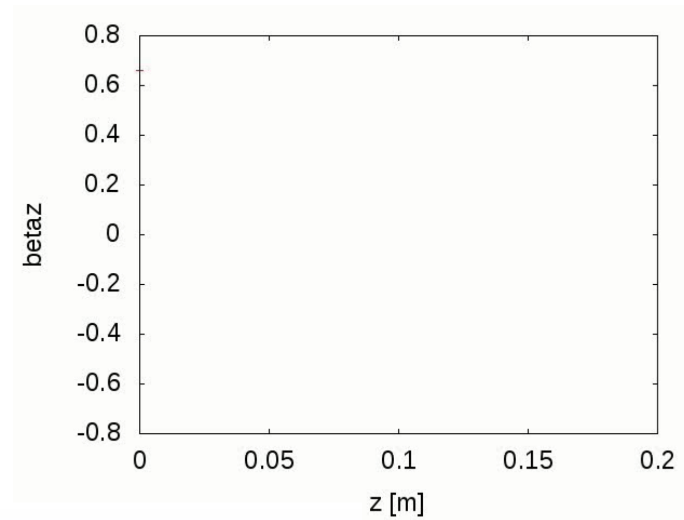
Difficulties (con't):

❖ Large amount of reflected electrons

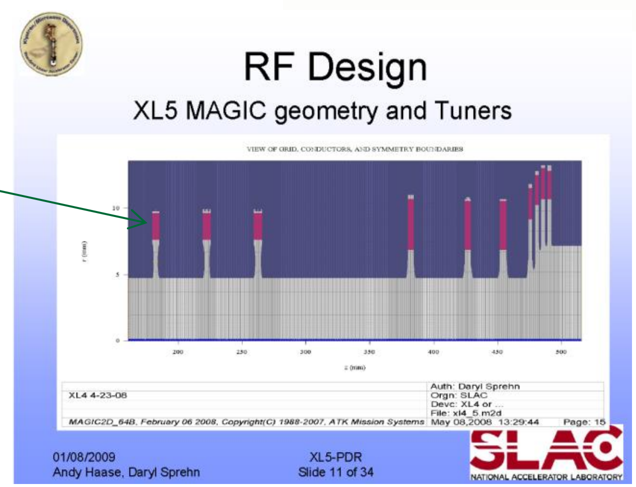
☞ These problems come from the fact that it is difficult to adjust the cavities at the right resonant frequency (even with the use of adaptative mesh)

Animation goes from 0 to 25 ns

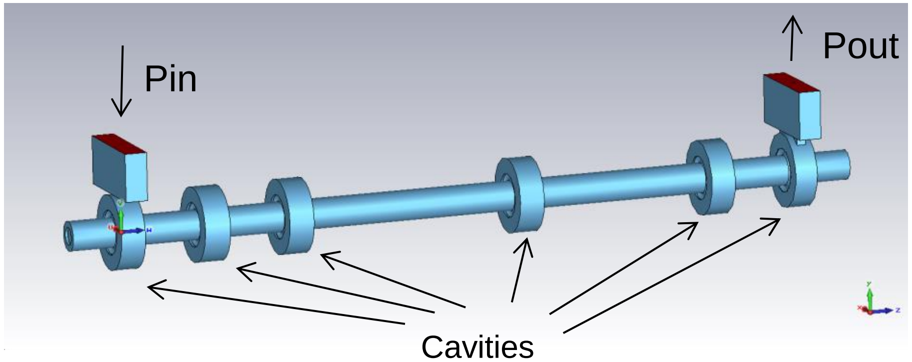


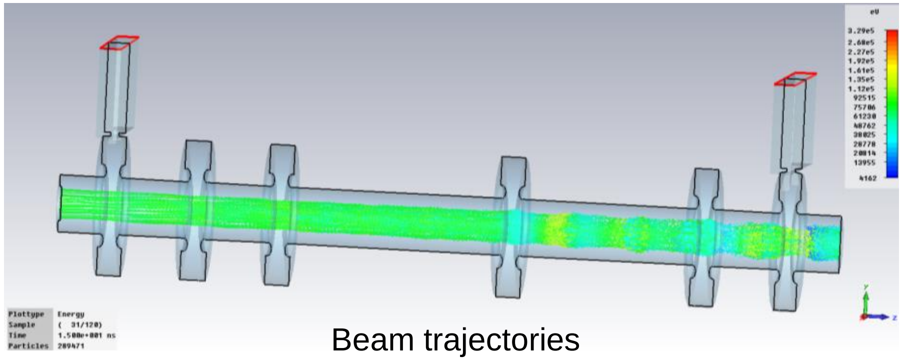


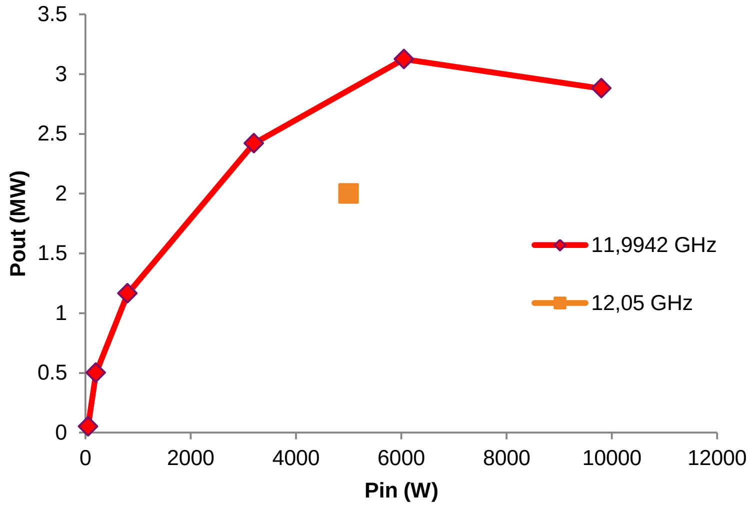
Possible solution:
Add dielectric material inside cavities and adjust dielectric parameters

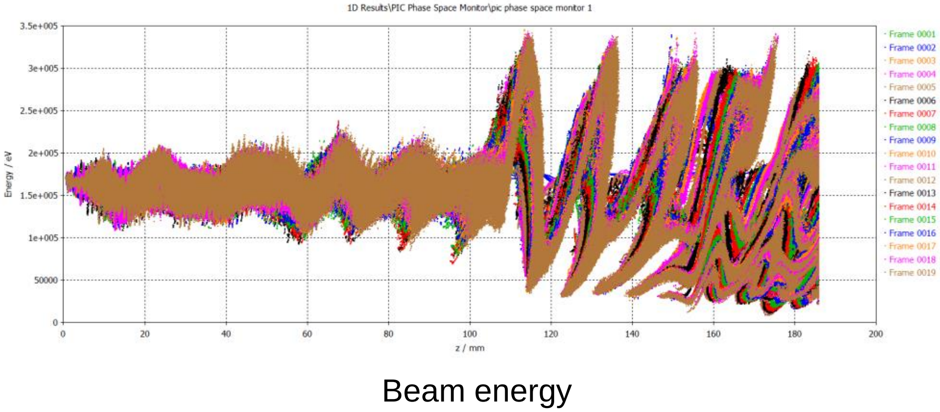


- The same 6 cavities klystron has been calculated with CST – Particle Studio
- Also very preliminary work…



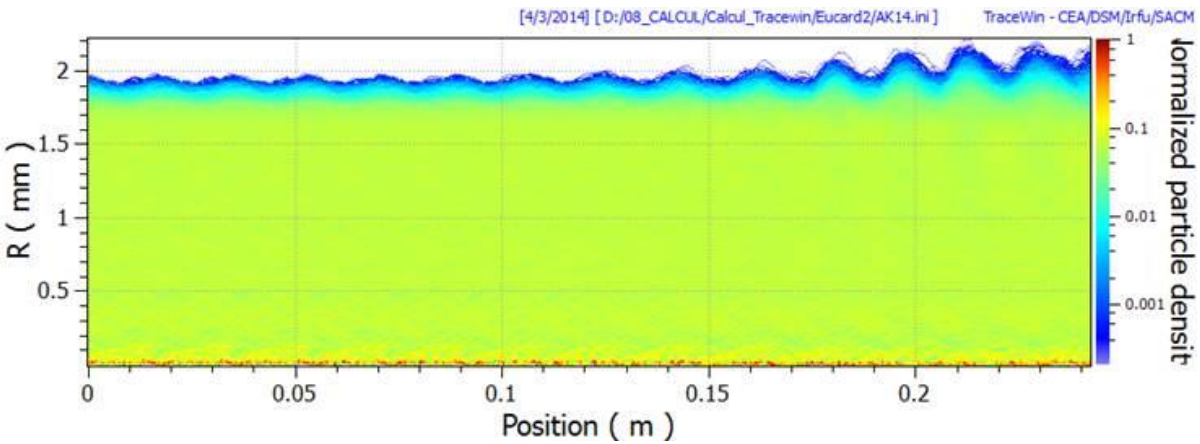


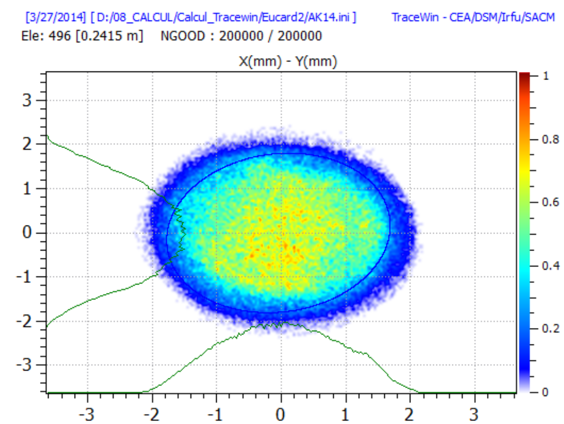


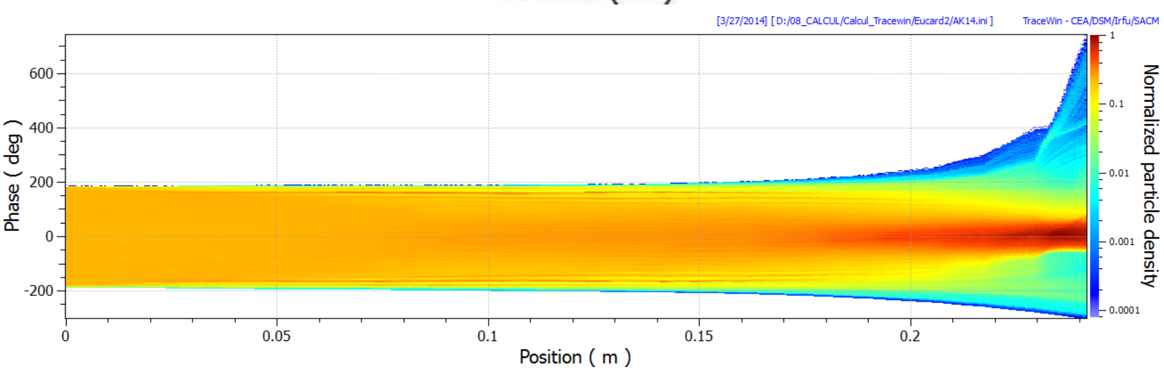


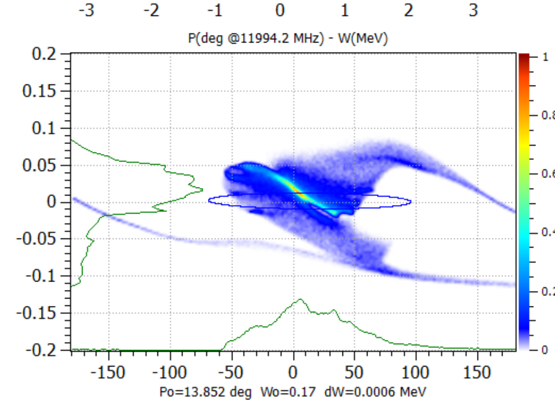
TRACKING CODE “TRACEWIN”

- a 3D code widely used in the accelerator community
- PARTRAN routine to simulate the space charge effects
- The idea is to inject the gap voltages calculated by AJDISK
- Allows to simulate a large number of particles (useful for Halo studies for example) and has automatic optimization procedures



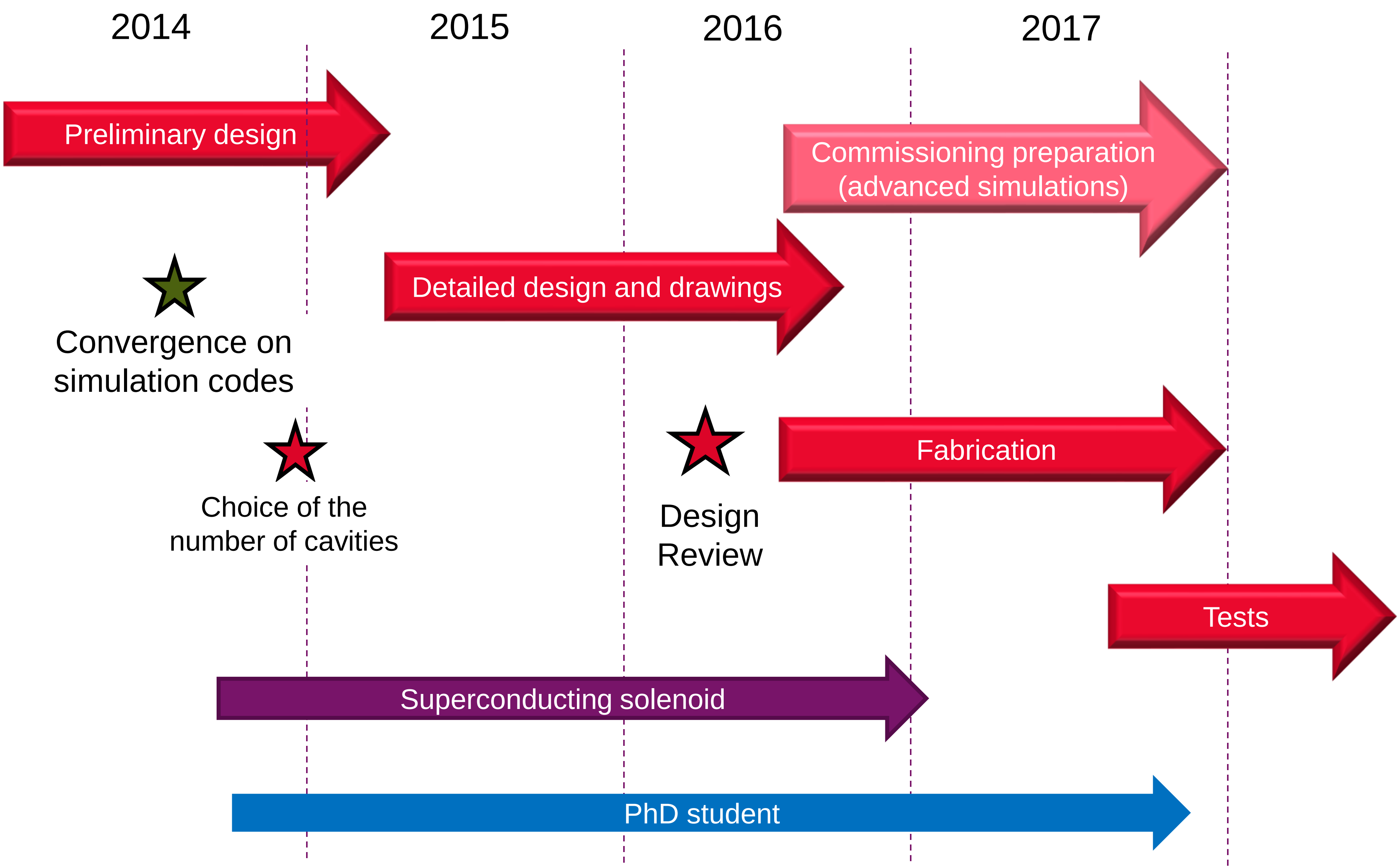






- Context and objectives
- New klystron concept
- Simulation codes
- **Klystron development plan**

THE 12 GHZ - 12 MW KLYSTRON PROTOTYPE PLANNING



TOWARDS HIGHER EFFICIENCY WITH THE ADIABATIC APPROACH

Tentative Road map

Medium Power klystron
170 kV – 12 MW
single beam

Proof of principle

High power klystron
170 kV – 50 MW
4 beams

Low power klystron
60 kV (gun in air)
1 MW single beam
or 4 to 6 MW multibeam

X-band frequency

Lower frequency klystron
1 GHz, 704 MHz or lower

Directly applicable to accelerator projects (ESS, CLIC, FCC…)

Higher frequency klystron
> 12 GHz

To check the limit of the concept
Need to find some applications

Advanced Focusing system: superconducting solenoid / Permanent magnet / RF focusing?...

Output RF structure: SW, TW, …

FABRICATION: collaboration with industry is mandatory:

Possible strategy:
- **Functional drawings by lab (CEA or CERN)**
- **Call for tender for the fabrication of one prototype**

☞ **NEW PROCEDURE for klystrons (but usual for Gyrotron in the fusion community)**

CONCLUSION

- Some clear and highly motivating objectives to develop high efficiency RF sources with high reliability have been presented

- The new adiabatic approach to optimize the bunching process of the beam have been proposed and declined in few designs

- We are working on new numerical tools for the klystron study

- We have also to think of **extending the Eucard2 project** to a larger collaboration, in particular with **CERN within the CLIC project**. CEA would be extremely interesting to pursue the CLIC collaboration if a new agreement (and new budget) could be found.

CEA TEAM

CEA permanent staff

Franck PEAUGER

Juliette PLOUIN

Barbara DALENA

Post-doctoral position

24 months from April 2014

Modelisation of the beam/wave interaction

Funding EUCARD2/CEA

with help of:

Antoine CHANCÉ

Beam dynamics, user of Tracewin and Warp

Lyes BOUDJAOUI

Internship

6 months from April 2014

Design of electron guns

Funding CEA

+ 1 PhD position with funding demand in progress

http://www-instn.cea.fr/spip.php?page=Publication_Sujet&idSujet=8343&lang=fr&langue=fr&id_rubrique=70

EXTERNAL CONTACTS FOR POSSIBLE COLLABORATIONS

- CERN: Igor SYRATCHEV, Chiara MARELLI, …
- THALES ELECTRON DEVICES: Rodolphe MARCHESIN
- PSI: Jean Yves RAGUIN

New collaborators are WELCOME!

KLYSTRON NAME !

1. Igor ‘s proposal…Kl-adi(adiabatic)-stron : « KLADISTRON »

2. From dictionary: **adiabatic (**/ˌædiəˈbætɪk/) = from the greek privative "a" + "diavaton“: « ADIAVATRON »

3. Simply « Adiabatic Klystron » or « AK »

4. Or « HAKA » for Hollow beam Adiabatic Klystron Amplifier (if hollow beam is chosen)

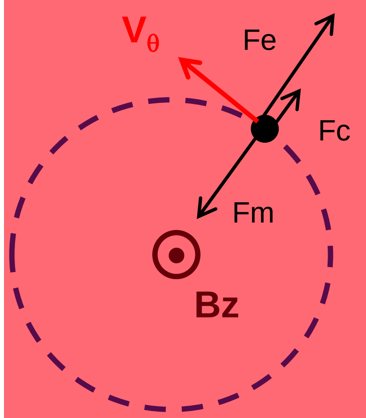
“The external forces vary more slowly than the interaction forces in the system”

Thank you for your attention

SPARE SLIDES

WORKING WITH A "MAGNETIZED BEAM"

- Principle: Injection of the beam with a non-null ortho-radial velocity
- Advantage: less sensitive to space charge force variations



- Lorentz force (focusing) $$F_m = -e \cdot V_\theta \cdot Bz$$
- Space charge forces (defocusing) $$F_e = e \cdot E_r$$ avec $$E_r = \frac{Ik}{2\pi r \varepsilon_0 V_z}$$
- Centrifugal force (defocusing) $$F_c = m \cdot \frac{{V_\theta}^2}{r}$$

Bush theorem

$$V_\theta = \frac{e}{2m} r(Bz - C \cdot Bk)$$

With r the beam radius, Bk the magnetic field at the cathod, rk the cathod radius and C the gun convergence defined by:

$$C = \frac{rk^2}{r^2}$$

Brillouin field Bb:

$$Bb = \frac{8.307 \cdot \sqrt{Ik}}{r \cdot Vk^{0.25}}$$

In stationnary regim, the beam radius is constant if: $Bz = \sqrt{Bb^2 + C^2 Bk^2}$

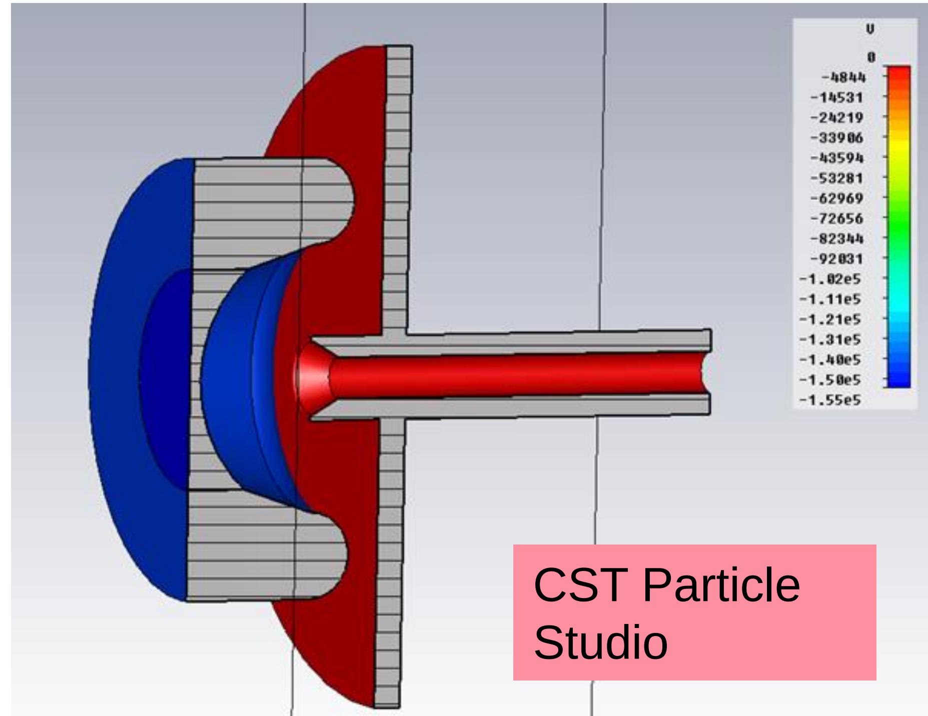
Exemple:

vitesse du faisceau		
Epsilon0	8.8541878E-12	
e	1.60E-19	
m	9.10E-31	
C	2.99792E+08	m/s
Vk	**170000**	**V**
Ik	**85**	**A**
gamma	1.332681018	
beta	0.661021334	
Vz	198 168 907.86	m/s
L	0.2	m
t	1.00924E-09	

Champ de brillouin Bb=	1 796.07	gauss
Bz=	4 351.87	gauss
C x Bk=	3 963.95	gauss
Rayon faisceau r=	2.10E-03	m
Vteta=	7 161 555.25	m/s
Vteta=	1.46E+02	Volt
teta=	2.07	deg
C=	20.00	
Bk	198.20	
Rk=	0.205	m

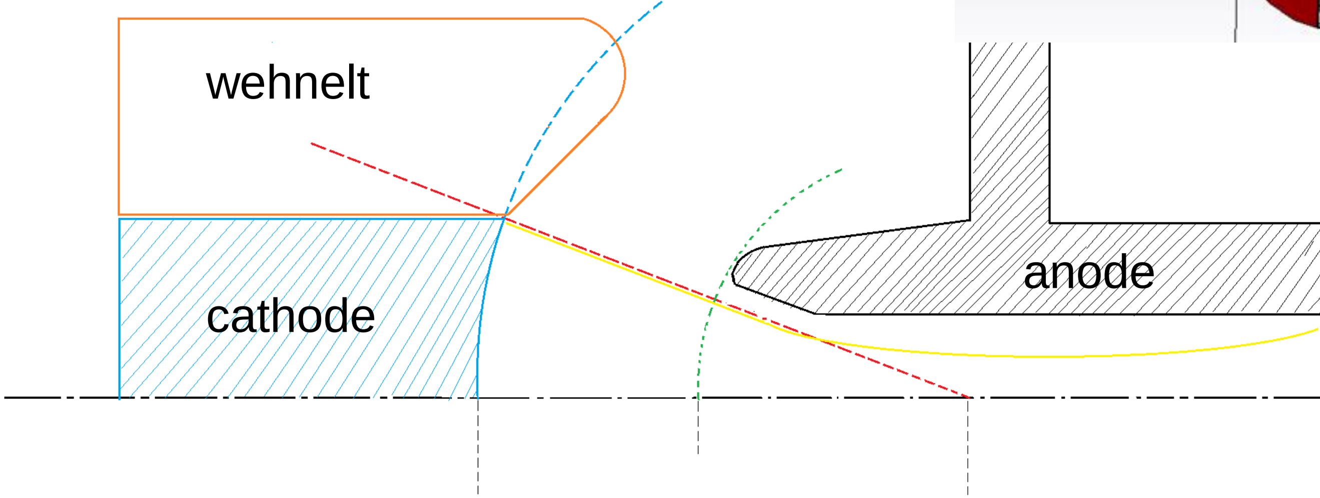
PIERCE GUN STUDY – VERY PRELIMINARY DESIGN

Cathode voltage (V)	**155000**
Beam current (A)	**115**
Microperveance (1e-6 A/V^1.5)	**1,88**



CST Particle Studio

Scheme of a Pierce cathode



TECHNICAL RISKS

- Peak gains: loop oscillation
- Monotron oscillation
  - Do we need RF damping in cavities ?