A Ka-Band accelerating structure as a linearizer for the Compact Light XLS project

presented by

Bruno Spataro
(INFN-LNF)

on behalf of Compact Light XLS project

Presentation summary

Optimization of the Ka-band cavity in order to minimize the surface electric field

- Field flatness achievement
- Frequencies spectrum

Modified Poynting vector and Pulse Heating estimations

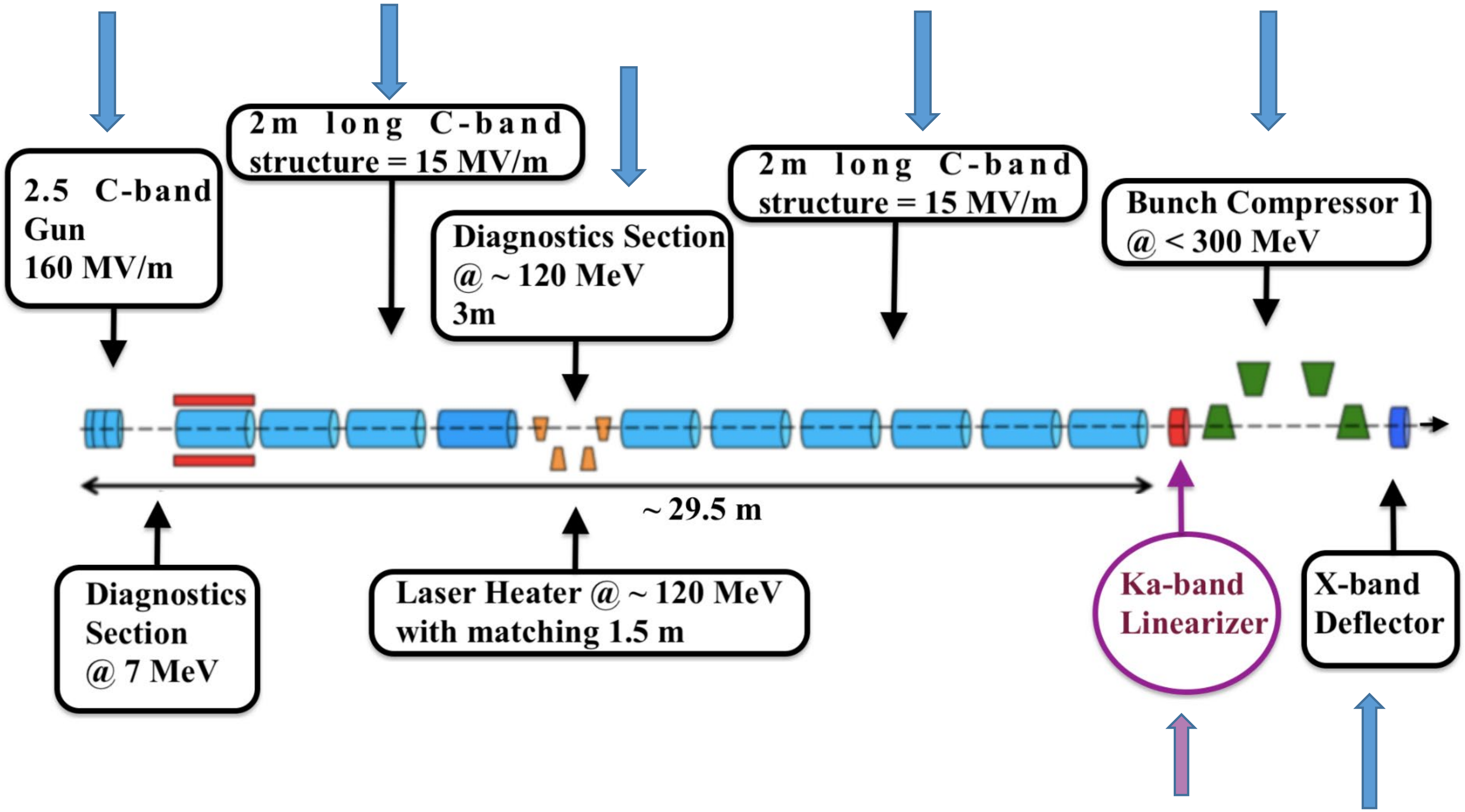
Comparison between normal conducting and cryogenic structures

Option with two long TW Ka-band structures (UNLANC-CERN)

Hints on the 36 GHz power sources

Schematic layout of the Linac for the Compact Light XLS Project (at March 15 - 2021)

European scientists are proposing an advanced light source Compact Light which aims to extend Free Electron Laser operation into the hard X-ray region 12-16 KeV (or 0.0775-0.103 nm) and thus beyond present state-of-the-art (1).
The baseline includes helical superconducting undulators such as main radiator (2)



Beam energy **300 MeV**

Beam charge **75 pC**

Pulse length **350 fs**

Normalized emittance

$\varepsilon_{x,y} \sim 0.2\ \mu$ mrad
[A. Latina (Cern)
C. Vaccarezza –LNF]

To correct the longitudinal bunch phase space non-linearity as arise in the C-Band Linac, a Ka-band (~ 36 GHz) short Linac is proposed, which has to work with an integrated voltage at least of 15 MeV (A. Latina - Cern) from Paul Emma's paper (SLAC-TN-05-004)

1) https://www.compactlight.eu/

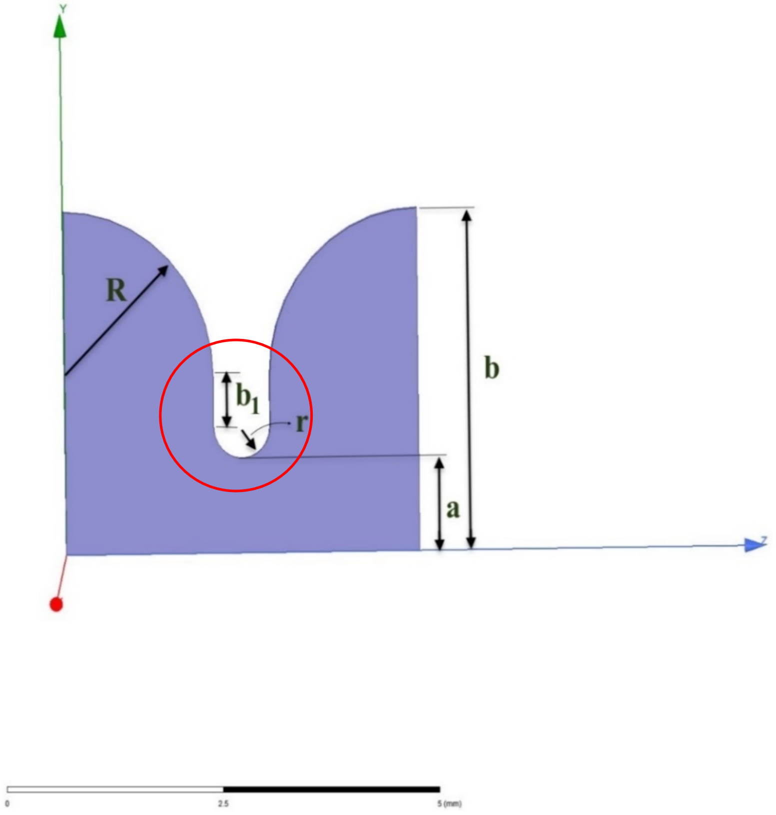
2) federico.nguyen@cern.ch

Ka-band (35.982 GHz) linearizer cavity geometry

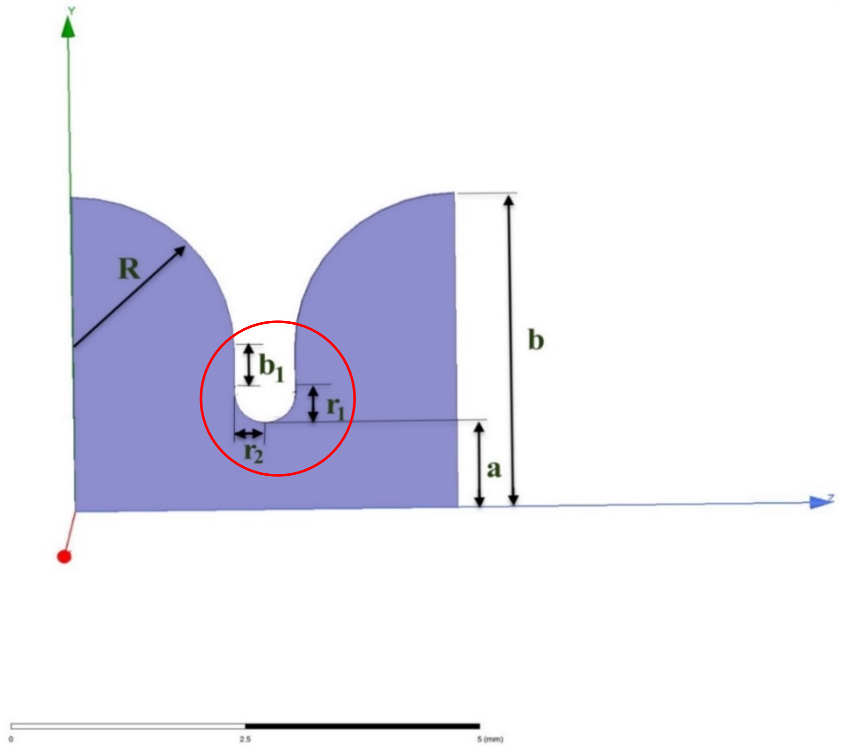
INFN
Istituto Nazionale di Fisica Nucleare

We show the investigated cavity geometries by assuming a thickness iris of h = 0.667 mm which comes out from the frequency scaling law of the 100 GHz structure already fabricated and tested at high power (SLAC – MIT)

The goal is to design the Ka-Band linearizer with a minimum surface electric field in order to increase the safety threshold of the breakdown



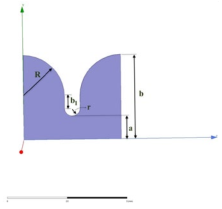
Rounded cavity geometry of the SW π mode with circular iris

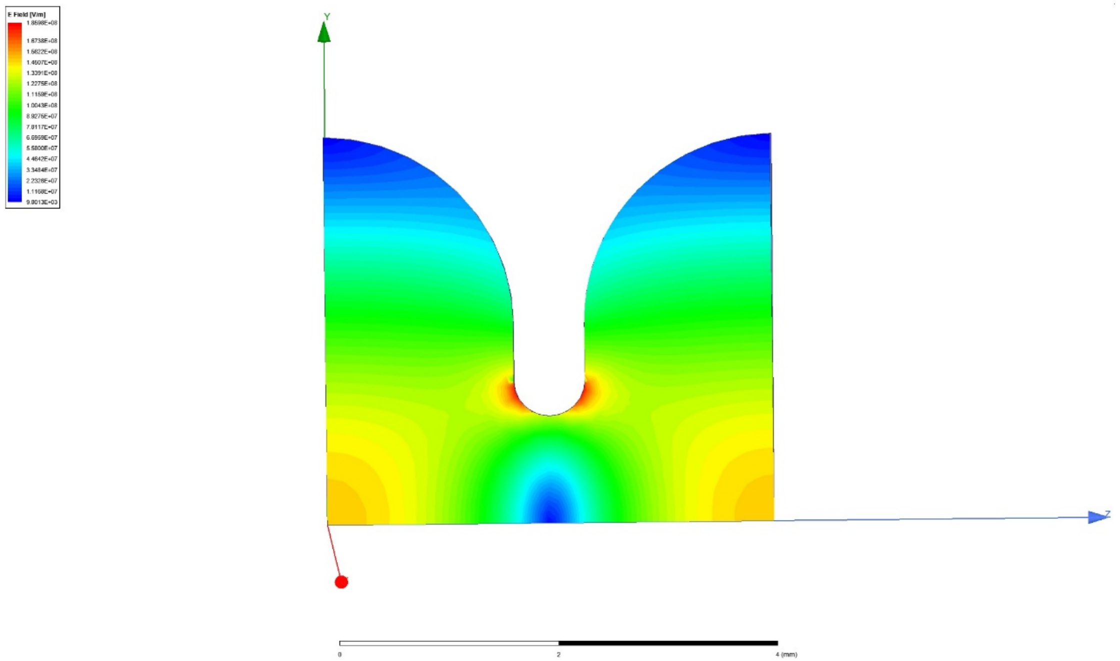


Rounded cavity geometry of the SW π mode with an elliptical iris of r_1 and r_2 semi-axes

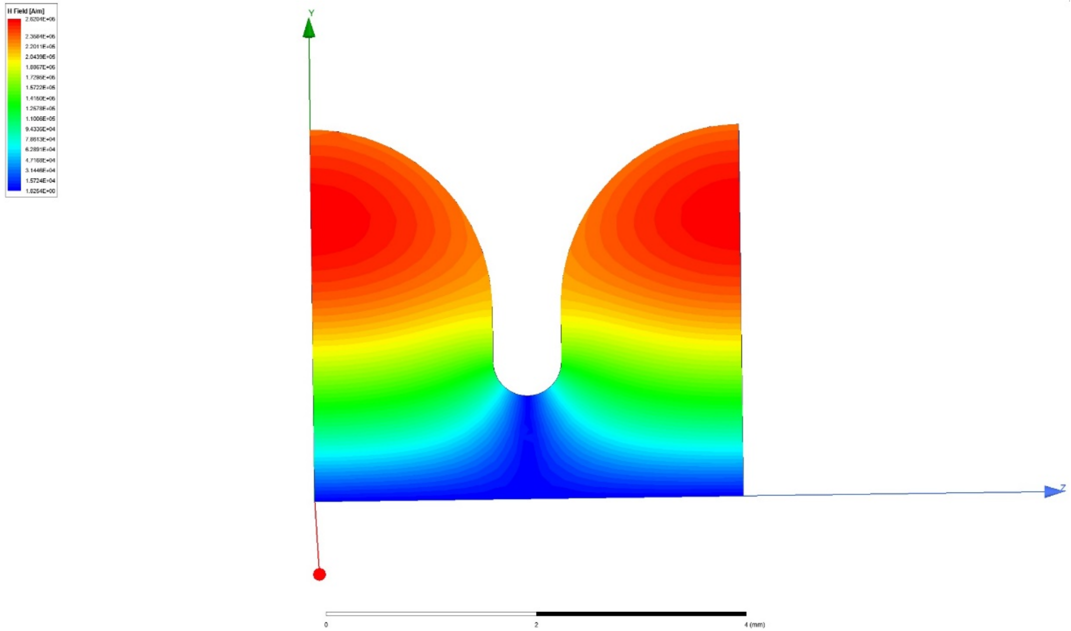
E field distribution and magnetic one of the ‘Rounded’ SW cavity geometry of the π mode configuration

INFN
Istituto Nazionale di Fisica Nucleare





Electric field distribution of the TM_{010} mode

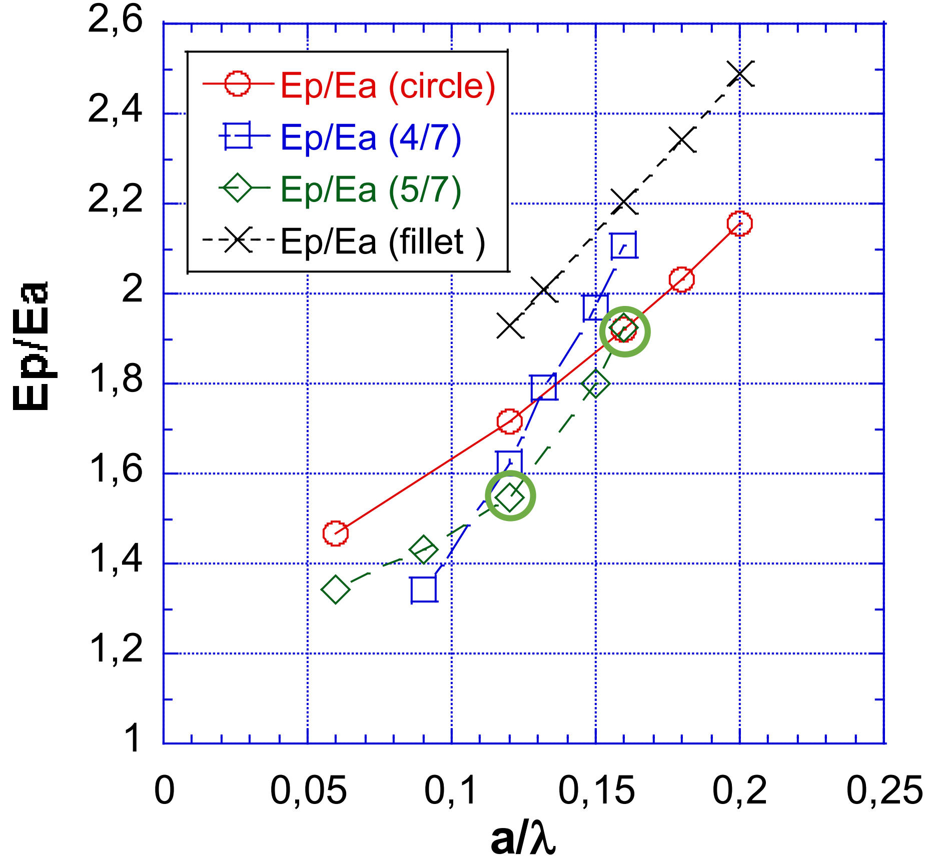


Magnetic field distribution of the TM_{010} mode

Minimum surface electric field estimations as function of the iris aperture radius for different iris geometries

INFN
Istituto Nazionale di Fisica Nucleare

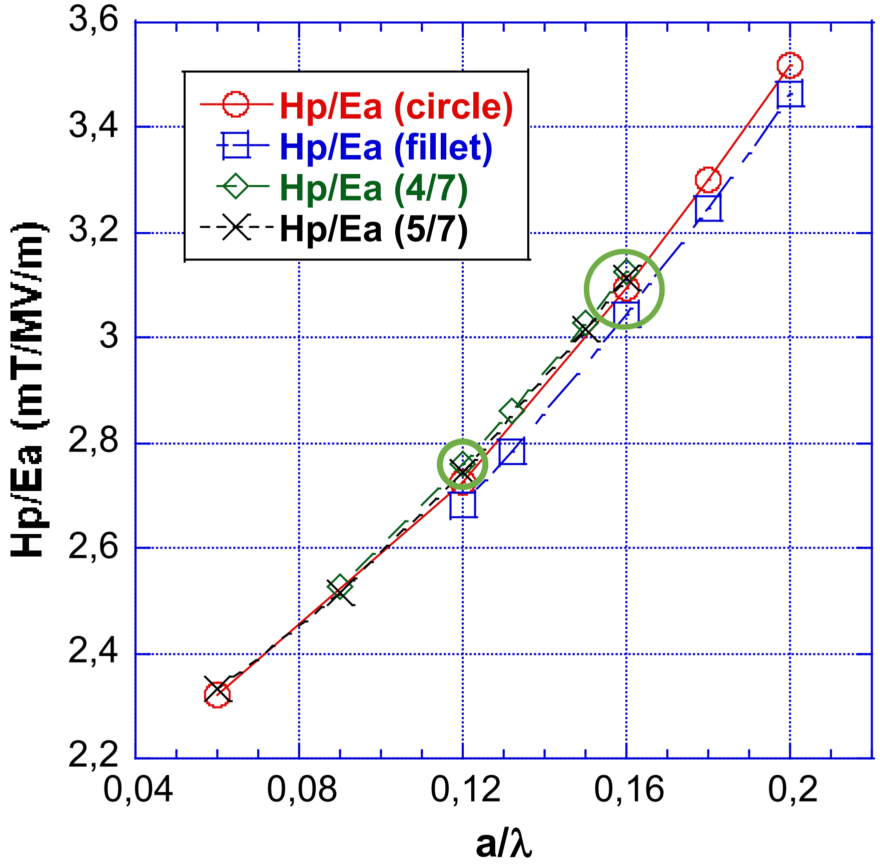
For a given iris aperture radius the Ep/Ea ratio is enough sensitive when comparing the estimations of the different irises geometries



At 1 mm iris aperture radius ($a/\lambda = 0.12$) the minimum ratio of the electric field is Ep/Ea ~ 1.55 with a $r_1/r_2 = 5/7$ semi-axes ratio (elliptical shape). This value is about 24 % less than the circular iris.

At 1.333 mm iris aperture radius ($a/\lambda = 0.16$) the electric field ratio becomes comparable with the circular iris geometry (about 1.92)

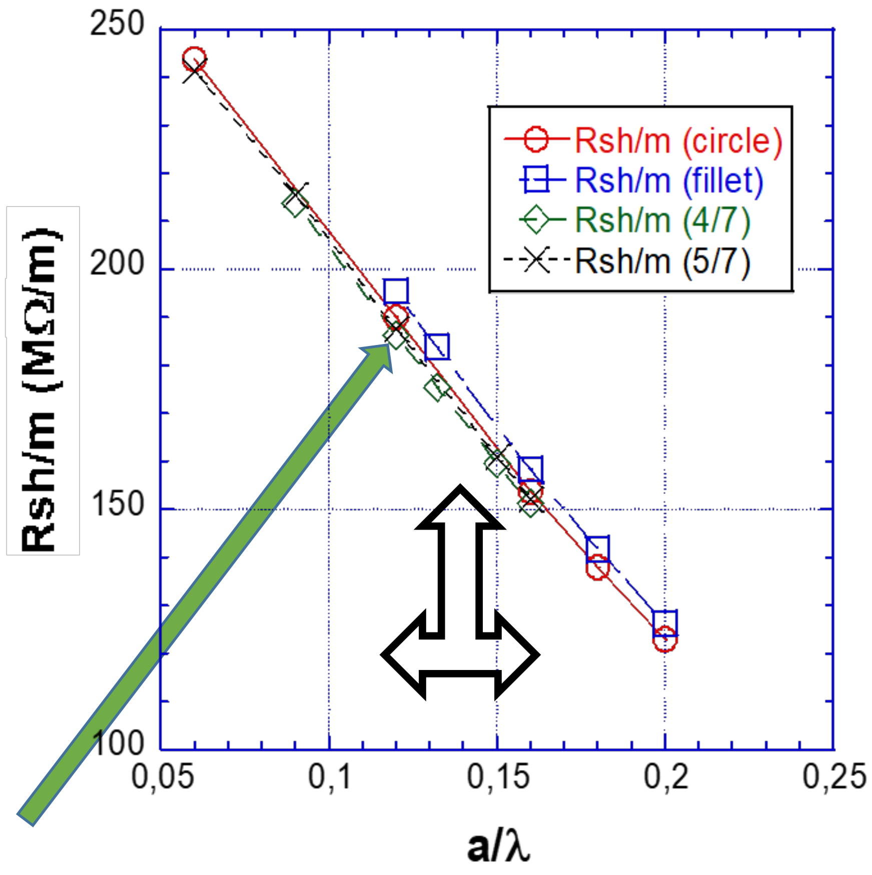
For a given iris aperture radius the Hp/Ea ratio changes little when comparing the estimations of the different irises geometries

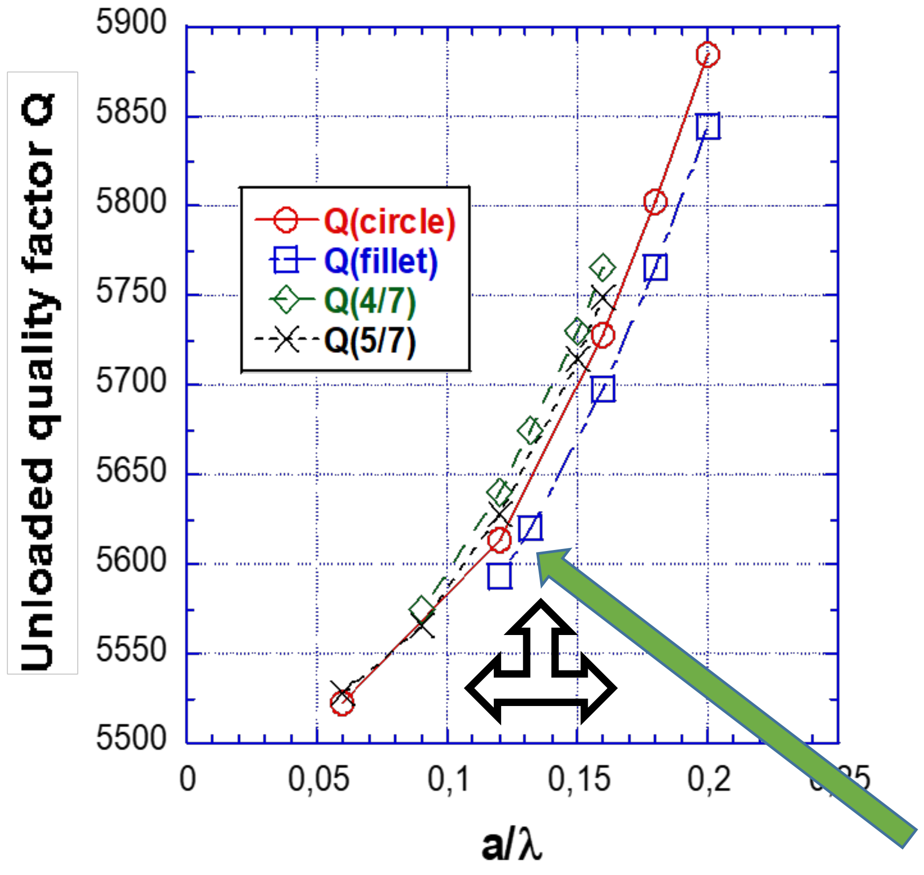


At 1 mm iris aperture radius ($a/\lambda = 0.12$) the magnetic field Hp/Ea ~ 2.7 mT/MV/m with a $r_1/r_2 = 5/7$ semi-axes ratio (elliptical shape). It differs by ~ 0.7% than circular iris tip.

At a 1.333 mm iris aperture radius ($a/\lambda = 0.16$) the magnetic field estimatons keep about the same trend in per cent

Shunt impedance and quality factor Q as function of the iris radius for different iris geometries





At 1 mm iris aperture radius (a/λ = 0.12) the shunt impedance is estimated to be R_{sh} ~ 189 MΩ/m with a r_1/r_2 = 5/7 semi-axes ratio (elliptical shape).

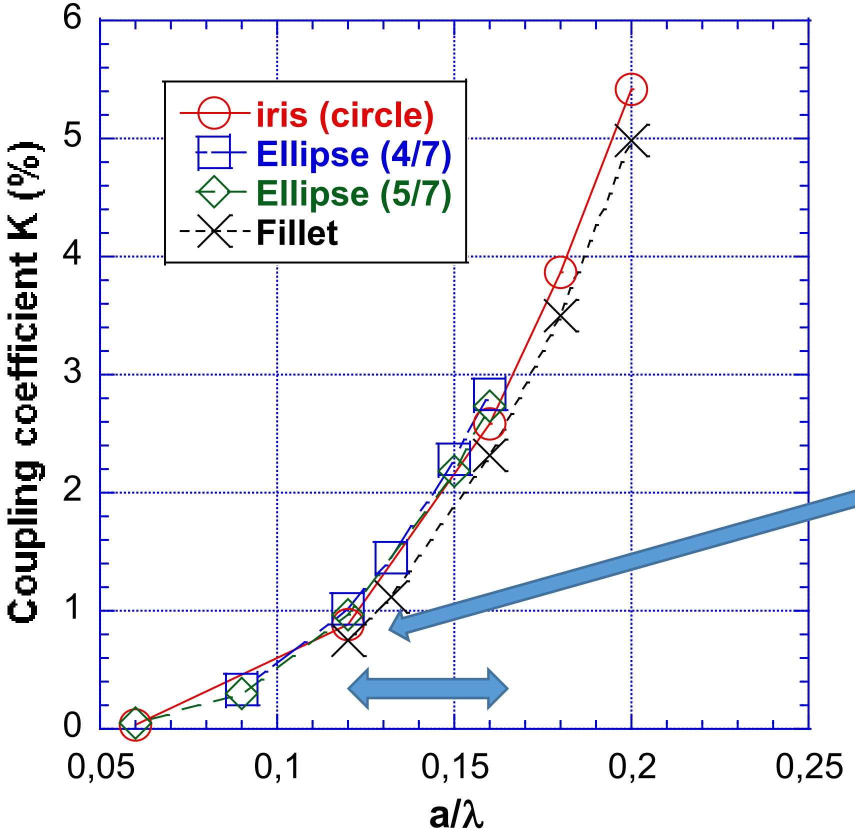
In the (1 - 1.333) mm iris aperture range [(0.12-0.16) a/λ range] the spread of the shunt impedance is about 20%.

At 1 mm iris aperture radius (a/λ = 0.12) the quality factor Q is estimated to be Q ~ 5628 with a r_1/r_2 = 5/7 semi-axes ratio (elliptical shape).

In the (1 - 1.333) mm iris aperture radius range [(0.12-0.16) a/λ range] the spread of the quality factor Q is about 2%.

Cell to cell coupling coefficient as function of the iris aperture radius for different iris geometries

INFN
Istituto Nazionale di Fisica Nucleare



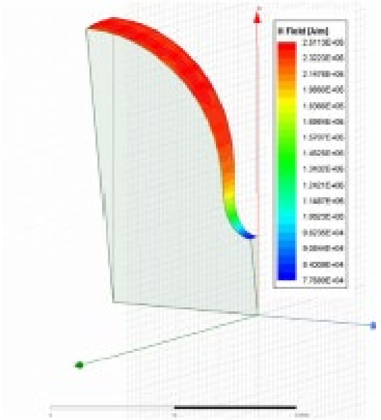
The coupling factor lying in the (0.7 - 2.8) % range correspond to iris aperture radii in the (1 - 1.333) mm range [a/λ = (0.12 – 0.16)]

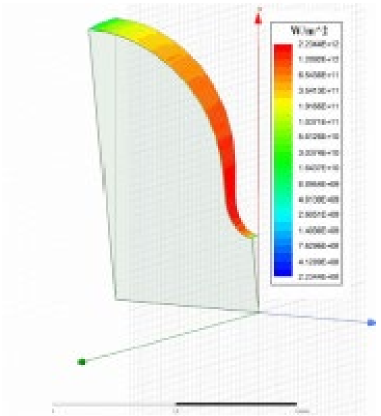
At 1 mm iris aperture radius (a/λ=0.12) the coupling coefficient K% is estimated to be about 0.97 % with a r_1/r_2 = 5/7 semi-axes ratio (elliptical shape).

Modified Poynting Vector (MPV) and Pulse Heating (PH) as function of the effective accelerating gradient for two irises geometries (circular iris and elliptical geometry with a 5/7 semi-axes ratio)

a) Magnetic field magnitude

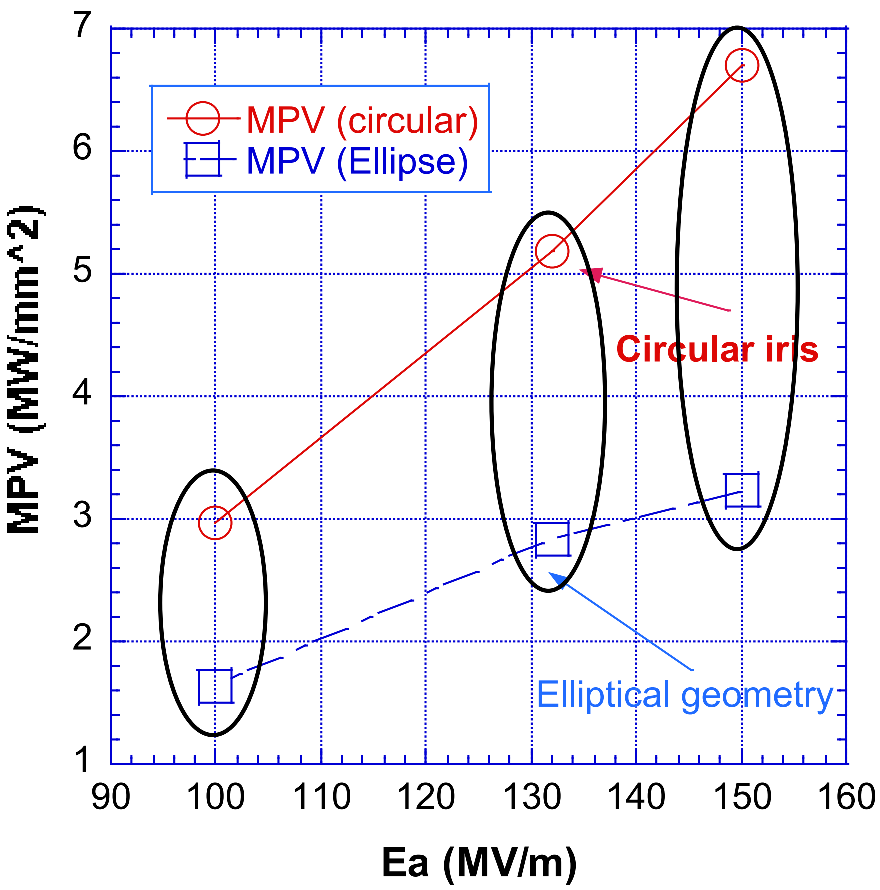
50 ns RF flat top   1 mm iris aperture radius   0.667 mm iris thickness





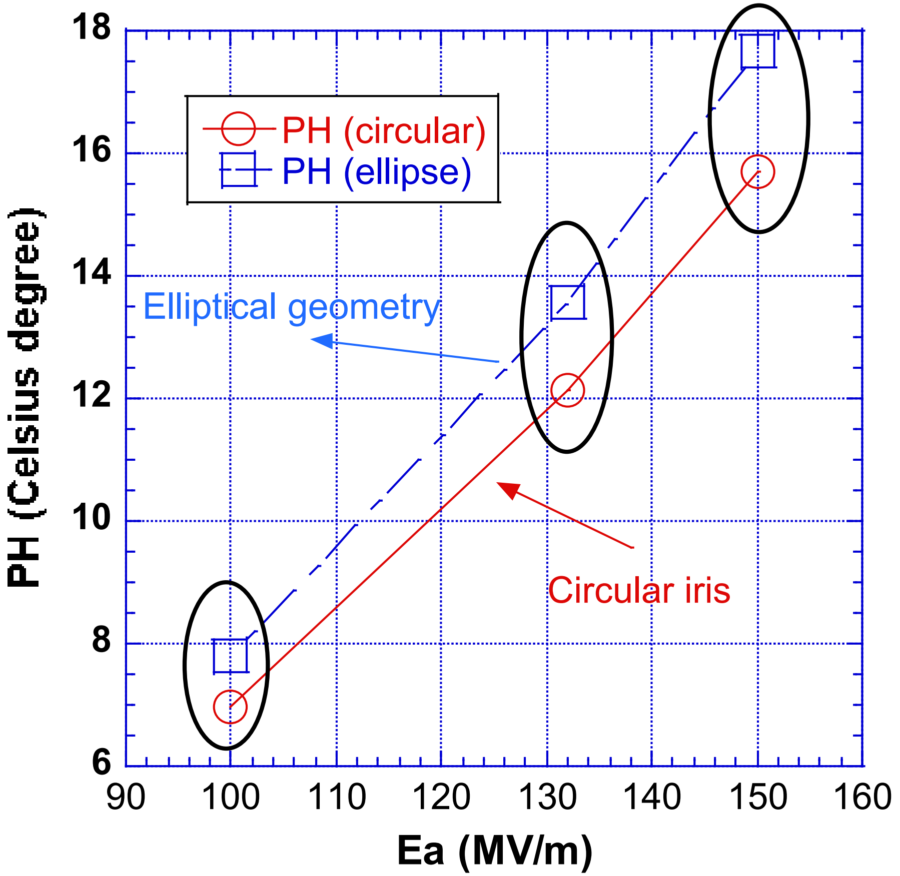
b) Modified Poynting Vector (MPV)

As a result, the growth rate of the Modified Poynting Vector (MPV) is faster for the circular iris



@ 132 MV/m the MPV is 3 MW/mm^2 for elliptical iris against of 5 MW/mm^2 than the circular one.

Safety threshold of the MPV is Sc < 6.3 MW/mm^2 @50ns RF flat top (CERN-SLAC)



@ 132 MV/m the PH is about 13.6 Celsius degree for the elliptical iris against of 12 Celsius degree than the circular one.

The safety threshold is estimated to be about 50 Celsius degree (SLAC-CERN). In all cases we are below the safety treshold

Some hints on the input power of the TW Ka-band linearizer

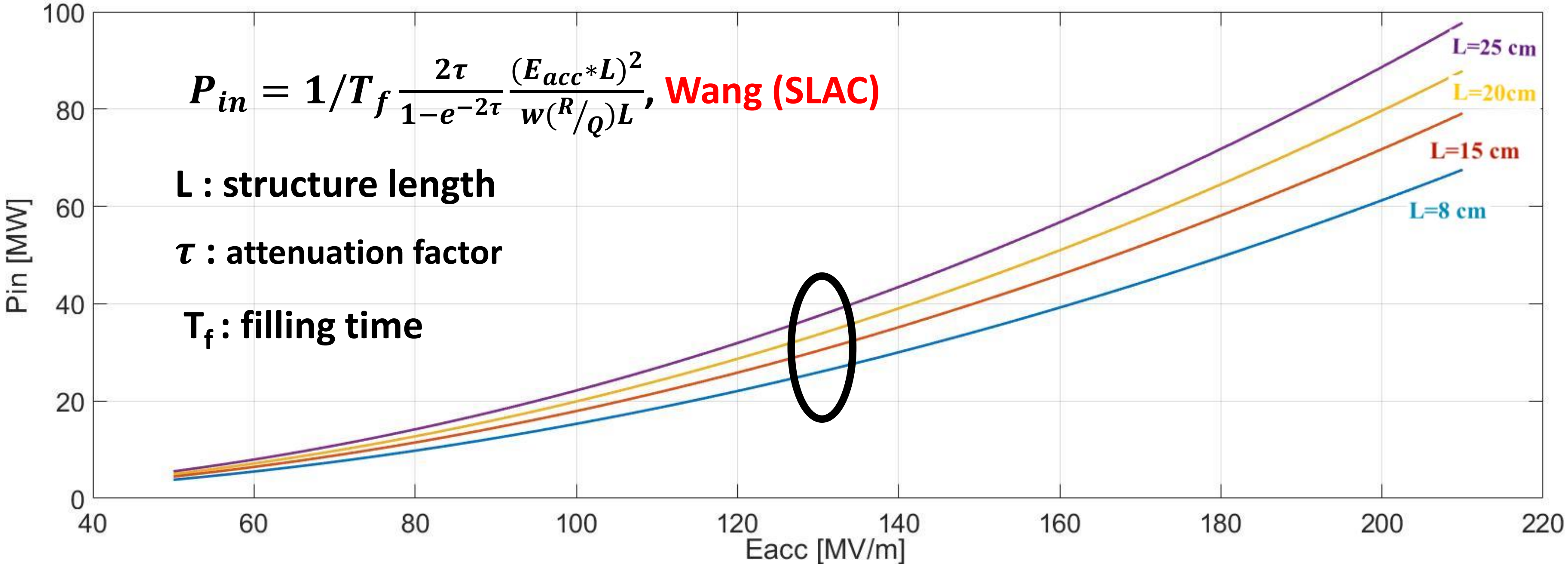
We carried out some preliminary estimations on the RF input power of the TW Ka-band structure (constant impedance) as function of the accelerating gradient for different structure length (by assuming an elliptical iris with a 5/7 semi-axes ratio and group velocity Vg ~ 3.65 %)

$$P_{in} = 1/T_f \frac{2\tau}{1-e^{-2\tau}} \frac{(E_{acc}*L)^2}{w(R/Q)L},$$ **Wang (SLAC)**

L : structure length

τ : attenuation factor

T_f : filling time



With a structure length of 25 cm, at about 132 MV/m, are required about 35 MW for feeding the structure

With a 8 cm structure length about 24 MW are required

Comparison between the SW and TW Normal Conducting structures (Ellipse iris 5/7 semi-axes ratio, iris aperture radius 1 mm)

Main RF Parameter	SW	TW
Frequency (GHz)	35.982	35.982
Effective accelerating Electric field (MV/m)	125	112
Input RF Power (MW)	6.6	6.6
Attenuation (m^{-1})	-	9.3
Shunt Impedance (MΩ/m)	189	189
Quality factor	5628	4065
Group velocity (%)	-	1
Coupling coefficient (%)	1	-
Structure Length (cm)	8	8
Build-up time (ns)	24.9	-
Filling Time (ns)	-	26.6
RF Pulse Length flat top (ns)	50	50
Repetition Rate (Hz)	100	100
Average RF power per meter (KW/m)	0.41	0.23

SW : Standing wave π mode

TW : Traveling wave 2π/3 mode (constant impedance)

INFN Istituto Nazionale di Fisica Nucleare

We also performed a comparison between SW and constant impedance TW structures, by assuming the same RF input power. We have optimized all RF parameters (build-up time, filling time, quality factor, etc.) in order to obtain a balanced comparison.

We observe, the SW solution is similar to the TW one in terms of performance with the same input RF Power of P_{in} = 6.6 MW

In our project, we could go toward a SW option (with short structures) in order to benefit from our decade-long experience with the design, fabrication, tuning and high-power testing of structures with similar geometries

The goal is also to work with a repetition rate frequency of 1 KHz…. But it is a big challenging….!

Cryogenic Temperature at 77 kelvin degree (SLAC-UCLA)

Main RF Parameter	SW_1	SW_2
Effective accelerating Electric field (MV/m)	125	125
Enhancement Factor at 77 K	2.2	
Input RF Power (MW)	3.0	3.6
Average RF power per meter (W/m)	188	228

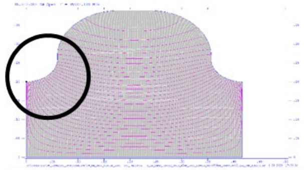
SW_1 : Standing wave π mode with a 1 mm iris aperture radius

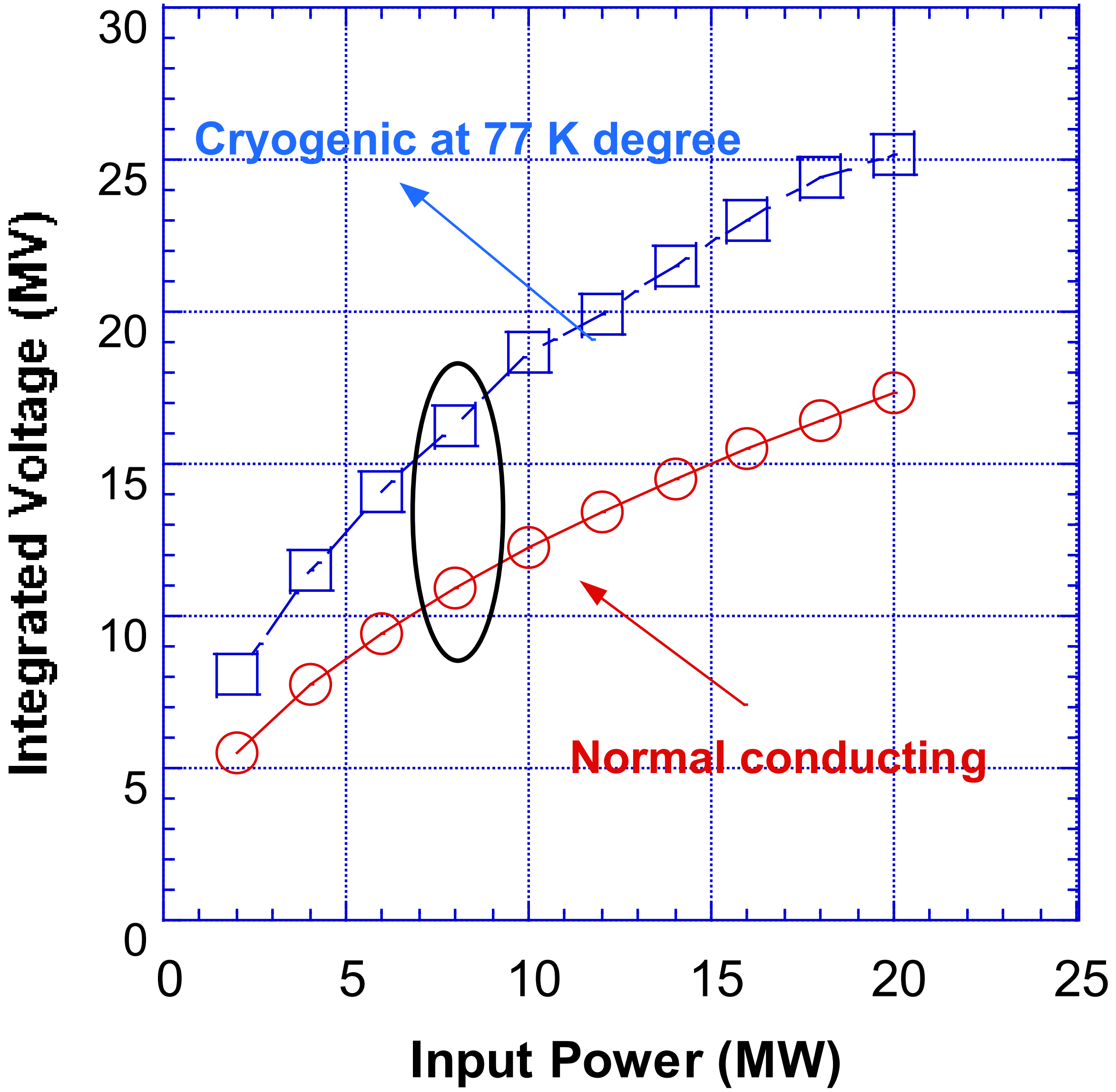
SW_2 : Standing wave π mode with a 1.333 mm iris aperture radius

8 cm structure length

One cryogenic structure provides an integrated voltage of about 17 MV with a 8 MW input power and with a 8 cm structure lenght

Integrated voltage as function of the input Power :
Normal Conducting and Cryogenic structures comparison





Structure lenght = 8 cm

Iris thickness = 0.667 mm

Iris radius = 1 mm with a $r_1/r_2 = 5/7$ semi-axes ratio (elliptical shape).

@ 77 K degree the enhancement factor is estimated to be 2.2 (SLAC - UCLA)

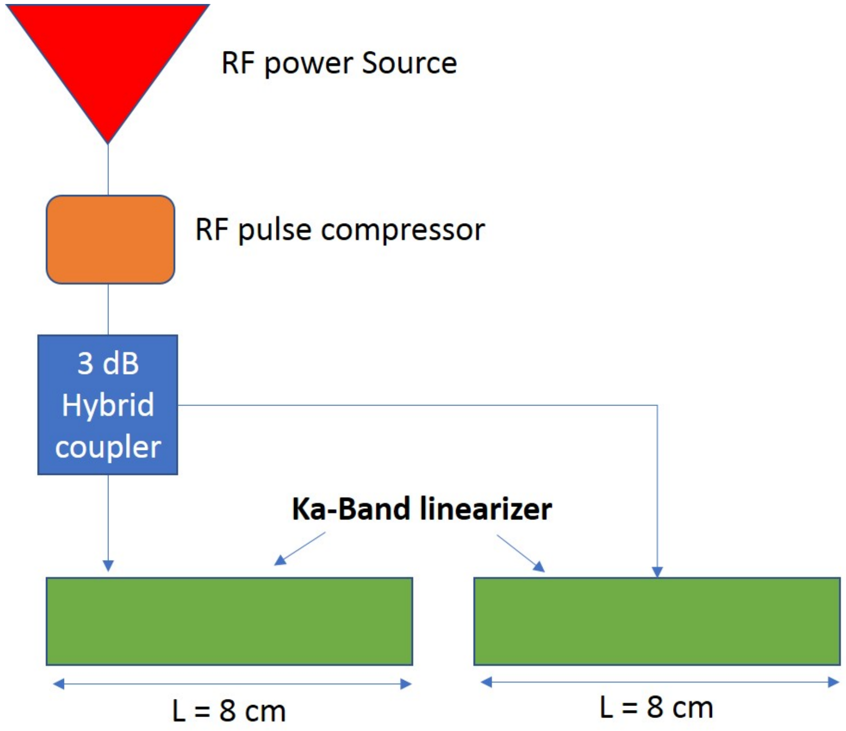
P = 8 MW

1) Normal conducting ~ 11 MV integrated voltage

As a result, two separated structures provide an integrated voltage of ~ 22 MV with an input power of 8 MW

2) Cryogenic operation (SLAC) provides ~ 17 MV integrated voltage with a single structure !!

Schematic network for the SW option



Valery (SLAC) - Igor (CERN)

Power Source

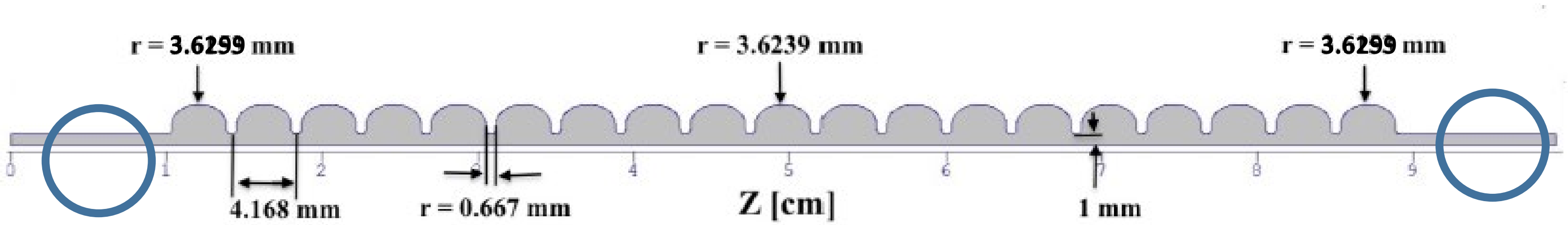
Power source by gyroklystron provides 3 MW (Cern-England) and with the pulse compressor we are able to get 12 MW by assuming a factor compressor of 4 (theoretical estimations). The Magnicon (Yale) gives about 10 MW (theoretical estimations) and with the pulse compressor we are able to get about 40 MW

Studies on the Multi-Beam Klystrons (MBK) are in progress, too (Cern-England). Theoretical estimations provide a 2.5 MW RF output.

Investigations and optmizations on the 36 GHz klystron design at INFN-LNF/ University Tor Vergata are in progress , too. So far, we have got a 42% efficiency with a 20 MW RF output by using the Igor's software. A cross-check of this estimation is in progress, too.

Field flatness compensation of the Ka Band strutcure

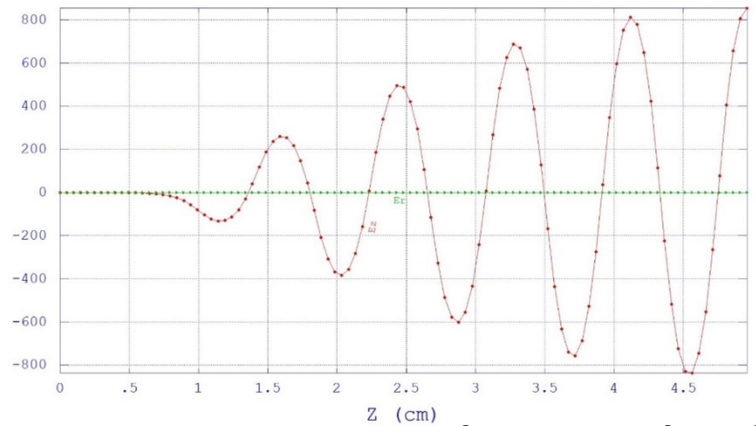
We investigated a multi cells structure made of 19 identical cavities



The perturbation introduced by the beam pipe affects the axial electric field distribution of the π mode

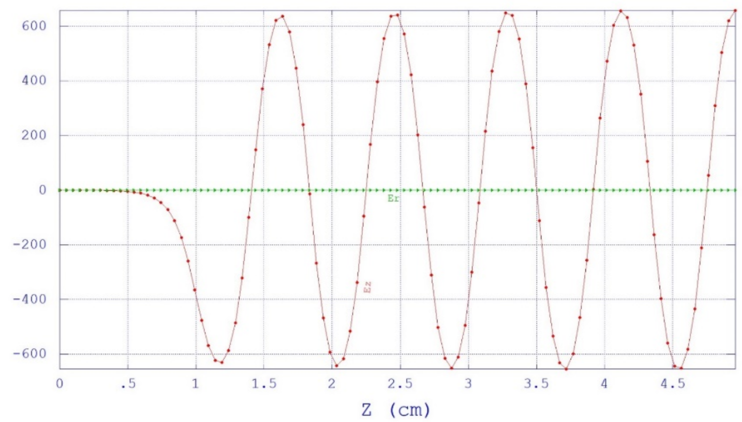
The field distribution profile of the accelerating π mode of the finite multi cells standing wave structure with beam tubes obtained by keeping the same cavities radius is shown

In order to get the field compensation on the longitudinal axis, the end-cells have to be engineered with a lower different radius for obtaining a π mode field flatness on axis



For symmetry reasons we have simulated only one beam tube with the first structure cavities connected to it.

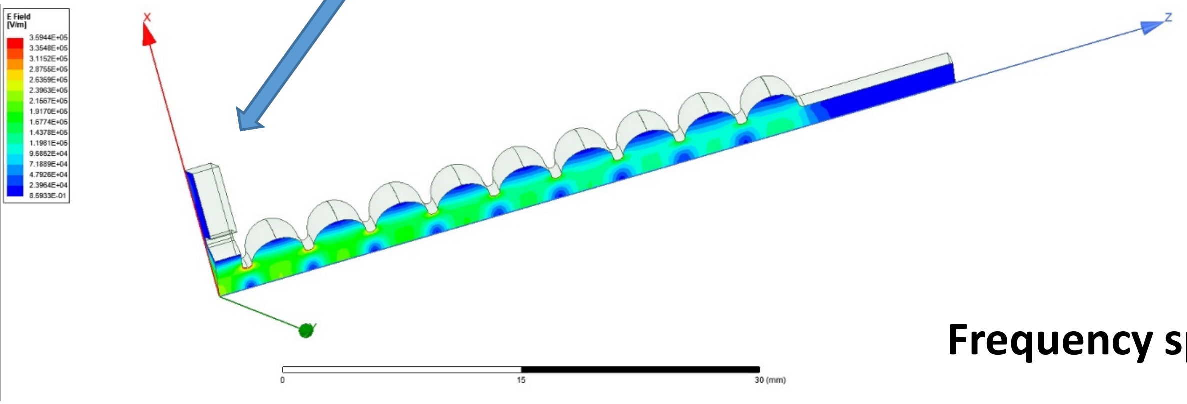
By the inspection of the figure, the field flatness is clearly not achieved as it is expected to be



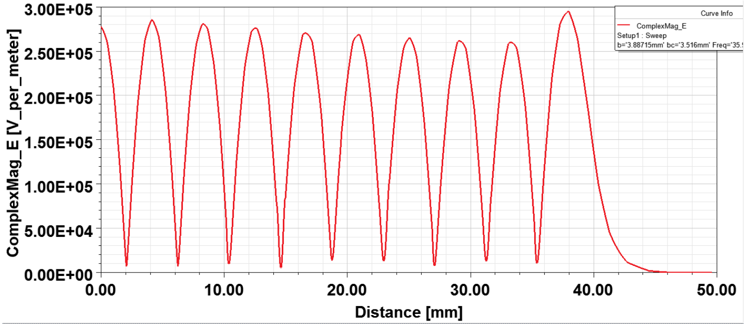
The field flatness is clearly achieved

Investigated geometry with the coupler (one quarter of the whole structure of 19 cells)

Mode launcher has 4 symmetric ports for feeding the structure. This device allows to cancel the dipolar and quadrupolar components due to the coupling holes.

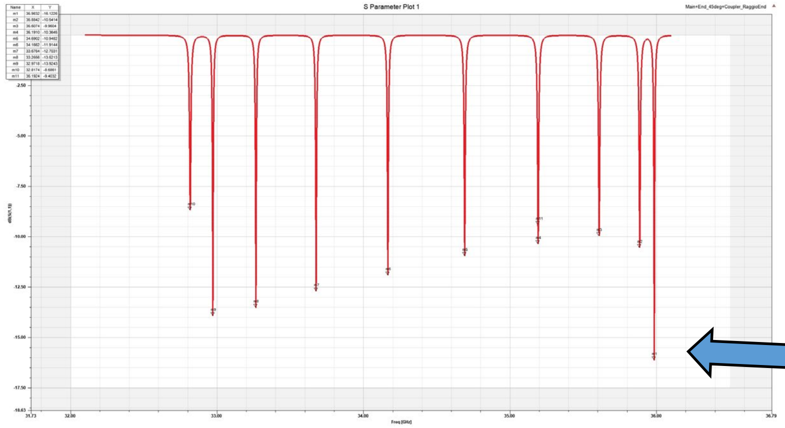


Electric field distribution on axis with the coupler of the working π mode



The field flatness is about within two per cent

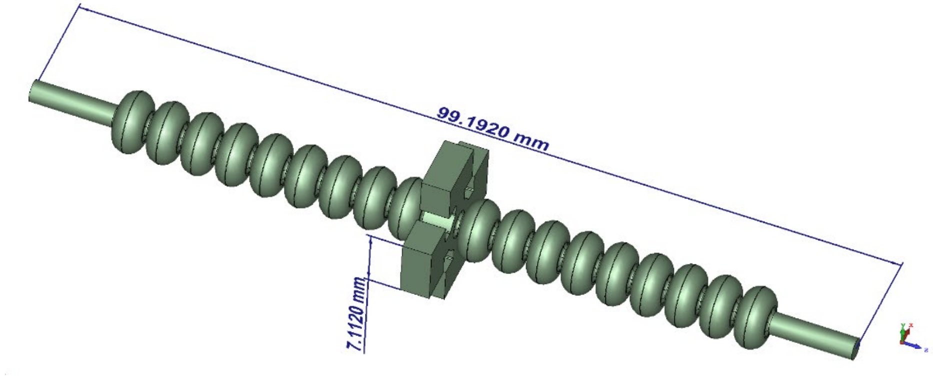
Frequency spectrum

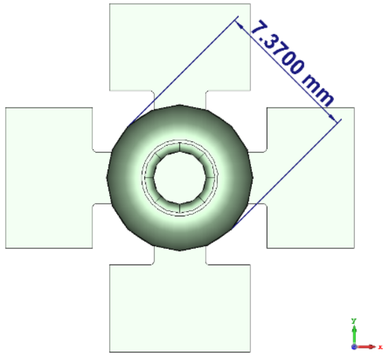


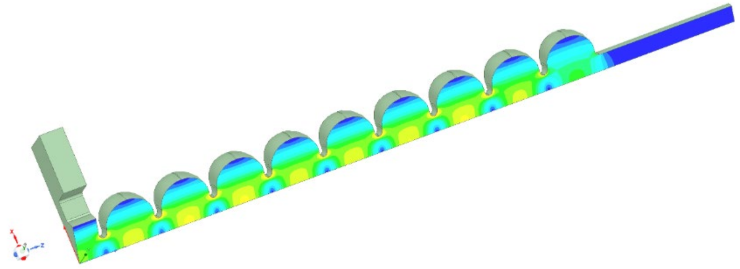
We observe, we can excite only ten over nineteen possible modes by the central coupler because we impose a non-zero field in the central cell.

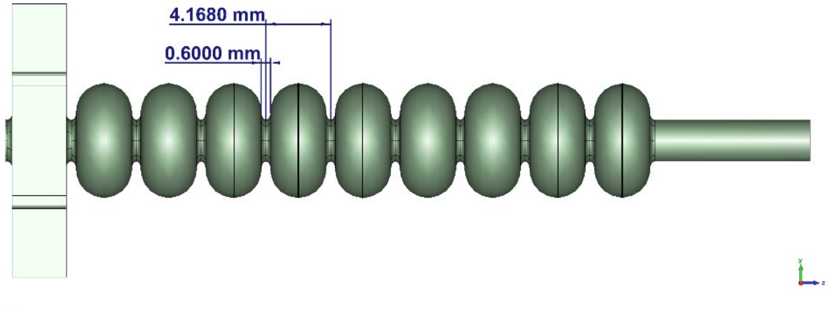
Dimensions of the Ka-Band structure

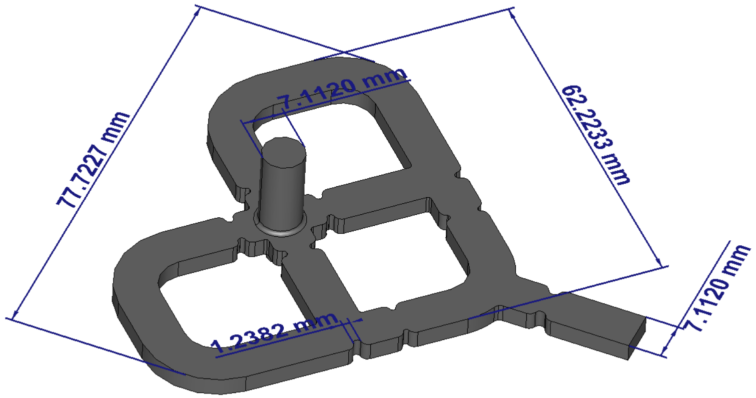
INFN
Istituto Nazionale di Fisica Nucleare











We are scheduling an intense technological activtiy in order to fabricate 'hard Ka- Band' structures and the 'W-Band' ones, in the framework of the collaboration among [INFN/LNF – LNS (INFN-Catania), SLAC, Comeb S. r. L.].

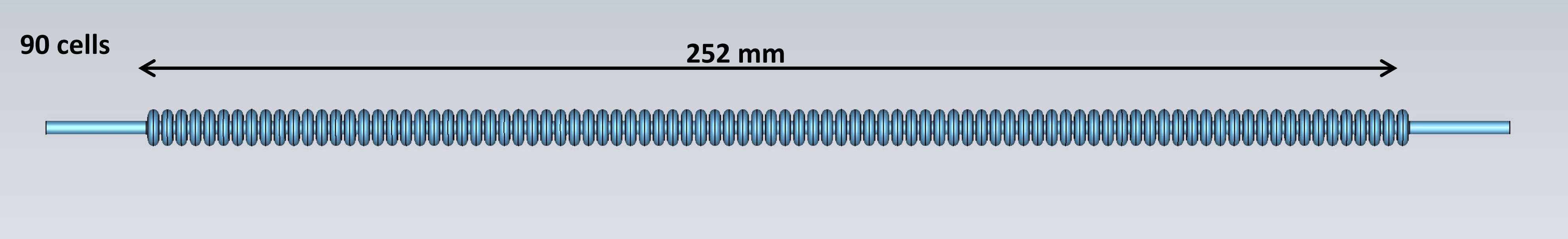
Our interest is to study the same approach already done with the fabricated 'hard X-Band devices' (two halves structures and so on by using the TIG method), currently under high power test at SLAC , in the framework of the collaboration among SLAC (V. Dolgashev, E. Nanni, S. Tantawi) – INFN/LNF - Comeb S. r. L.)

[L. Faillace already discussed this topic in detail at this HG2021]

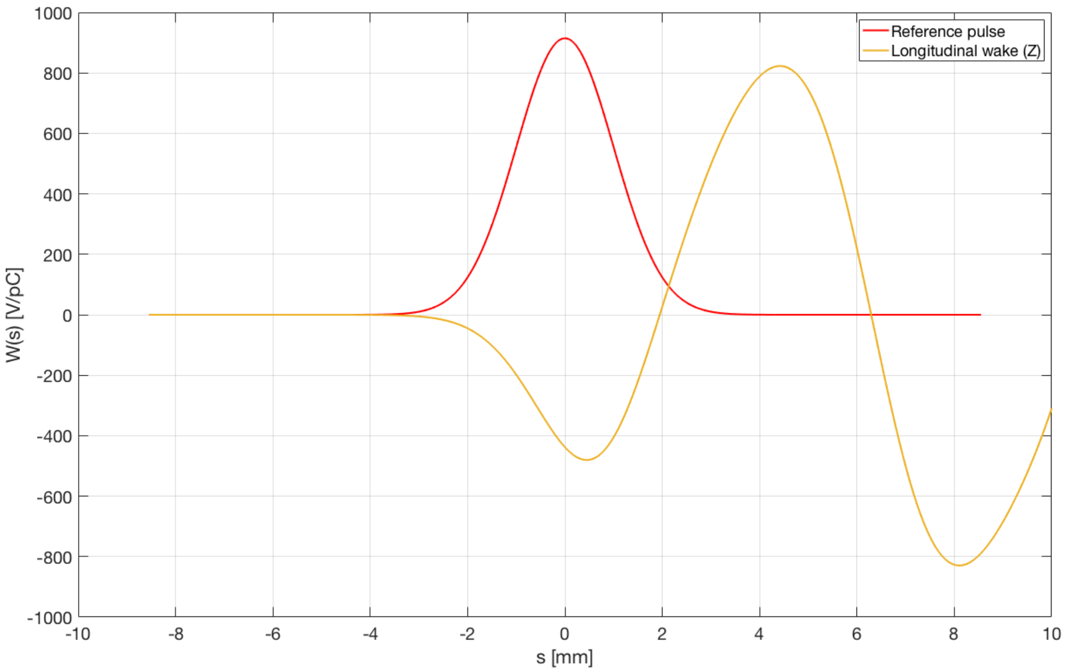
In principle, a Ka-band structure should be interesting for medical and industrial applications, too

(L. Faillace already discussed this topic in detail at La Biodola EAAC19 workshop and IPAC 2020)

Wake fields studies on the 35.982 GHz structure (CST and ABCI softwares)

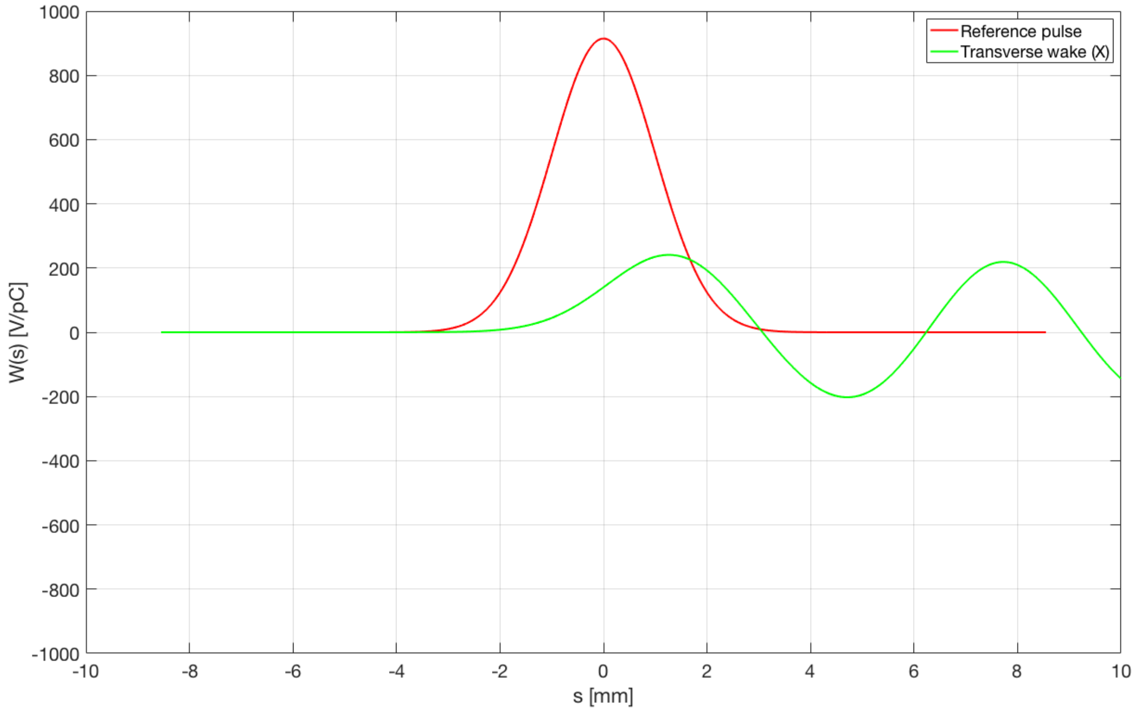


Longitudinal wakefields as function of the bunch head for a 1 mm bunch length (whole structure estimation)



$K_L \sim 320$ V/pC

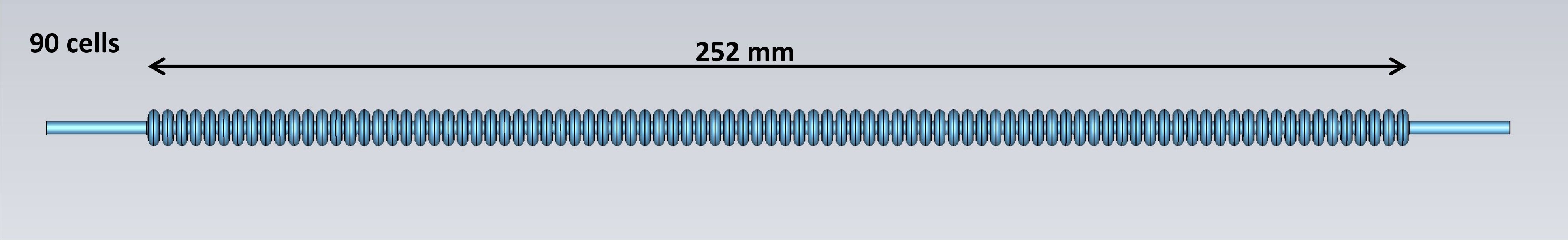
Transverse wakefields as function of the bunch head for a 1 mm bunch length (whole structure estimation)



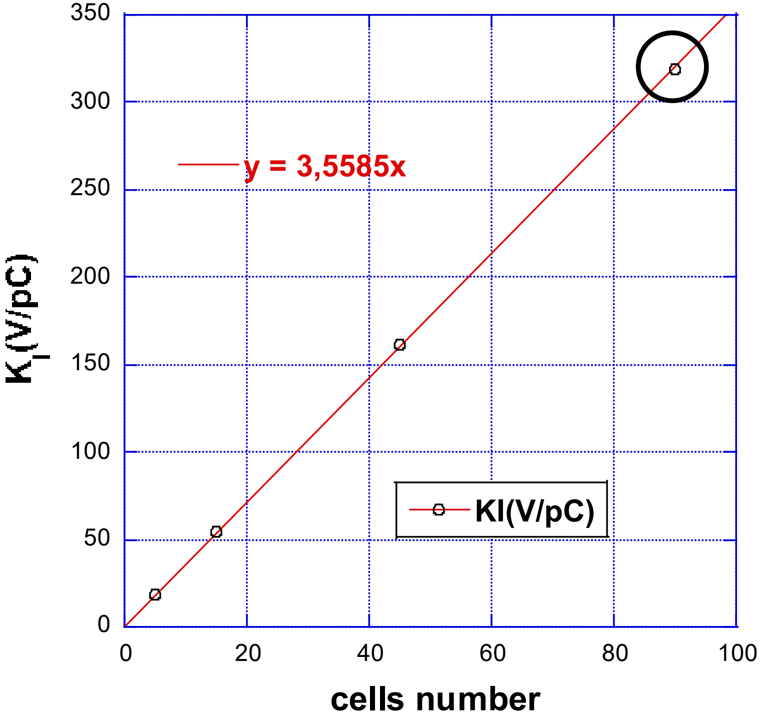
$K_T \sim 2.7\ 10^5$ V/pC/m

Wake fields studies on the 35.982 GHz structure (CST and ABCI softwares) by assuming a 1 mm bunch length

Istituto Nazionale di Fisica Nucleare



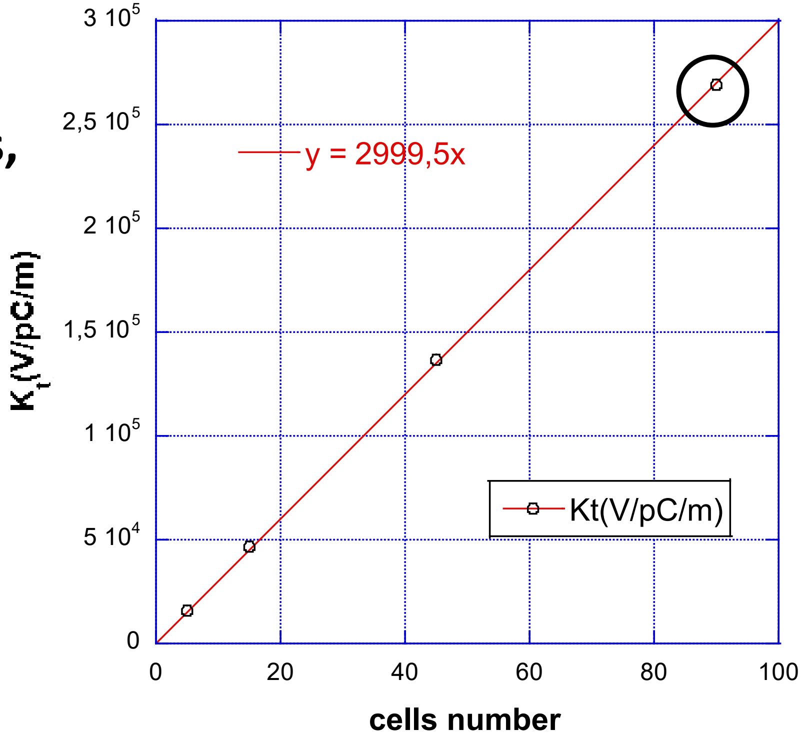
Longitudunal loss parameter as function of the cells number of the structure at F = 35.982 GHz



With N = 90 cells,
$K_l \cong$ 320 V/pC,
Q = 75 pC

$E_{losses} \cong$ 24 KeV (negligible)

Transverse loss parameter as function of the cells number of the structure at F = 35.982 GHz



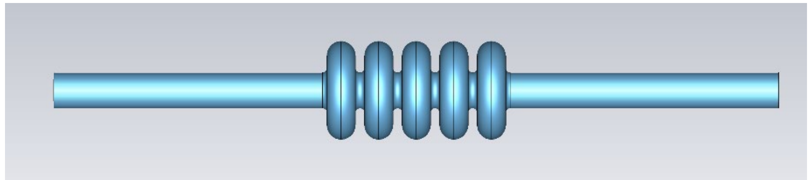
With N = 90 cells,
$K_t \cong 2.7\ 10^5$ V/pC/m,
Q = 75 pC
$y(0) = 2\ 10^{-6}$ m
E = 300 MeV

$$\theta = \frac{y(0)}{E/e} Q\, K_t \cong 0.1\ \mu\text{rad}$$

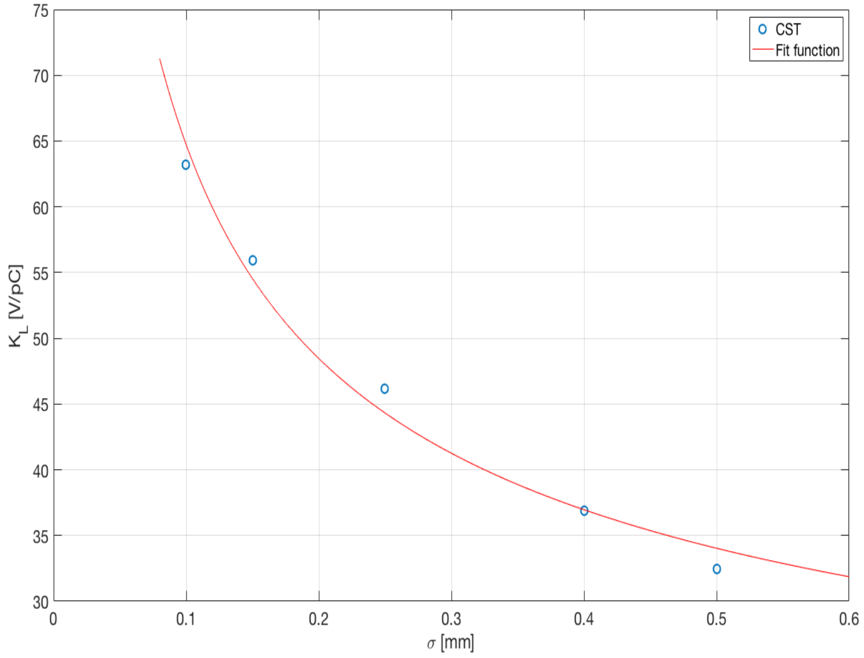
(negligible)

Longitudinal and transverse loss parameter as function of the bunch length σ

5 cells simulations



Longitudinal

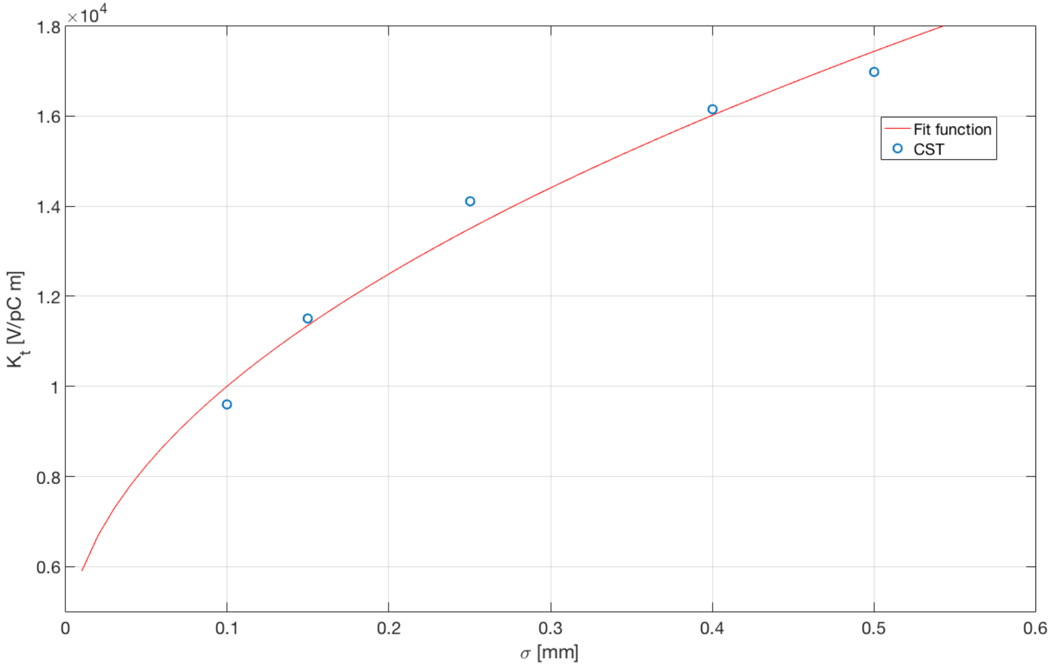


Scaling law **(K. Bane-SLAC)**

$$K_l \propto \omega^2 \frac{1}{\sqrt{\sigma}} \frac{1}{a^2}$$

With σ = 0.1 mm ; N = 19 cells
Q= 75 pC ;
E_{losses} ~ 90 KeV (negligible)

Transverse



Scaling law **(K. Bane-SLAC)**

$$K_t \propto \omega^2 \sqrt{\sigma} \frac{1}{a^4}$$

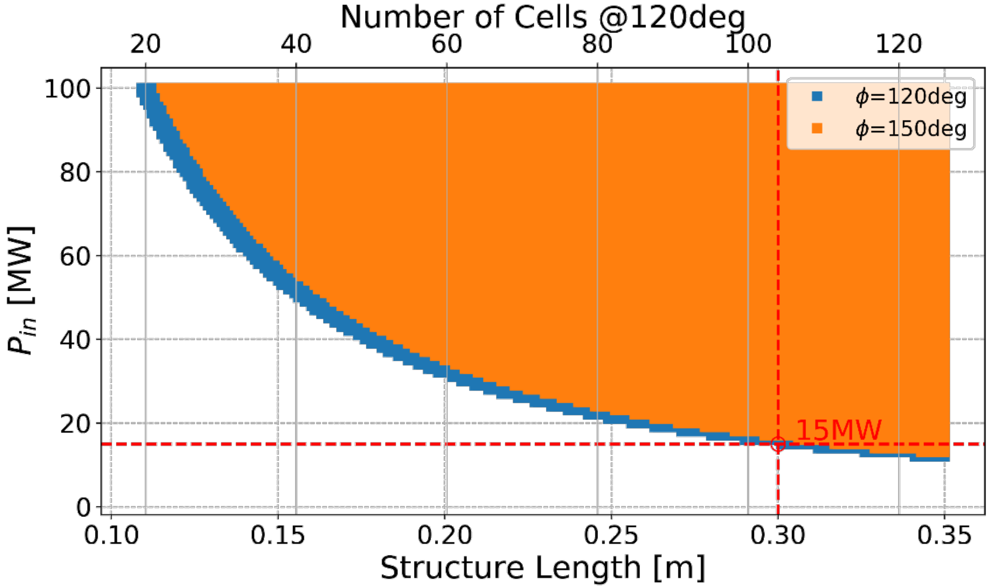
With σ = 0.1 mm ; N = 19 cells
Q= 75 pC , θ = 0.08 μrad
(negligible)

Funded by the
European Union

Compact

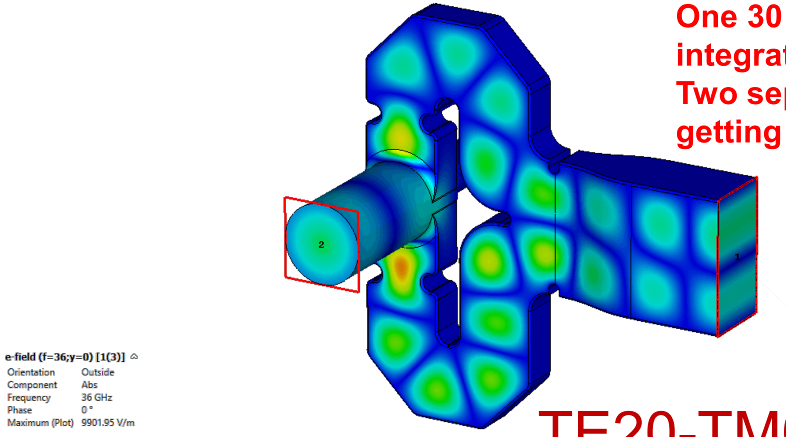
Ka-band Travelling Wave Structure ($E_{acc} = 42.5$ MV/m)

Alejandro.Castilla.Loeza@cern.ch

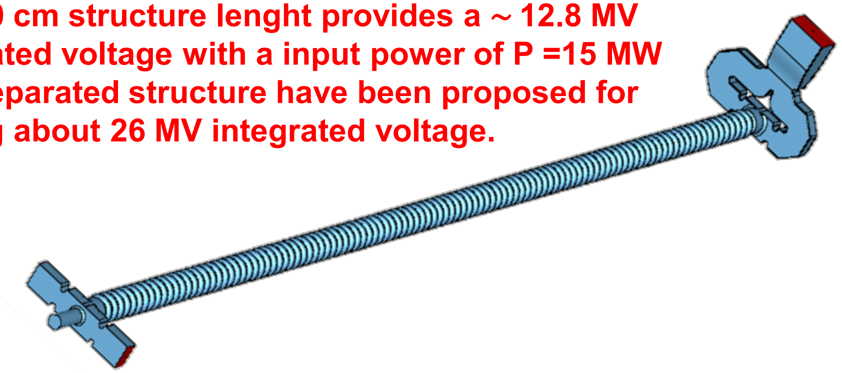


Parameter	$\phi = 2\pi/3$,	$5\pi/6$,	$6\pi/7$	Units
Frequency f		36		GHz
Q factor	4392	5251	5365	- -
Shunt impedance r_L	106	109	109	MΩ / m
Group velocity ν_g	0.119	0.138	0.145	c
Attenuation α_0	0.7	0.5	0.5	m^{-1}
Peak surface field E_p^*	2.57	2.99	3.05	MV/m
Peak surface field B_p^*	4.45	4.76	4.83	mT
Cavity radius R	3.96	3.86	3.85	mm
Iris radius R_i		2.00		mm
Cell length L_c	2.78	3.47	3.57	mm
Iris thickness L_i		0.60		mm
Cavity blending radius r_b		1.00		mm

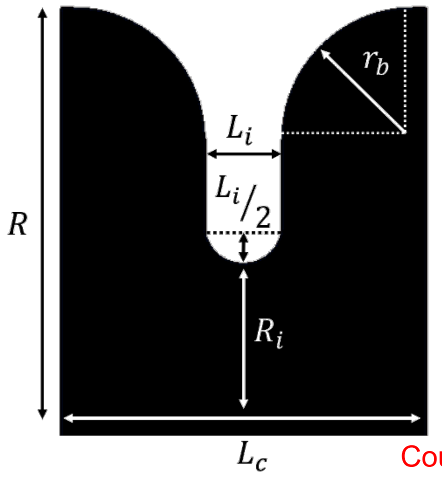
*normalized to $E_{acc} = 1$MV/m



One 30 cm structure lenght provides a ~ 12.8 MV integrated voltage with a input power of P =15 MW
Two separated structure have been proposed for getting about 26 MV integrated voltage.



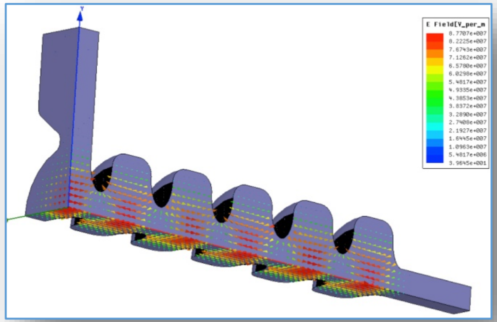
TE20-TM01 Input Coupler

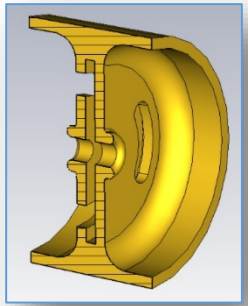


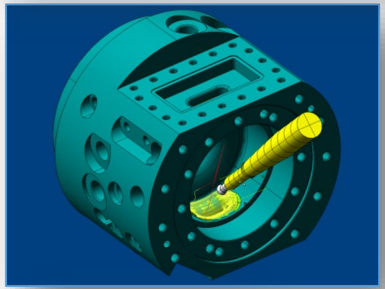
Courtesy of Alejandro Casilla

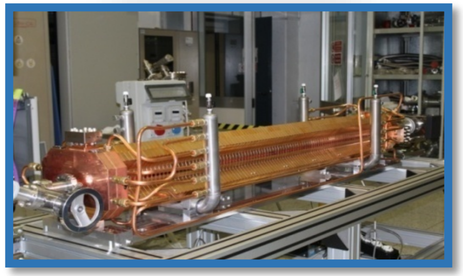
ISO 9001
BUREAU VERITAS
Certification

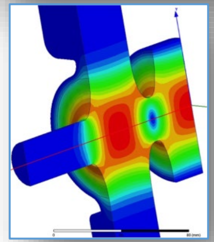
Company Profile: Capabilities

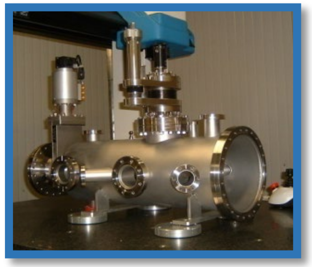












- Our workshop is equipped with high-precision state-of-the-art equipment: CNC lathes and milling machines.
- In-house brazing: vacuum furnaces.
- 2D and 3D mechanical design.
- CNC programming softwares for our high-precision devices: Inventor and Hypermill.
- 2D and 3D RF design softwares: SUPERFISH, ANSYS HFSS and CST MICROWAVE STUDIO are employed for high frequency electromagnetic (RF) simulations.
- 2D and 3D Beam dynamics simulators: PARMELA and CST are used for particle beam dynamics simulations.

http://www.comeb.it　　*Via dei Ranuncoli 2 - 00134 Rome - Italy*

Conclusions

The Ka band linearizer has to provide at least an integrated voltage of 15 MeV according to the A. Latina (Cern) estimations

Gyroklystron gives about P = 3 MW (Cern – England) and by using the pulse compressor system we are able to get P = 12 MW
The Magnicon (Yale) provides a P ~ 10 MW (theoretical) and with the pulse compressor it is possible to get a P = 40 MW

Investigations and optmizations on the 36 GHz klystron design are in progress at INFN-LNF/University of Tor Vergata (Roma). So far, we have achieved a 42% efficiency with a 20 MW RF output by using the Igor's software (Cern). A cross-check of this estimation is in progress, too.

Assume a structure length of 8 cm, 1 mm iris aperture radius, an iris elliptical shape (5/7 semiaxes ratio) and an input power of 8 MW

Normal conducting operation : two separated structures provide an integrated voltage of about 22 MV

Cryogenic operation at 77 Kelvin degree: only one structure provides an integrated voltage of about 17 MV (SLAC) !

Cryogenic operation at 1 KHz remains to be studied. For average losses of 2 KW, 45 litres of liquid nitrogen is required per hour (G. Burt estimations)

In all cases, the Modified Poynting vector and Pulse Heating are well below the safety treshold. The longitudinal and transvere wakefields effects on the beam dynamic are negligible, too.

The cold Ka-band structure can be used for the UC-XFEL to be constructed at UCLA. A paper has been submitted to review for the publication

Thank you very much for your attention !