Kickers for Injection and Extraction in Damping, Combiner and Storage Rings

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An activity concerning the study, the design and the realization of devices for beam injection and extraction has been recently carried out at LNF.
The devices developed are different for typology and application:

- **CTF3 collaboration**

  Realization of RF deflectors for injection and extraction in:
  - **Delay loop**
  - **Combiner ring**

- **ILC collaboration**

  Study and R&D of injection and extraction kickers
  for the Damping Ring

- **DAFNE**

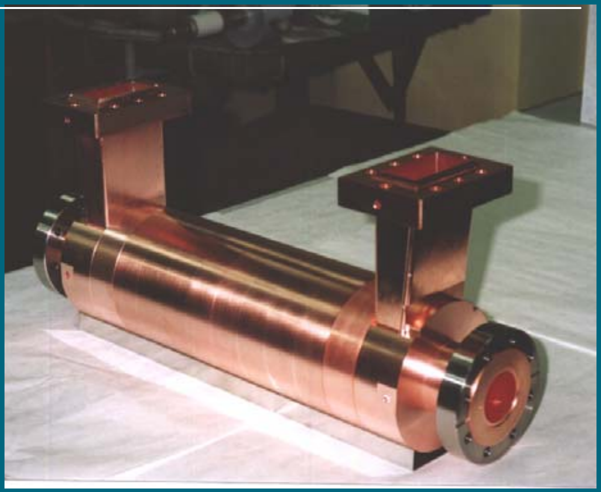
  Realization of the new injection kickers for the Storage Rings

CLIC TEST FACILITY 3

DELAY LOOP

- RF DEFLECTOR
- STANDING WAVE STRUCTURE
  - high efficency (deflection vs. rf power) per unit length.
  - filling time proportional to the quality factor: generally slow.
  - deflecting fields scales as the square root of the number of cells.
  - in pulsed regime a circulator is generally needed.
- 2 CAVITIES COUPLED TO THE KLYSTRON THROUGH A HYBRID JUNCTION.

COMBINER RING



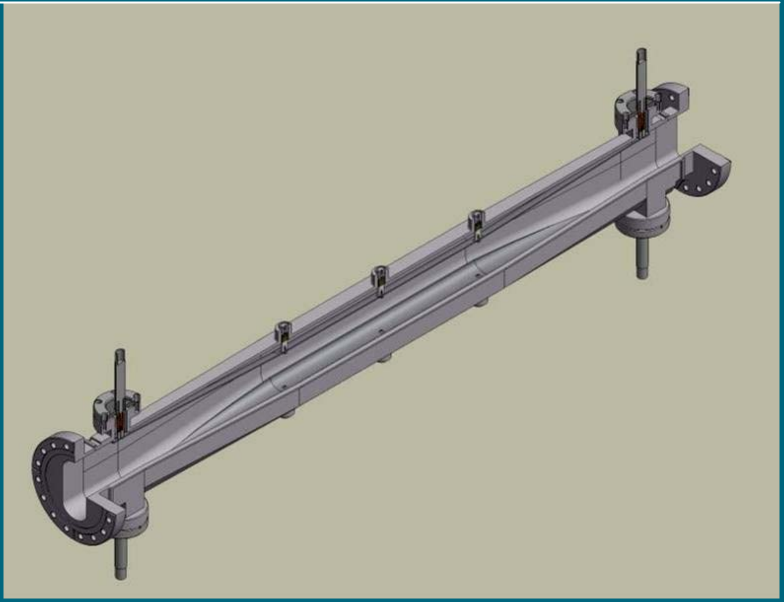
- RF DEFLECTOR
- TRAVELING WAVE STRUCTURE
  - low efficency (deflection vs. rf power) per unit length.
  - filling time proportional to the group velocity and the structure length: generally fast.
  - deflecting fields scales as number of cells.
  - circulator not necessary.

DAMPING RING OF THE INTERNATIONAL LINEAR COLLIDER

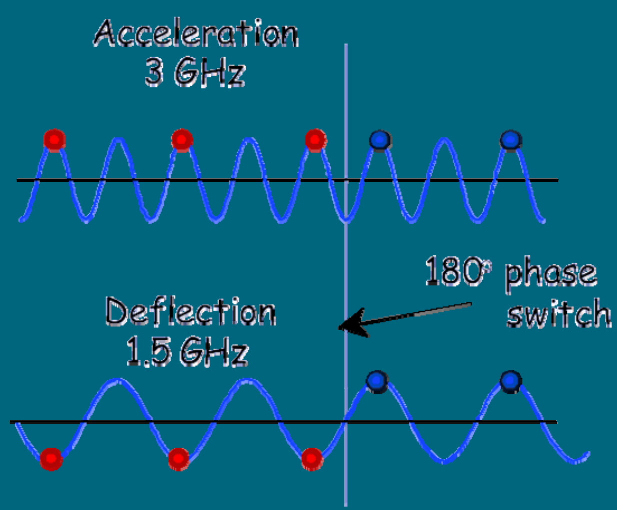
1. RF TRAVELING WAVE DEFLECTOR IN MULTIFREQUENCY MODE
2. FAST PULSE STRIPLINE ELECTRODE KICKER

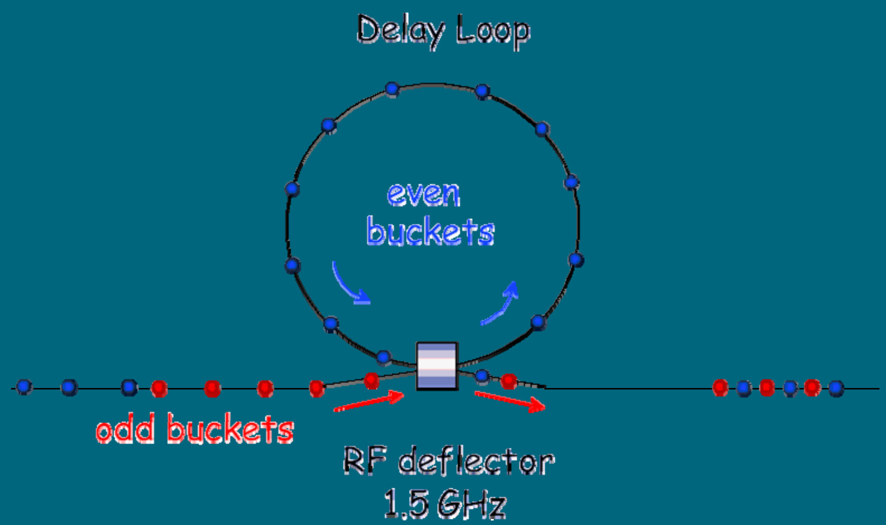
DAFNE STORAGE RINGS

FAST PULSE STRIPLINE
ELECTRODE KICKER



The CTF3 Delay Loop





Even and odd trains are deflected by kicks of the same amplitude but opposite sign. Only even trains are injected into the ring.

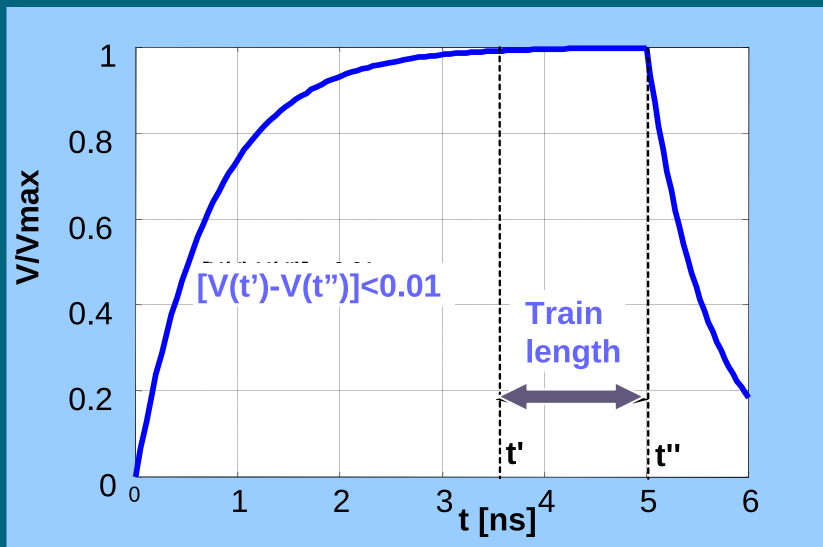
DESIGN PARAMETER

Frequency **[GHz]**	**1.499275**
angle of deflection **[mrad]**	**15**
Max. Beam energy **[MeV]**	**300**
Klystron output Power **[MW]**	**20**
Pulse length **[μs]**	**5**

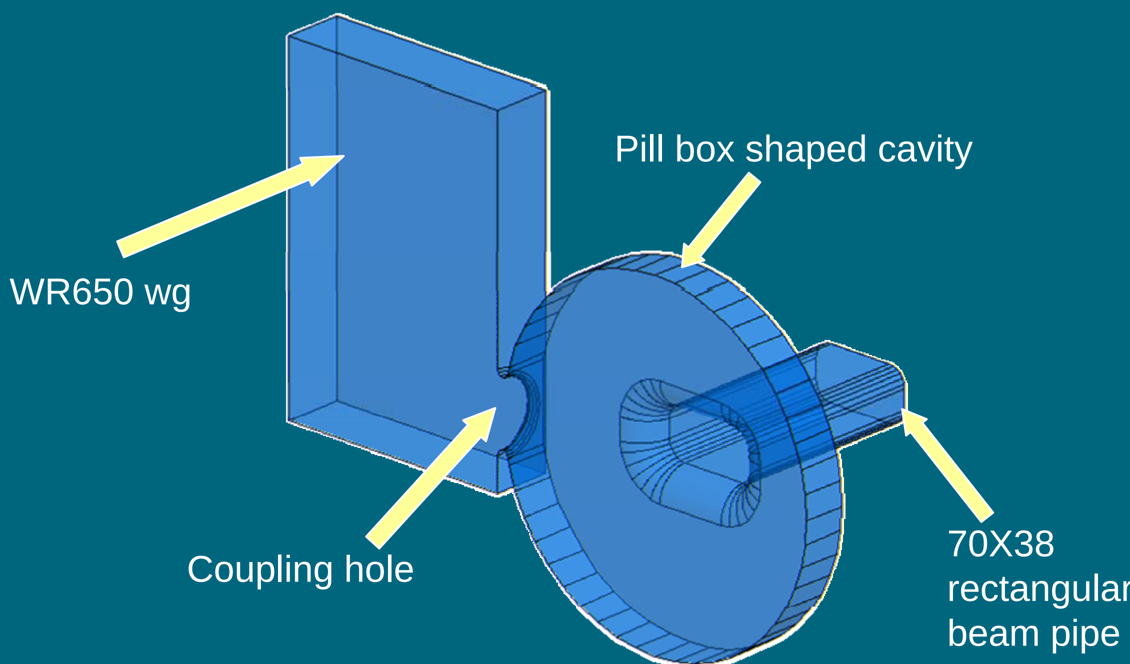
The required deflection is too large to get with a traveling wave structure of reasonable dimensions.
It is necessary to resort to a standing wave resonator.

Delay Loop Deflector

CAVITY VOLTAGE vs. TIME



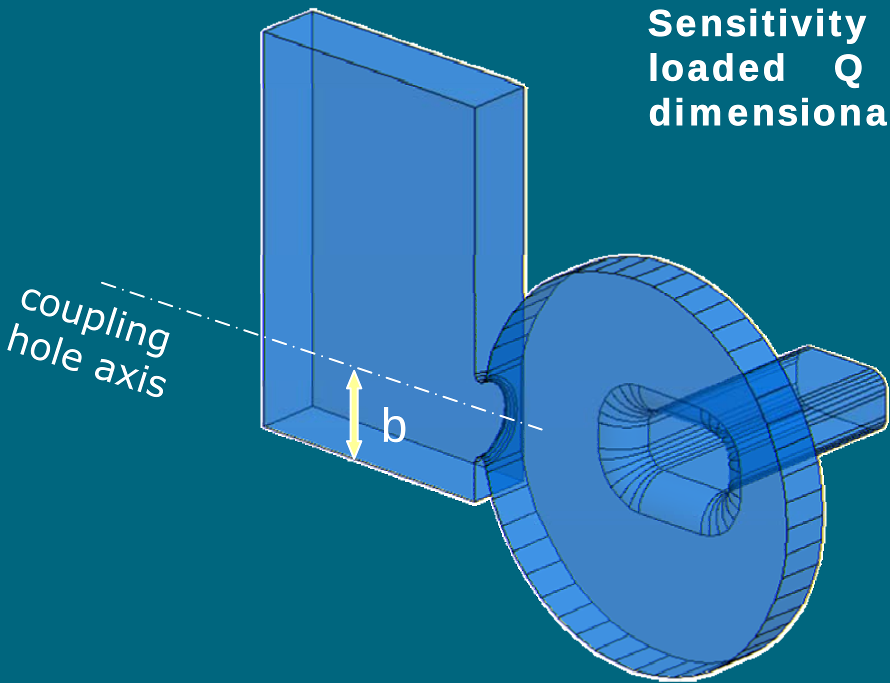
The major drawback of this choice is the slow filling time of a resonant SW cavity. To keep acceptable the difference (less than 1%) of deflection angle between the head and the tail of the train the cavity Q must be reduced, but not beyond a certain threshold, when the shunt impedance becomes too low.
A good compromise is obtained with a loaded Q value between 3000 and 3500.

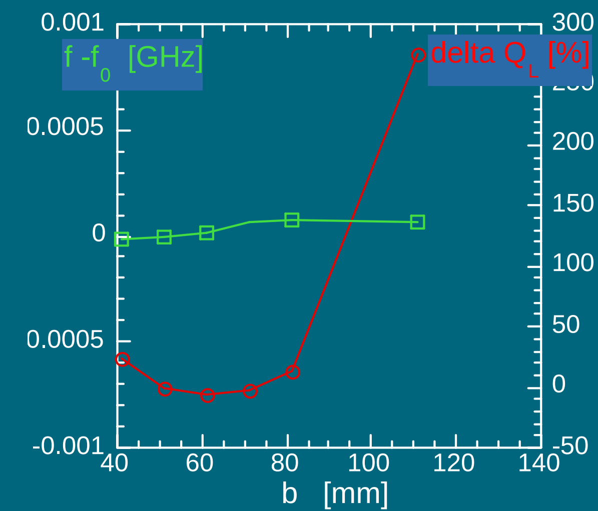


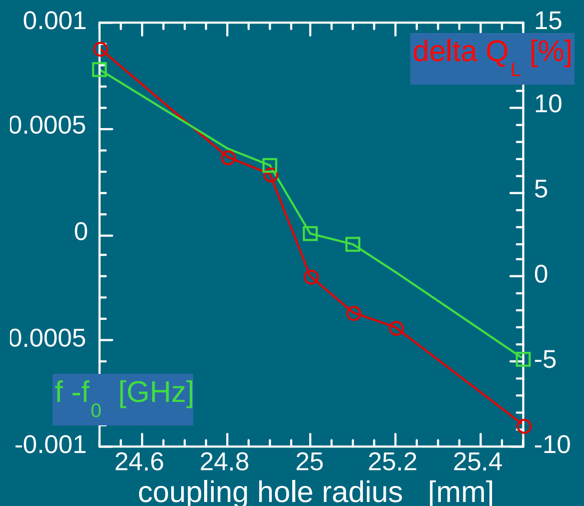
The cavity deflector has been designed starting from a simple pill box shape.
The cavity is externally coupled to a rectangular waveguide (WR650, the same standard of the klystron output) through a hole.
The hole dimensions set the input coupling coefficient β and they have been chosen to obtain the wanted cavity loaded Q.

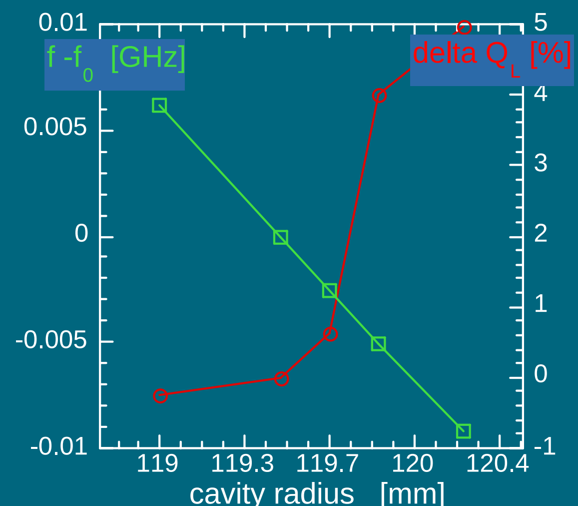
Delay Loop Deflector

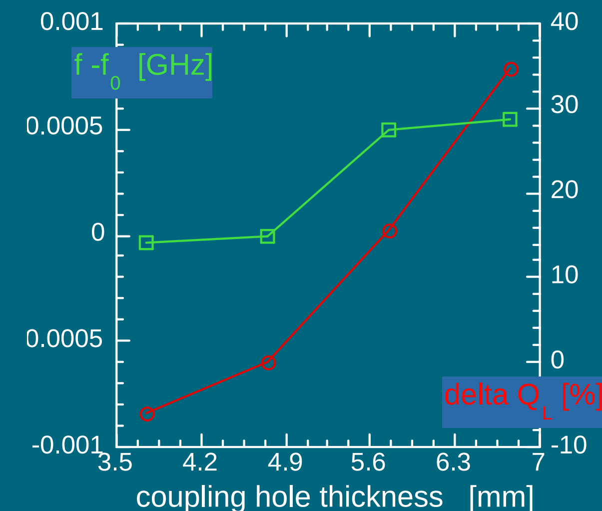
Sensitivity of the resonant frequency and of the loaded Q to small variations of the main dimensional parameters has been evaluated.



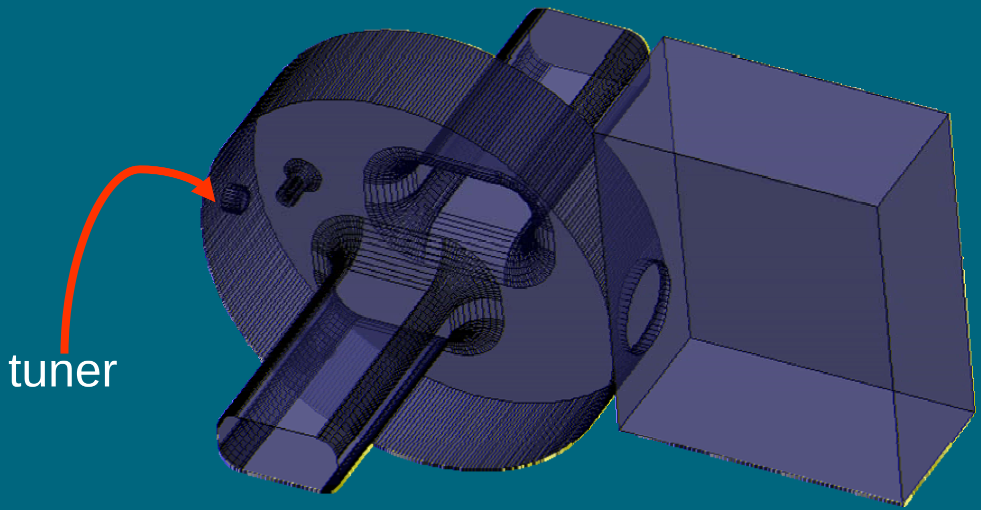


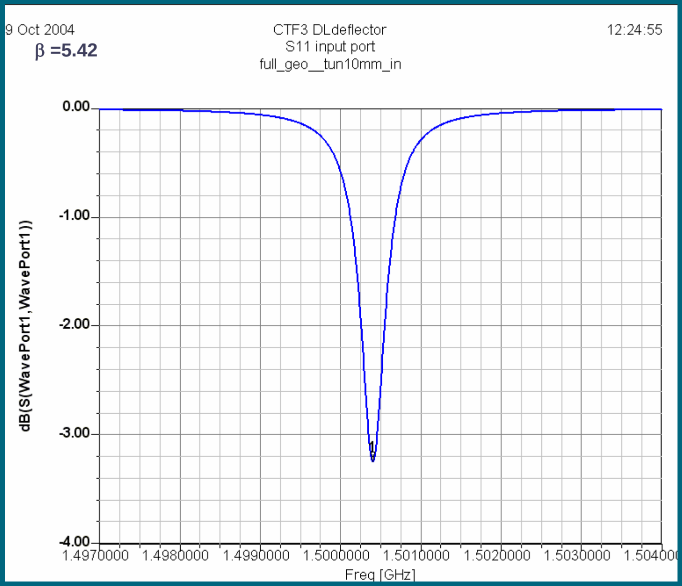


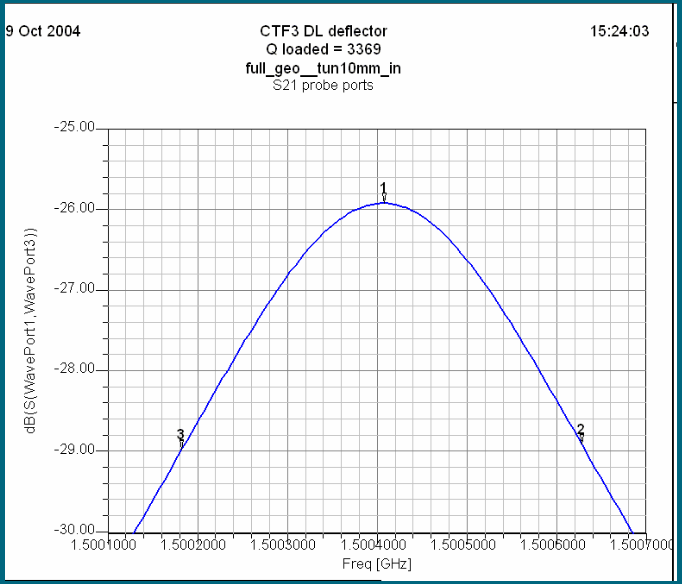




Delay Loop Deflector







Tuning sensitivity and range of tuning

$$\Phi = 30mm \Rightarrow \quad \frac{\partial f}{\partial ID} = 562.9 \; [kHz/mm]$$

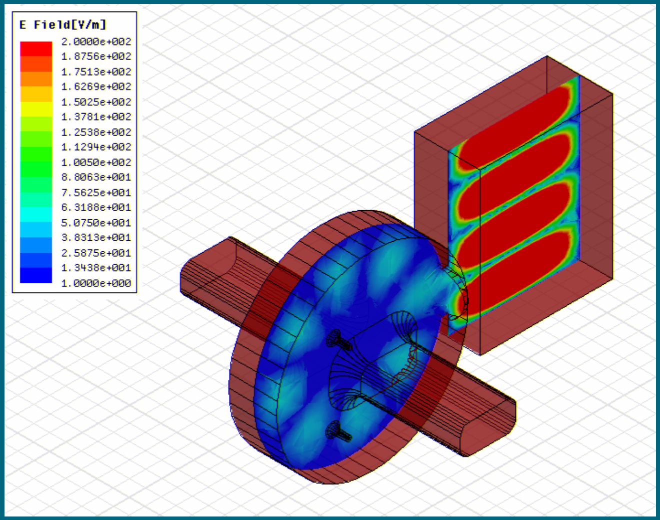
$$\Phi = 20mm \Rightarrow \quad \frac{\partial f}{\partial ID} = 257.6 \; [kHz/mm]$$

$$\Phi = 15mm \Rightarrow \frac{\partial f}{\partial ID} = 152.4 \; [kHz/mm]$$

$$ID\max = 19mm \;\Rightarrow\; \Delta f = 2.9MHz$$

$ID = Insertion \;\; Depth \qquad \Phi = tuner \;\; diameter$

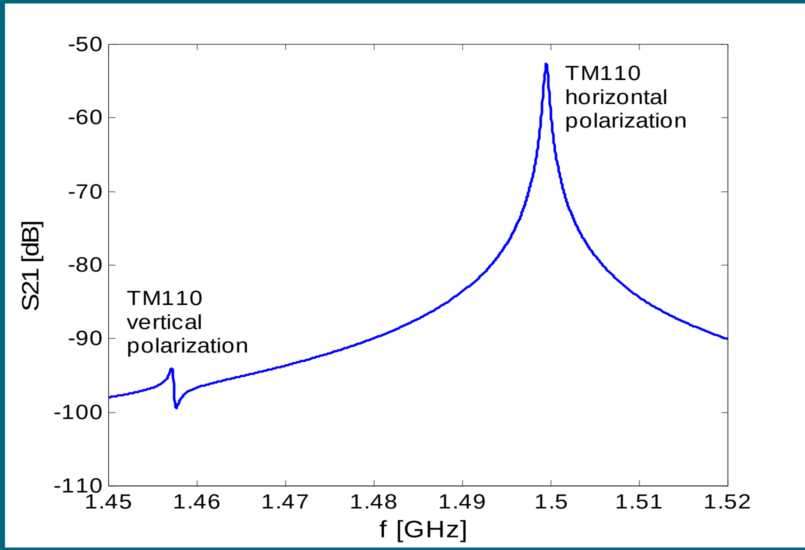
Delay Loop Deflector



Example of HOM (octupole–2.98GHz).
Electric field (magnitude) representation.

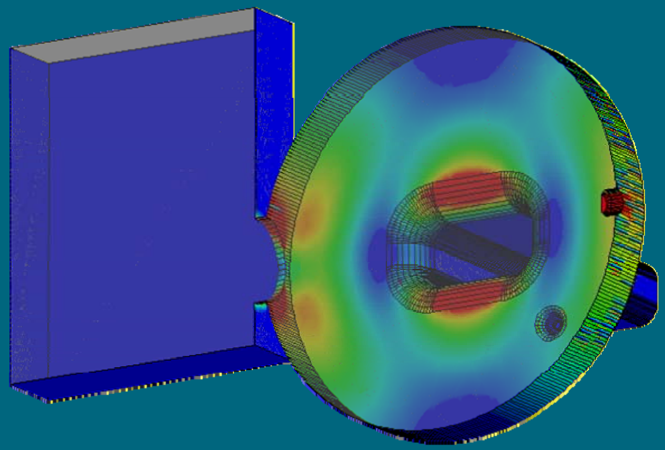
CAVITY PARASITIC MODES

Resonant frequencies of the most dangerous parasitic modes for the beam dynamics (monopoles and dipoles) are far enough from the lines of the beam power spectrum.



The vertical polarization of the TM110 results more than 40 MHz apart from the horizontal one.

THERMAL ANALYSIS

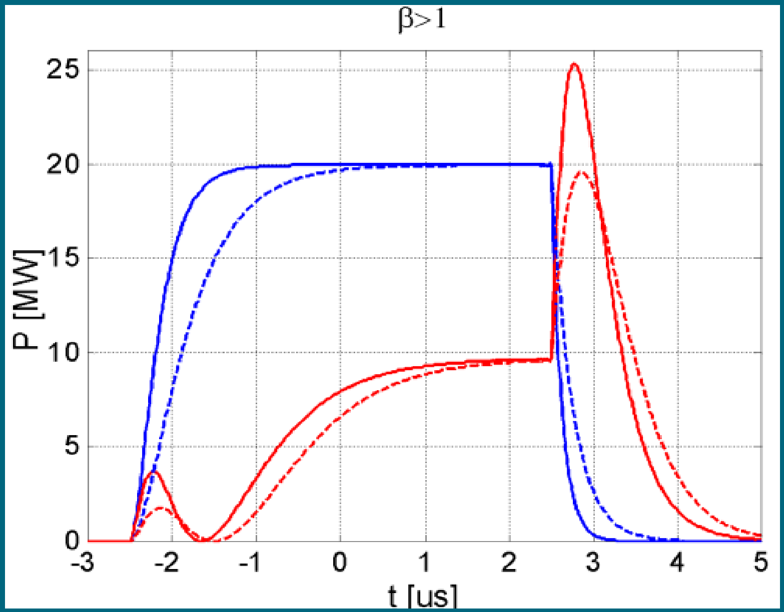


Distribution of losses on the cavity walls.
Average power dissipated in each cavity is 2.5 kW at full power operation (i.e. 20 MW klystron output peak power).
Each cavity has been provided with 5 coils for cooling.

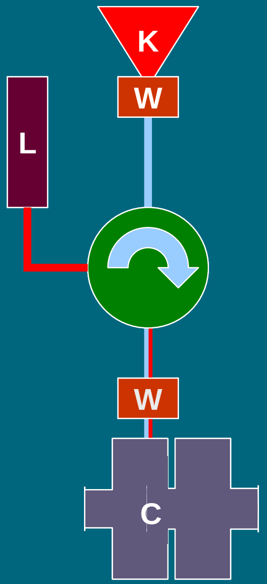
Delay Loop Deflector

TIME DOMAIN CAVITY RESPONSE

The reflected power depends on:
- the cavity input coupling coefficient
- the pulse rise time

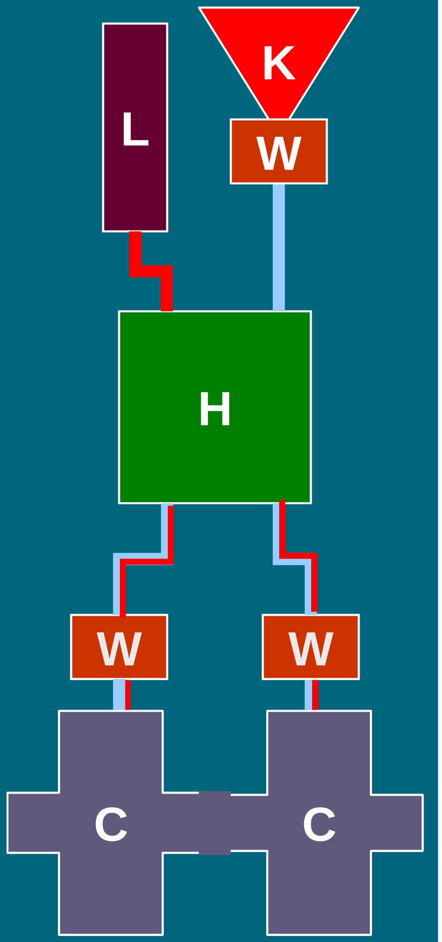


Reflected power for 2 arbitrary slopes of the input pulse
Blue – RF input pulse.
Red – cavity reflected power.



Klystron needs to be isolated from the reflected power.
This can be done by a circulator...
...or by a 90 deg hybrid junction similarly to the sled scheme used in the linac technology.

Power coming from klystron is split in equal parts by the hybrid and feeds two cavities, excited in the TM110 deflecting mode. Power reflected at the cavity inputs add in phase at the fourth port of the hybrid, where it is connected a load. In principle no power reaches the klystron.
With 2 cavities the total shunt impedance is doubled.
Deflecting voltage results increased by a factor √2.



Delay Loop Deflector

WHOLE DEFLECTOR STRUCTURE DESIGN

Basic components:

1)Two identical cavities (the same described above).

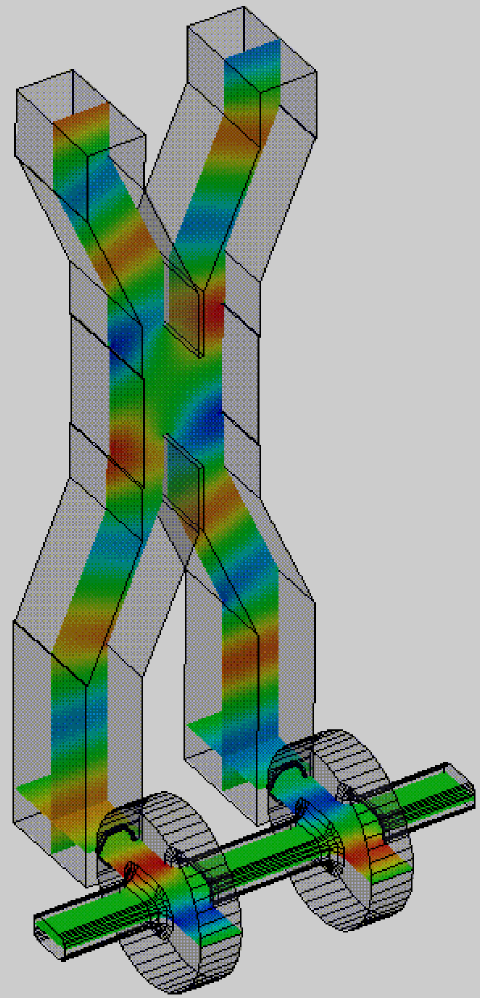
2) One 3dB hybrid coupler.

The hybrid is longitudinally aligned at the center of the two cavities.

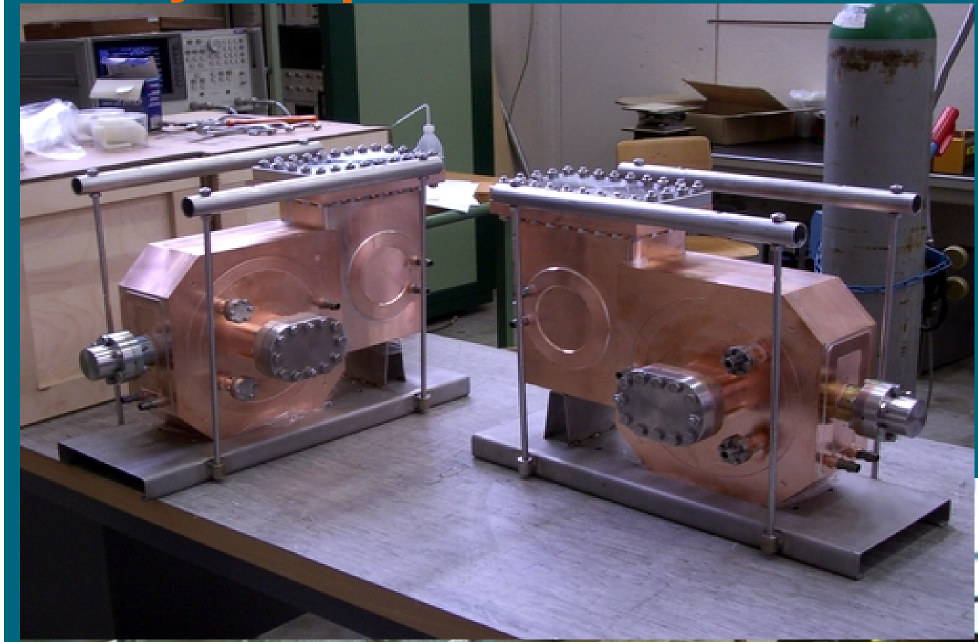
The fields in the two cavities resonates in quadrature.

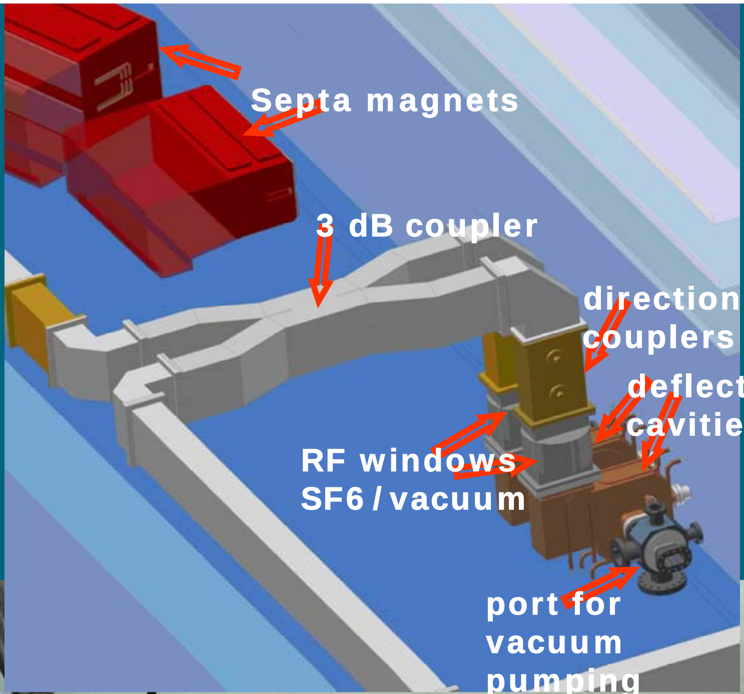
Then the cavities have to be placed an odd multiple integer of $\lambda/4$ of the RF wavelength apart along the beam line to kick the beam with the same amplitude and phase.

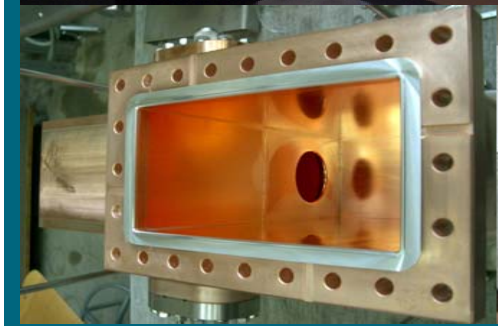
For reasons of space the distance between the gaps has been chosen 250mm, i.e. $5/4\ \lambda_{RF}$

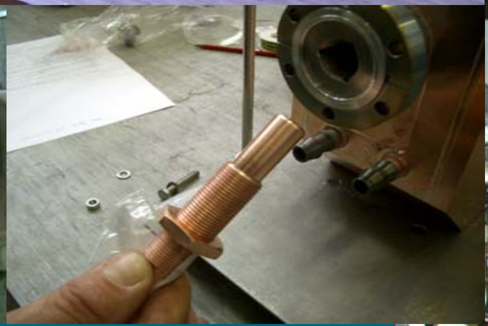


Delay Loop Deflector



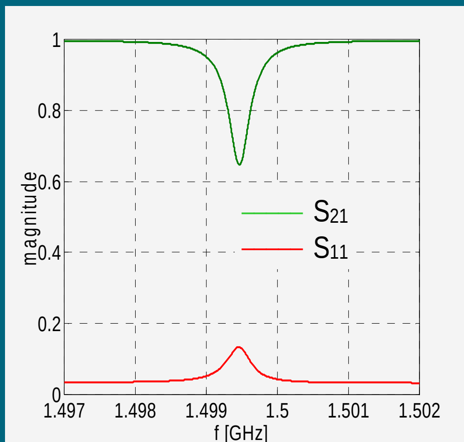




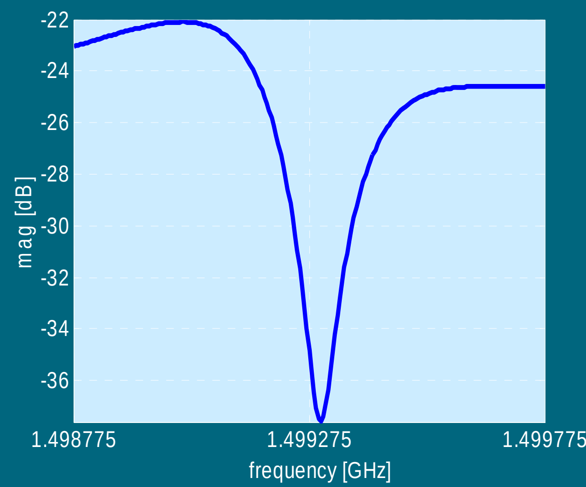


Delay Loop Deflector

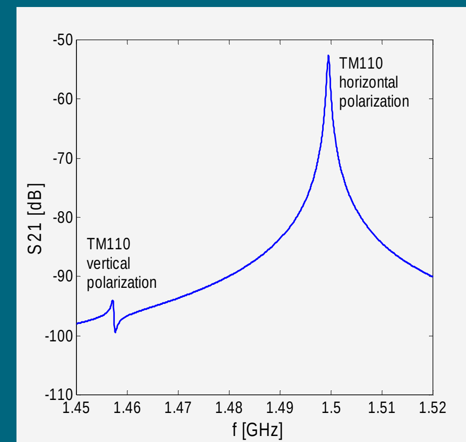
The frequency responses of each component of the system have been measured to verify their correspondence with the design specification and with the results obtained from HFSS simulation code.
To optimize the isolation of the klystron from the reflected power the impedance sees from the cavity side ports of the HJ must be as equal as possible. Accurate tuning of the resonant frequency of the cavity operating mode is therefore necessary.

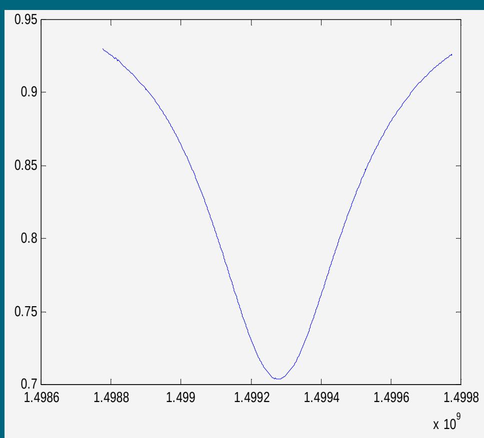


Reflection at the klystron port (red). Transmission between klystron and load ports (green). HFSS result.

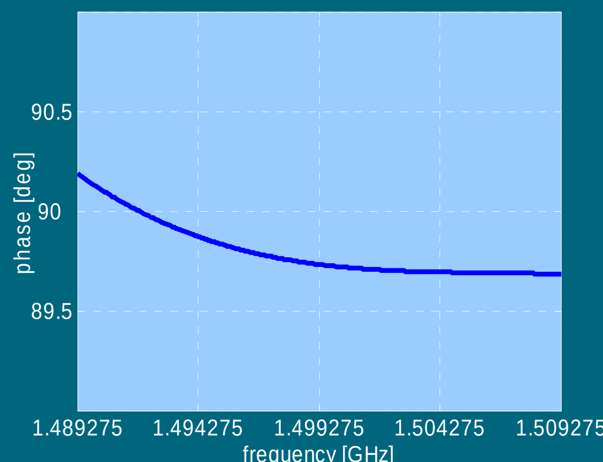


S11 measured at the HJ input port

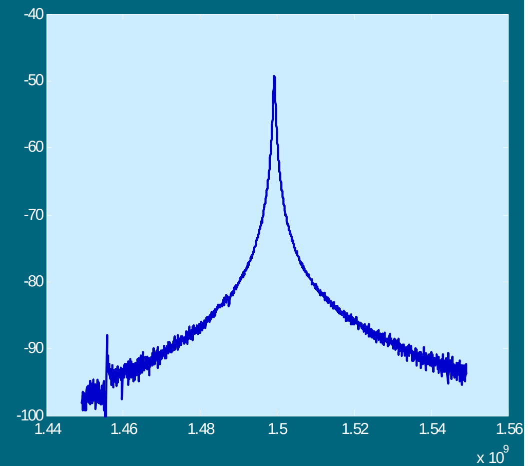




Measured transmission between klystron and load ports.

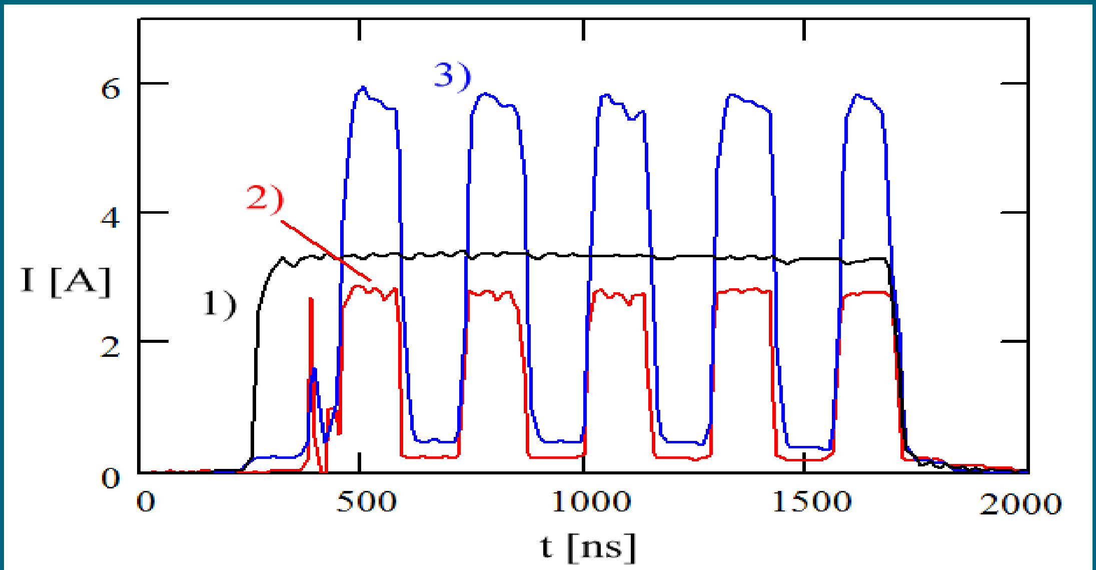


phase difference between the signals taken from the two cavities fed through the HJ



The two polarizations of TM110 deflecting mode.
HFSS simulation (above)
Measured (below)

Delay Loop Deflector

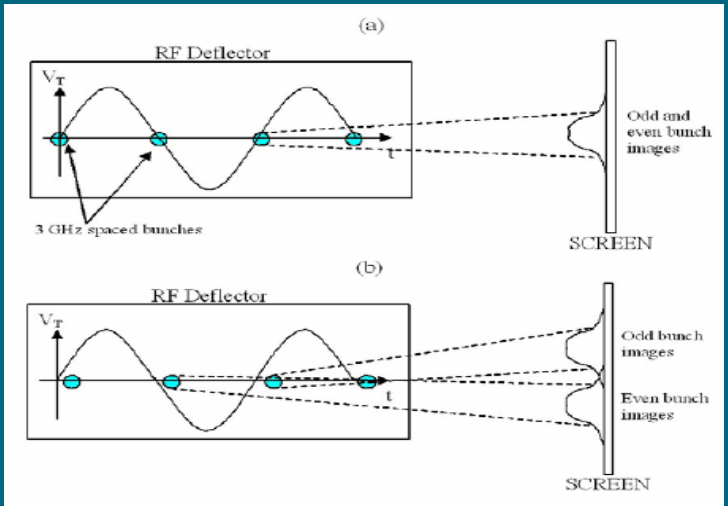


RESULTS OF TRAIN RECOMBINATION

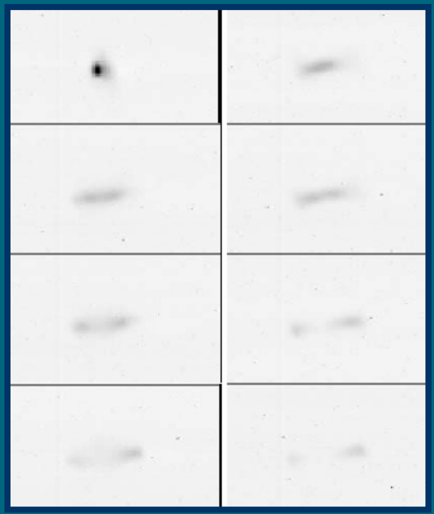
The beam current, equally distributed along the ten incoming sub-trains, results almost doubled where the trains are recombined and near to zero elsewhere.

Beam current in transfer line before the DL (black), in the DL (red) and after recombination (blue)

BUNCH LENGTH MEASUREMENTS WITH RFD

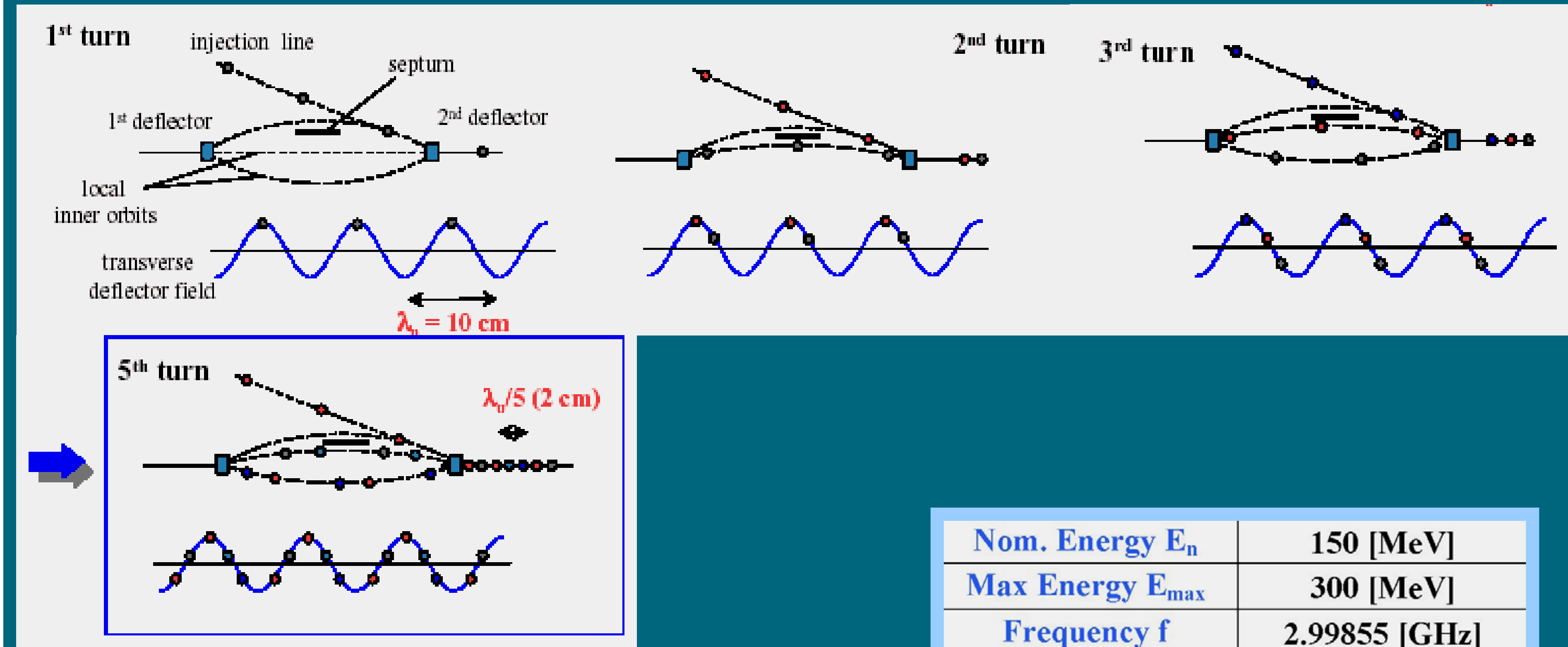


Action of the RFD on the bunches:
a) at the zero-crossing phase
b) out of the zero-crossing



Bunch images. From top left: RFD switched off, at zero crossing, 5° up, 5° down, 10° up, 10° down, 15° up, 15° down.

The CTF3 Combiner Ring

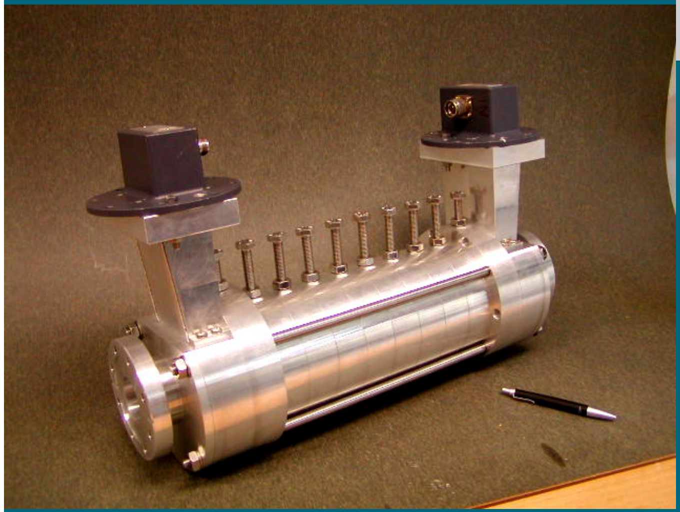


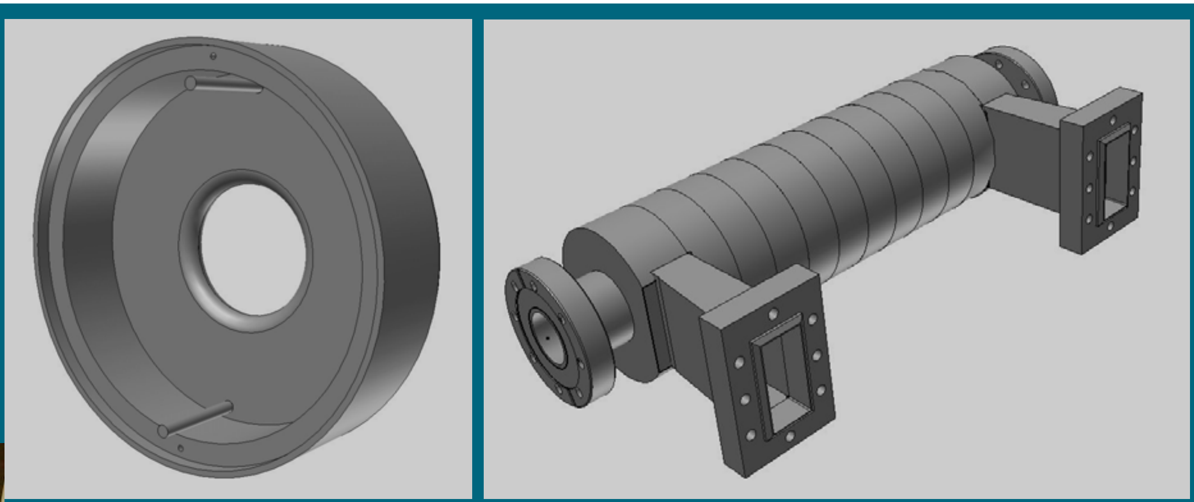
Nom. Energy E_n	150 [MeV]
Max Energy E_{max}	300 [MeV]
Frequency f	2.99855 [GHz]
Number of cell	10
De-phasing/cell	$2\pi/3$
Cell length d	33.33 [cm]
Group velocity v_g/c	-0.0244
Phase velocity v_{ph}/c	1
RF power P_{RF}	~1.5 [MW] (@ E_n)
Deflection ϕ	5 [mrad]
$R/Q=v_g/\omega \cdot (F_\perp/e)^2/P_{RF}$	1380 [Ω/m]

SCALING RESULTS OBTAINED BY LENGELER FOR 2.855GHz T.W. DEFLECTING STRUCTURES

Combiner Ring Deflector

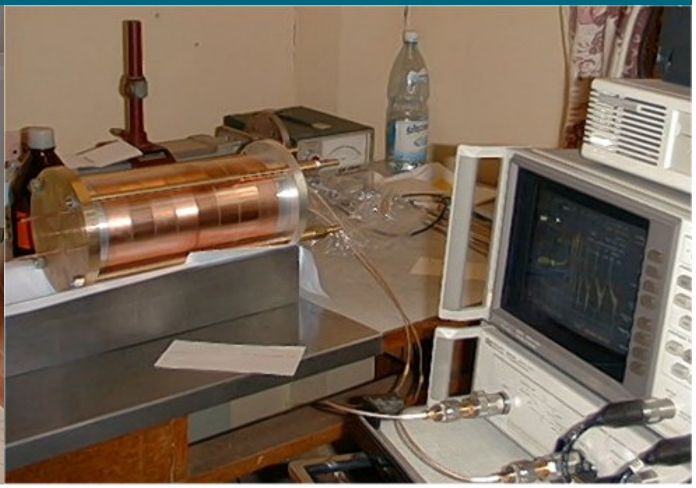
ALUMINIUM PROTOTYPE



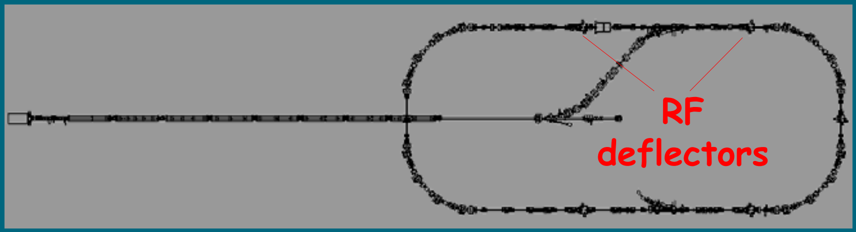


MECHANICAL DRAWING

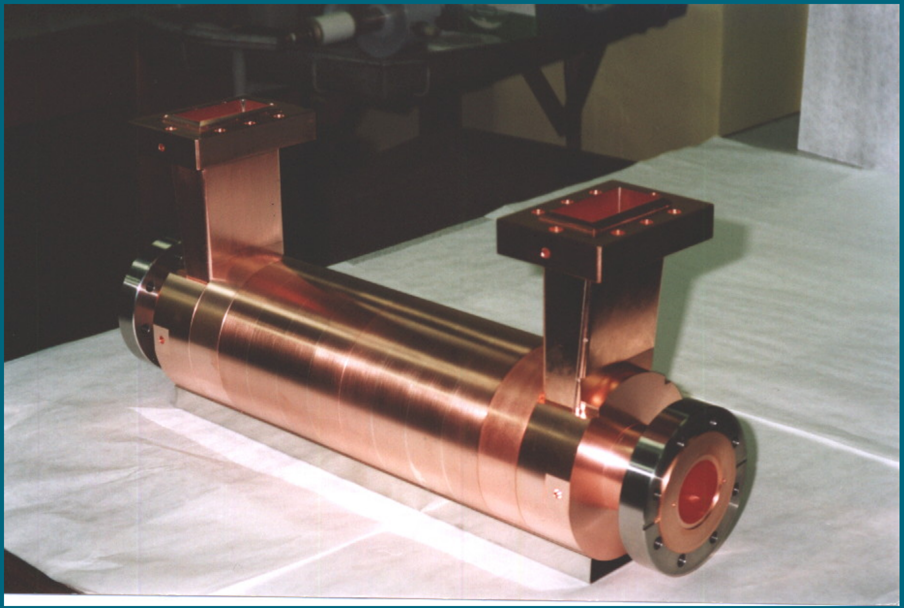
FABRICATION STEPS

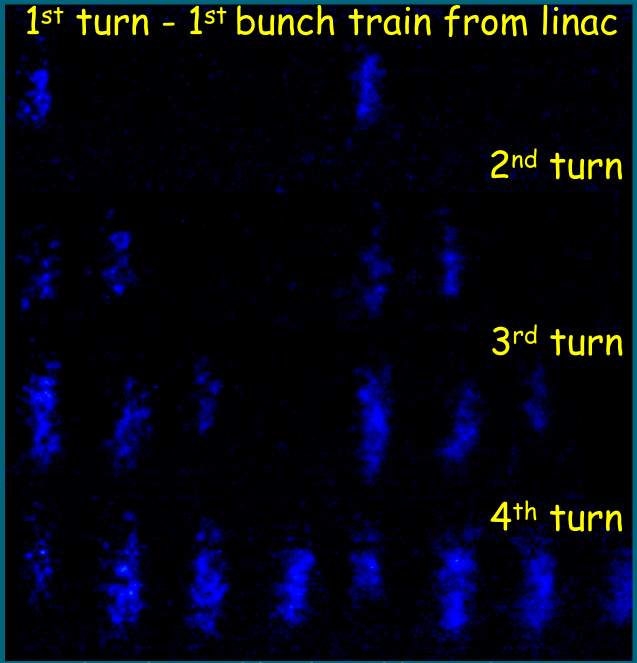


Combiner Ring Deflector



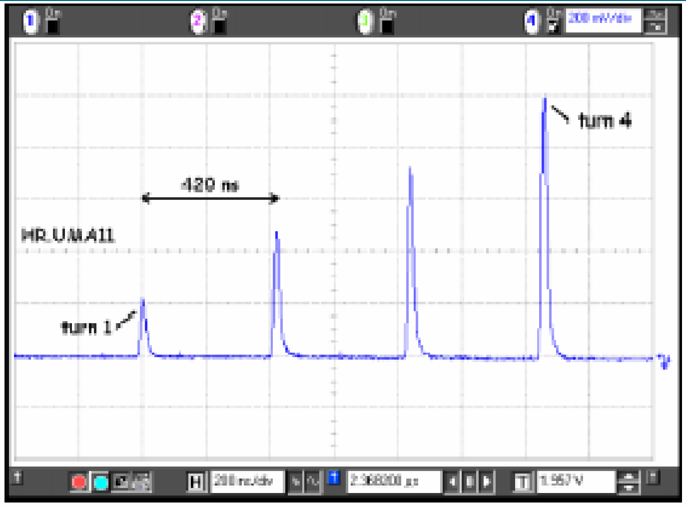
RF deflectors has been used in the CTF3 Preliminary Phase, a low current test of the bunch train combination in the EPA ring of the former LEP Pre-Injector (LPI) complex at CERN.





Bunch train combination of factor four, as observed with a streak camera

LOW-CHARGE DEMONSTRATION OF THE ELECTRON PULSE COMPRESSION AND FREQUENCY MULTIPLICATION

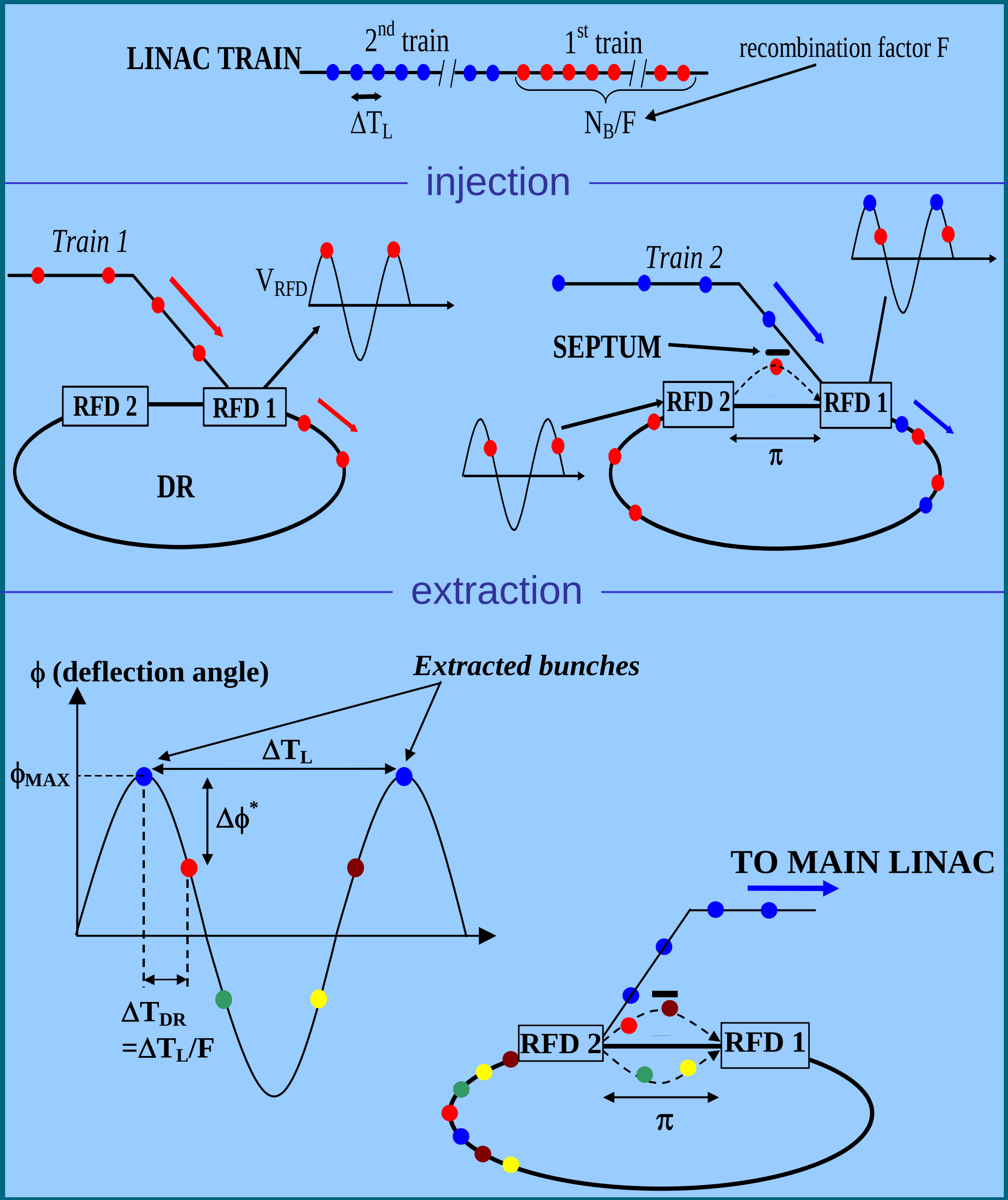


Intensity signal of a beam position monitor in the ring for a bunch combination by factor four.

ILC DAMPING RING

RF deflectors in multifrequency mode

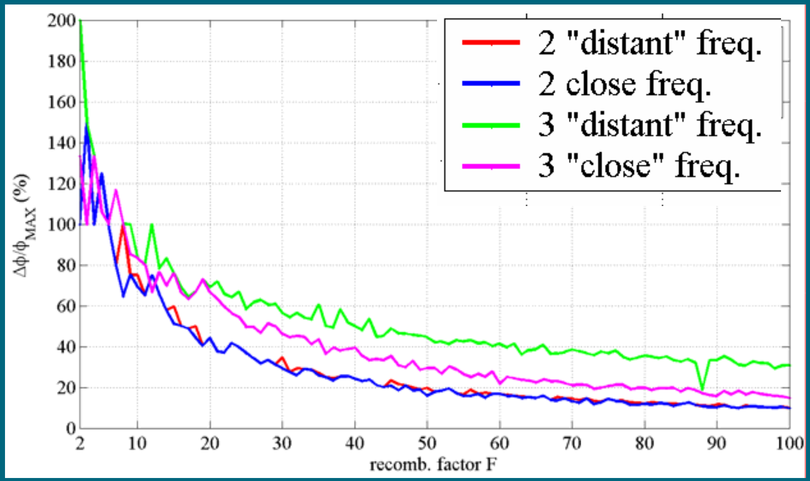
The proposed injection and extraction schemes allow to reduce the ring length by a factor F with respect to the linac train length. Like in the ctf3 combiner ring the first group of RF deflectors allows to inject or to extract the bunches and the second group closes the orbit bump due to the residual kick.



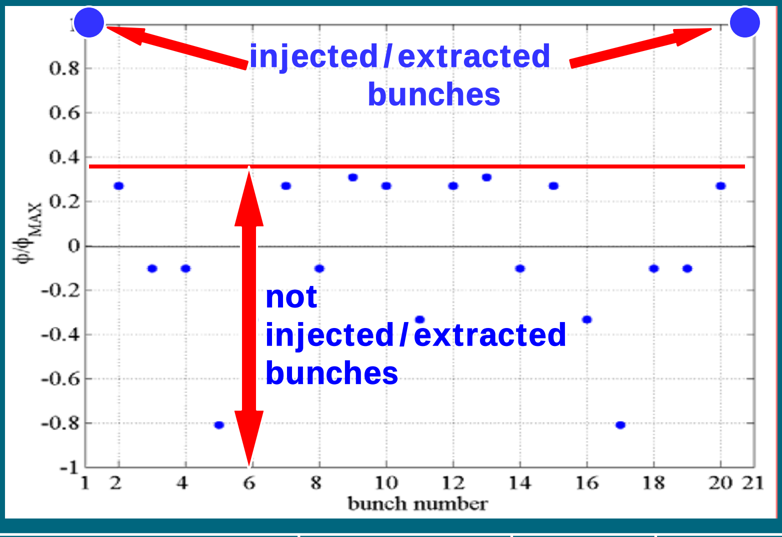
ILC Damping Ring RF Deflector

INJECTION/EXTRACTION WITH 2 OR MORE RF FREQUENCIES NEAR 1.3 GHZ

For a given value of ϕ_{MAX}, this technique allows to greatly increase the ratio $\Delta\phi/\phi_{MAX}$.



3 frequencies case, F=20



freq [GHz]	RFD length [m]	Filling time [ns]	$\Delta\phi/\phi_{MAX}$
f_{RF1}=1317.5 f_{RF2}=1296.7 f_{RF3}=1290.8	0.78	58	63%

Fast Pulse Kickers

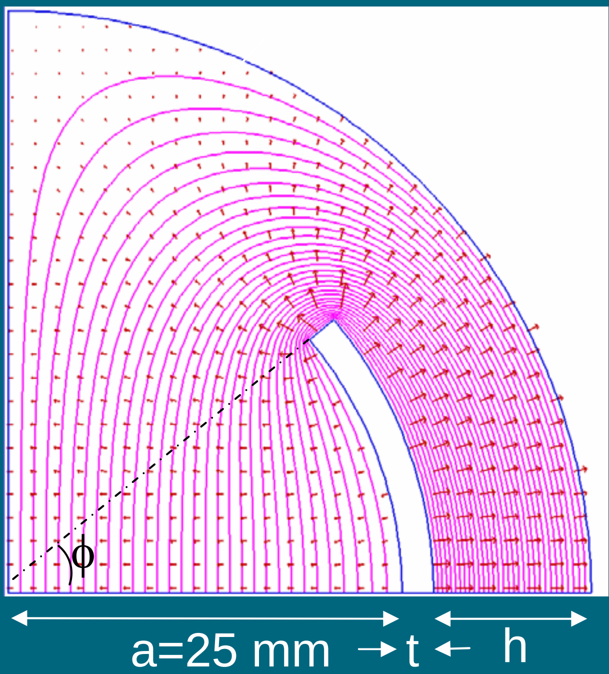
Recent developments of new technologies, have made realistic the hypothesis of using fast HV pulse generators to feed kickers capable to give transverse momentum to the bunch injected in a ring without perturbing the orbit of the adjacent ones.
FID GmbH has developed a series of fast power generators. The pulsers can produce trapezoidal voltage pulses with the amplitude up to tens of kV, the rise time from 100 ps to 1ns and the pulse width from 5 ns to 50 ns.
Pulse repetion frequency can reach some hundred of kHz.

The use of these fast pulse generators seems very promising for the ILC Damping Ring and several groups from different labs are working on the design of stripline electrode kickers or on development of pulsers with the same characteristics of FID pulsers.

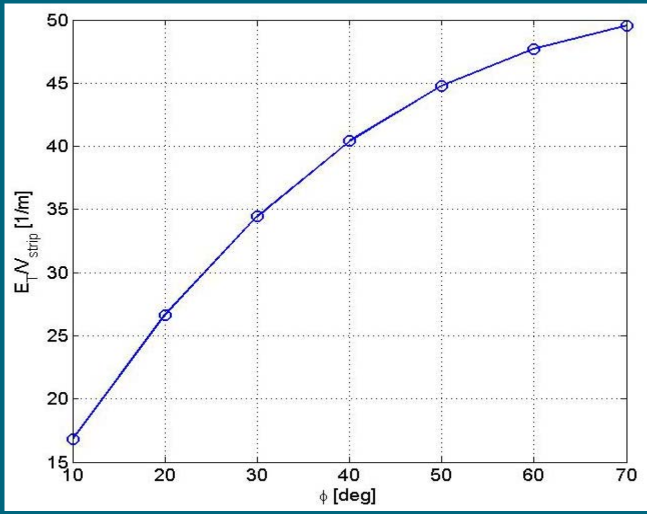
At LNF we have studied this solution for the upgrade of the DAFNE injection system.
A special stripline kicker has been designed and its realization is in progress.
This activity is also a valid R&D of the injection and extraction kicker for the ILC Damping Ring.

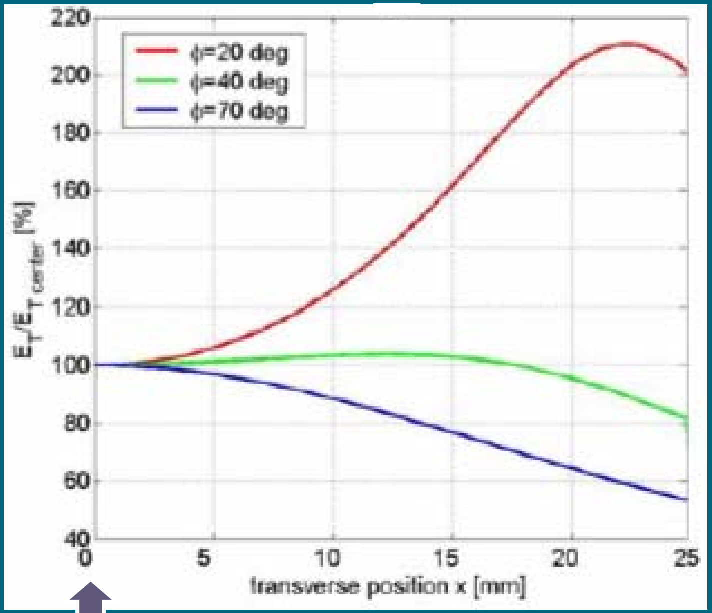
General considerations about striplines: transverse field profile properties

CIRCULAR CROSS SECTION (50 Ω)



Horizontal component of the electric field (E_T) on the kicker axis as a function of the electrode coverage angle.





kicker axis

Horizontal component of the electric field (E_T) along the horizontal axis of the kicker cross section. The value is normalized to the value assumed by E_T on the center of the structure. Two different covarage angles for the electrode (20, 40 and 70 deg) are considered.

General considerations: kicker length and pulse length

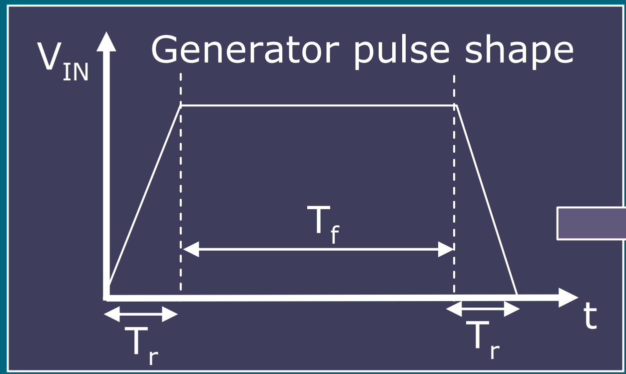
L=kicker length

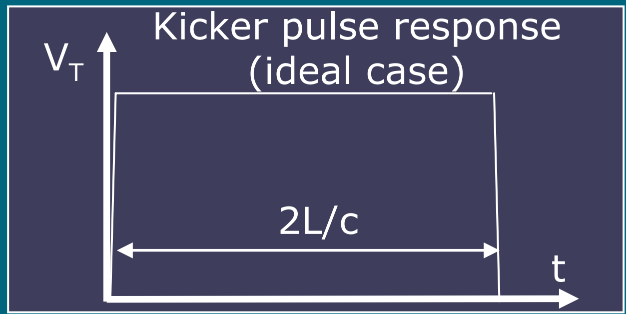
T_r=rise time length

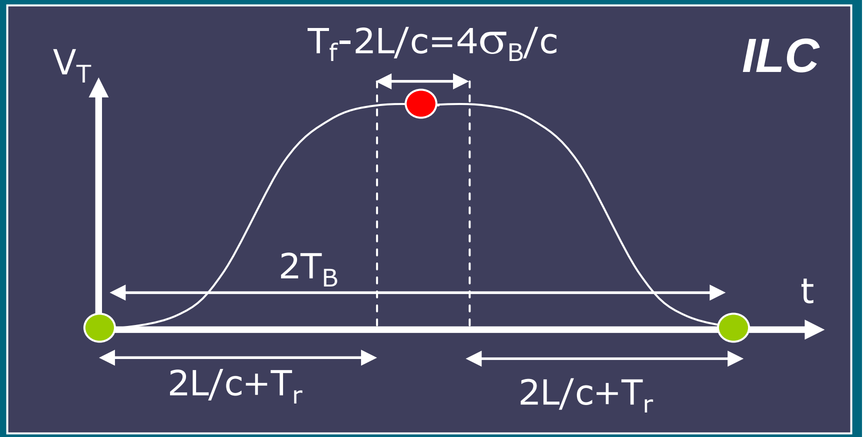
T_f=flat top length

σ_B=bunch length

T_B=bunch spacing

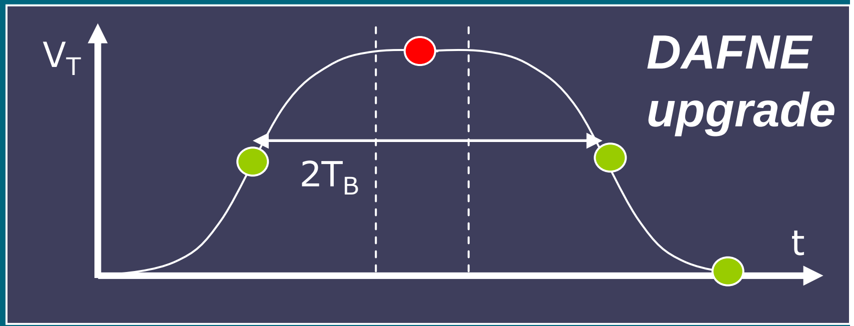






Injected bunch

Stored bunches

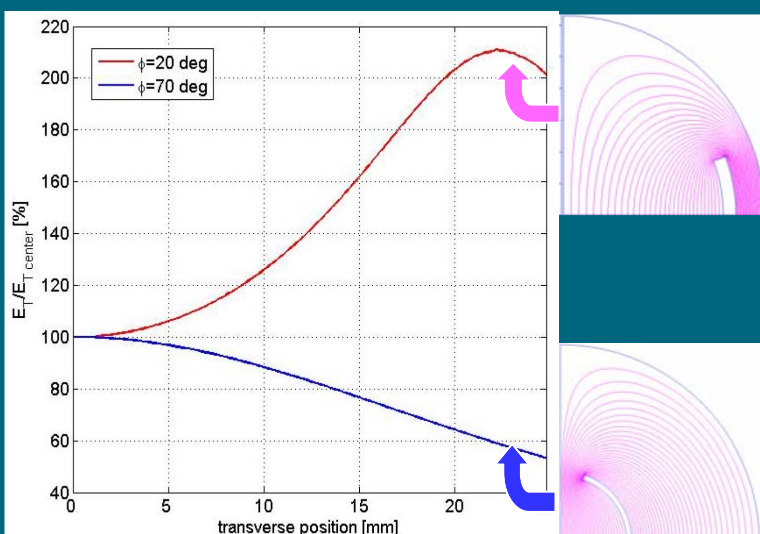


assuming T_r=300ps	DAFNE
E [GeV]	0.51
T_B [ns]	2.7
σ_B [mm]	35
Defl. [mrad]	5
L [cm]	73
T_f [ns]	5.3
σ_x [mm] @ septum and kicker	2
σ_y [mm] @ septum and kicker	1

Correction of the deflecting field flatness using tapers

a) **Tapers** are usually used to avoid abrupt steps in the section of the vacuum chamber in order to **reduce the intensity of wakefields** and HOM (impedance of the machine).

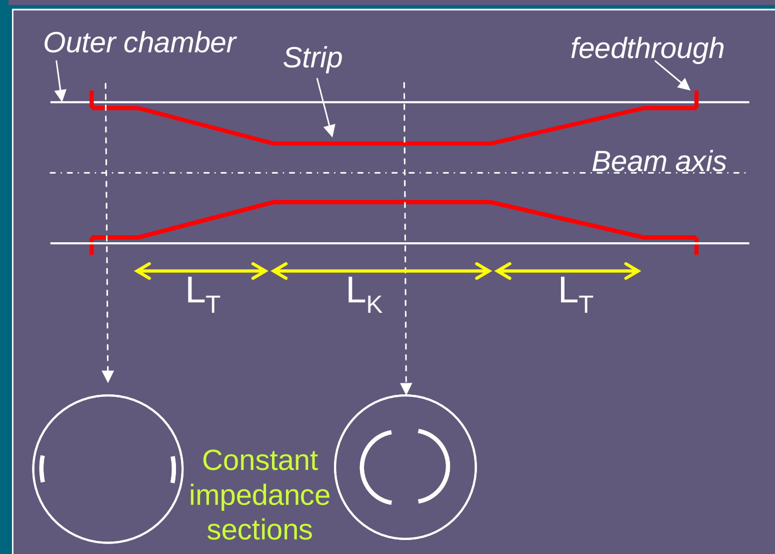
b) The **uniformity of the deflection** depends on the coverage angle.



Tapering the transition between the kicker structure and the adjacent beam pipe it is possible to minimize:

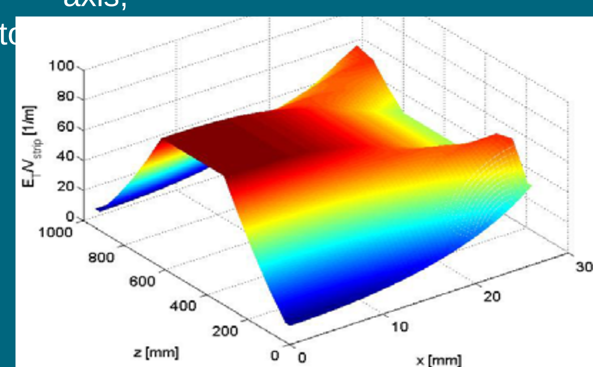
a) The contribution of the kicker to the impedance of the machine;

b) The non uniformity of transverse deflection as a function of the transverse position.

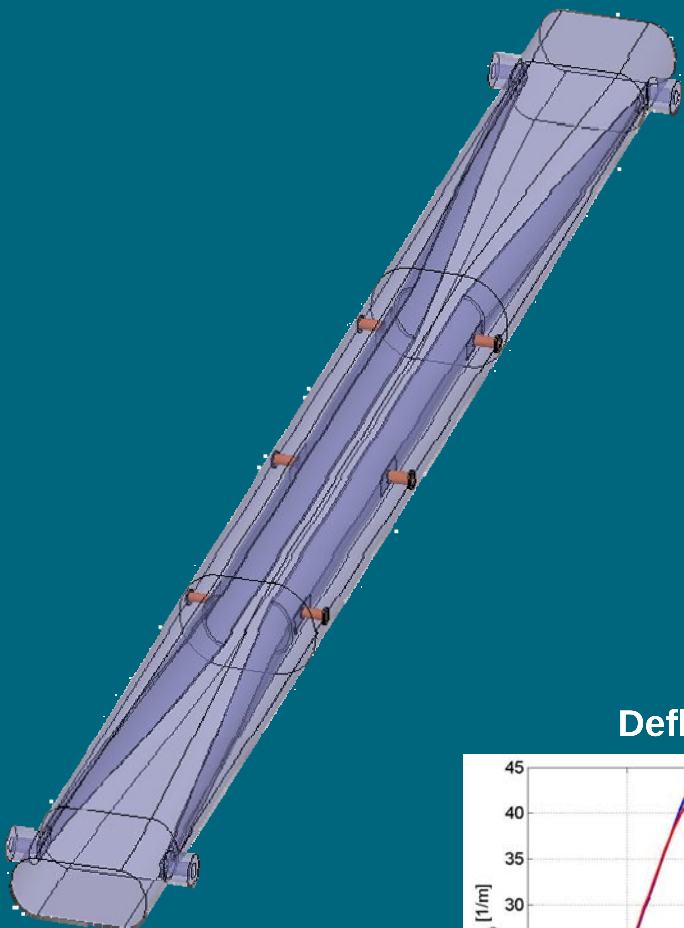


L_k and L_T lengths have been optimized to achieve at the same time:

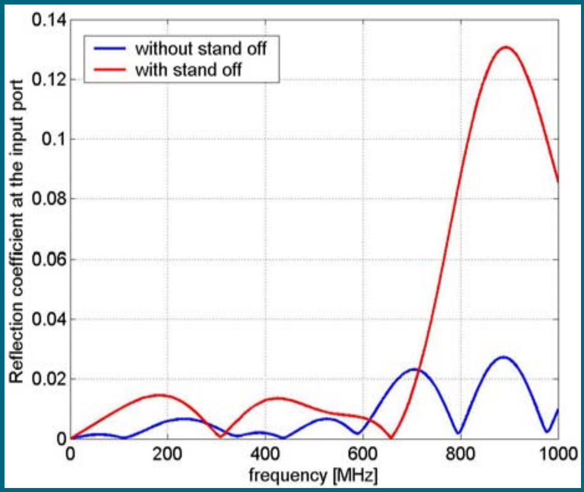
- optimum deflecting field uniformity along the horizontal axis;
- t… h the bunch



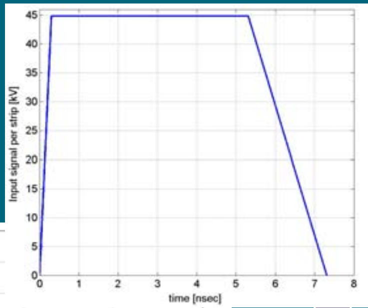
DAFNE kicker design: 3D simulations



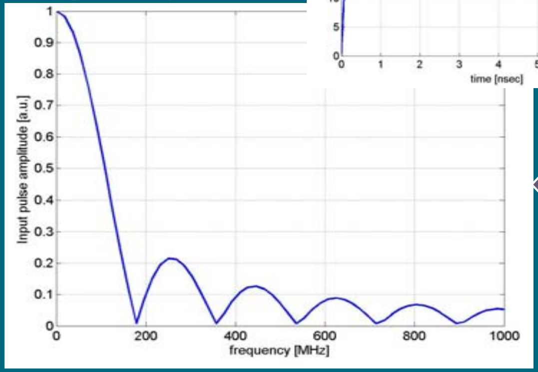
Reflection at the input coax port



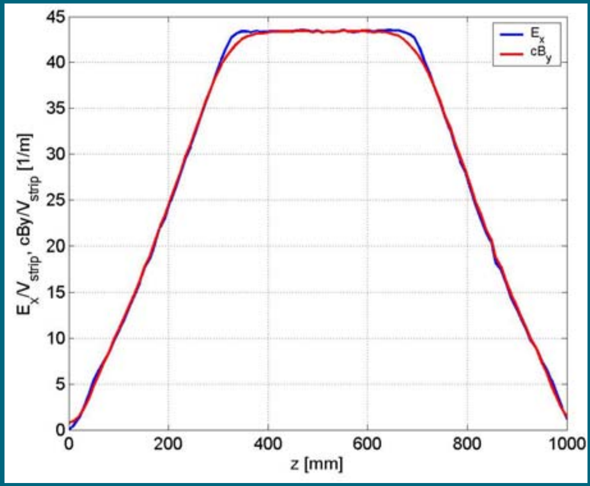
Pulse model vs. time



Pulse model vs. frequency

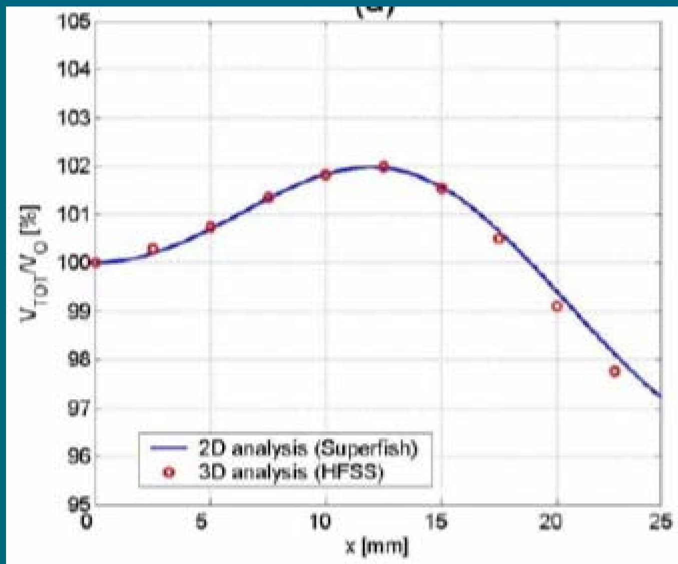


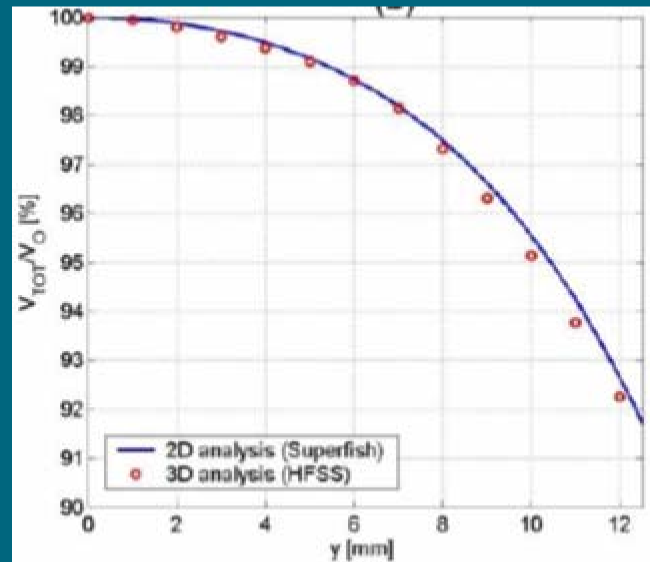
Deflecting field



DAFNE kicker design: 3D simulations

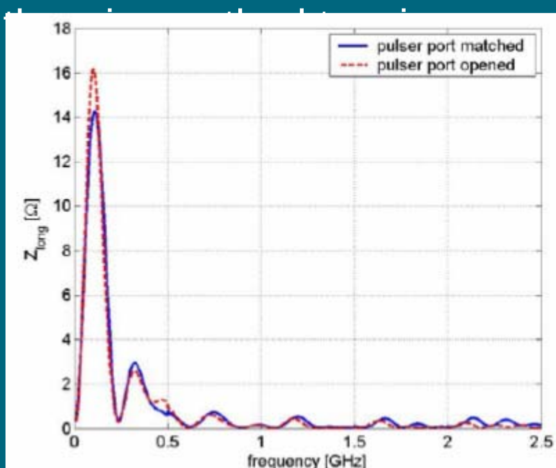
Deflecting field uniformity in the transverse plane (3D compared with 2D results)



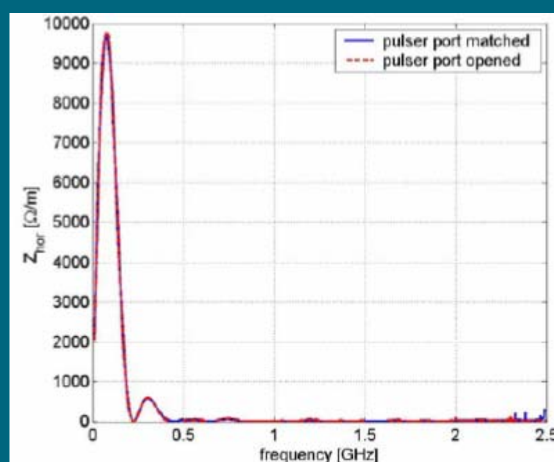


BEAM COUPLING IMPEDANCE

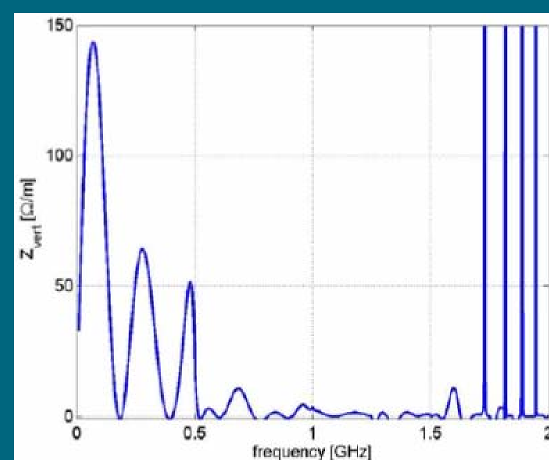
Evaluation of beam coupling impedance and transfer impedance using



Longitudinal impedance



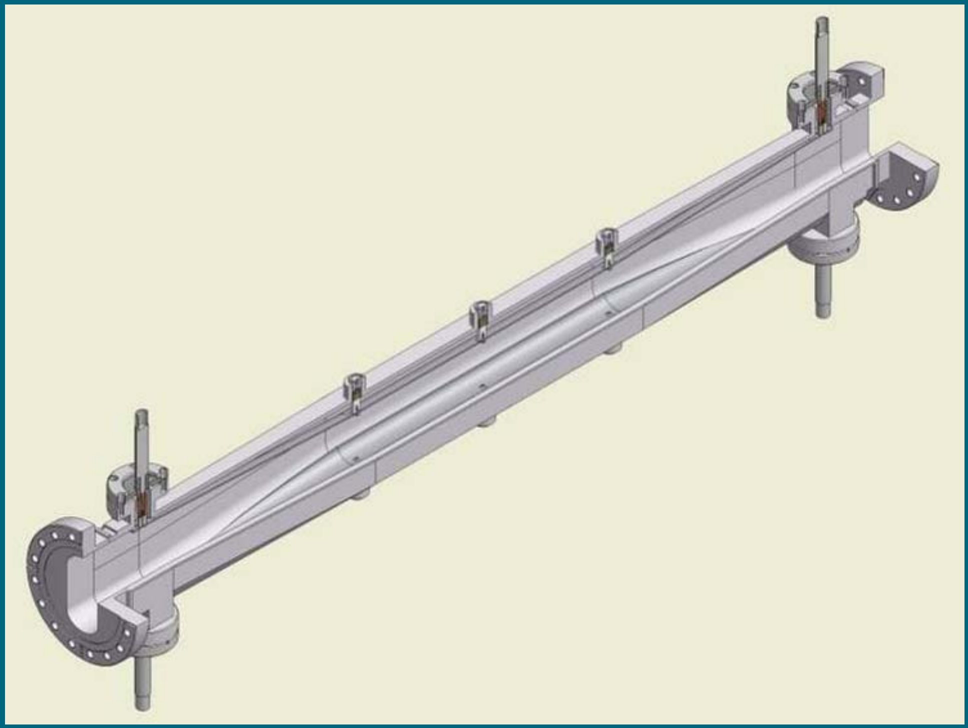
horizontal impedance

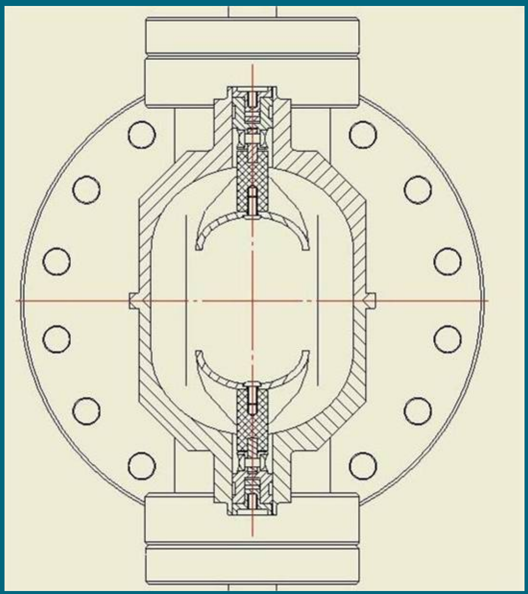


vertical impedance

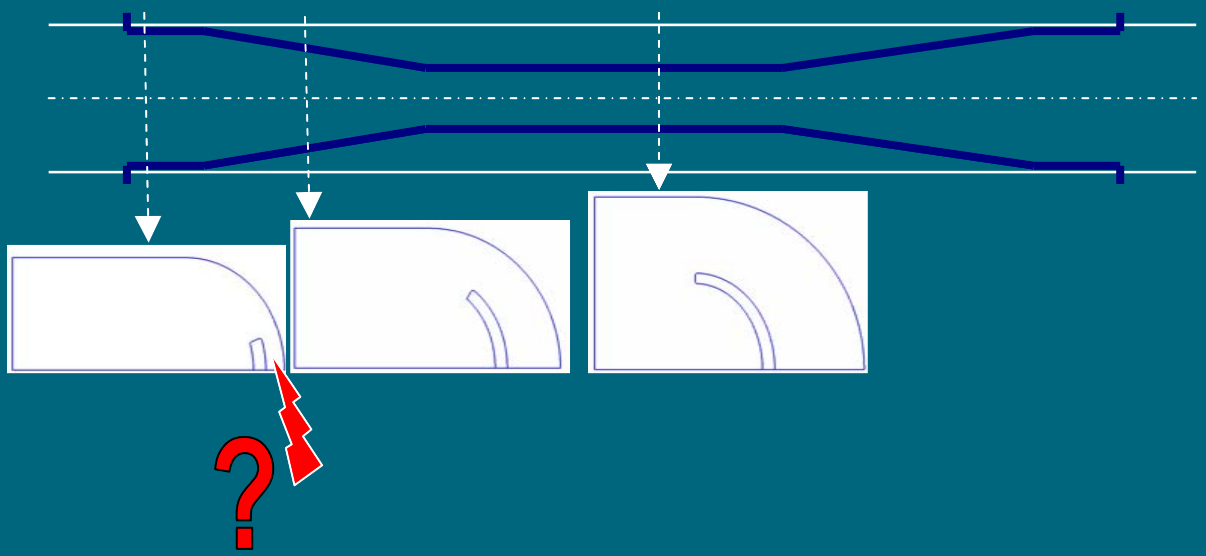
DAFNE kicker design: mechanical drawings

The kicker for the injection upgrade of DAFNE has been almost completely designed. The mechanical drawings are ready as well.
To get the required deflection, very high voltage (about 45 kV) has to be applied to each electrode.
HV tests on the most critical parts and components of the kicker are necessary for defining the final version of the drawings.

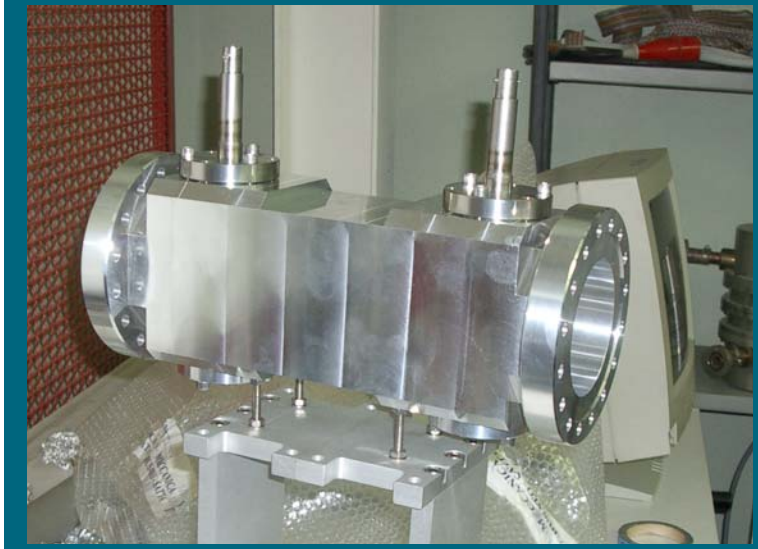




R&D and HV tests: the test stripline



When HV is applied the possibility of discharges is higher in the end-section of the kicker electrodes, where the electrode itself is closer to the vacuum tube.



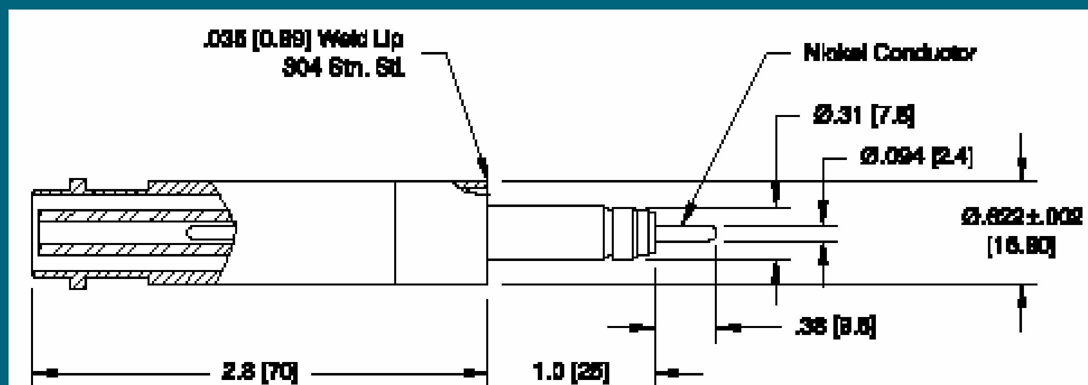
A stripline with the same dimension and the same distance from the chamber of the kicker stripline in the end section has been built. Coax ceramic feedthrough can be mounted on this test device to apply the HV to the stripline.

R&D and HV tests: the feedthrough

The ideal feedthrough for our purpose has to:

- be able to tolerate the applied voltage (45-50 kV)
- have a constant 50 Ω characteristic impedance.

Second statement is important to keep low the beam impedance of the kicker even well beyond the frequencies contained in the spectrum of the pulse.
It is not obvious to find a feedthrough fulfilling at the same time this 2 specifications.
The design of a dedicated feedthrough is in progress at LNF.

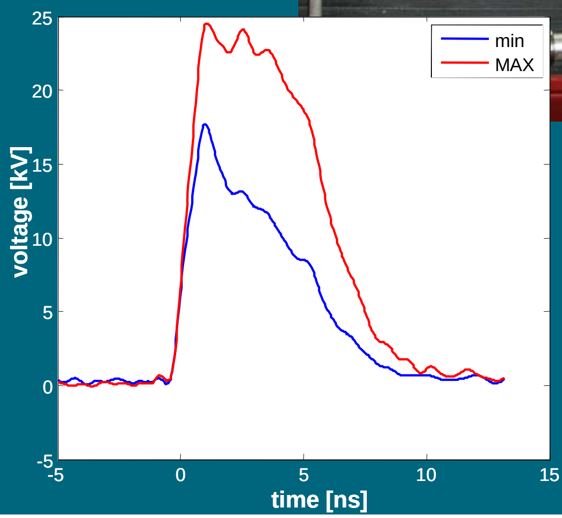


First tests have been done with a commercial feedthrough (SHV20 standard).
It is specified for 20kV DC (but our pulse lenght is 5ns).
The value of the characteristic impedance is not specified, but it is not constant.

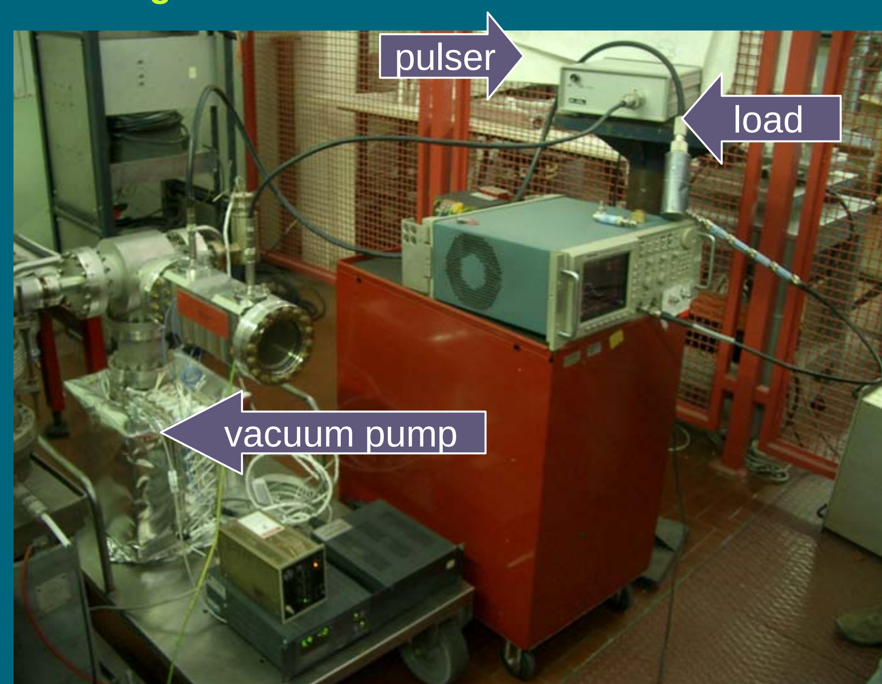
R&D and HV tests: the FID F10K10N207 pulser - V_{OUT} 16÷24kV.

First HV tests have been performed using a pulser borrowed from FID GmbH in the meanwhile that the 50kV final pulser (FPG 50-01SP) was fabricated.
This test pulser has pulse length and rise time similar to the FPG 50-01SP, while the pulse amplitude is only 20kV.

PULSE MEASURED AT THE GENERATOR OUTPUT CONNECTOR

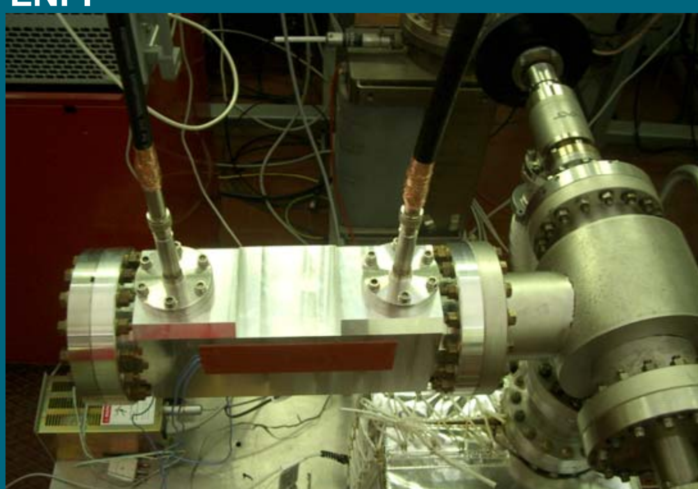


no phenomena attributable to electric discharges have been observed



R&D and HV tests:
the FPG 50-01SP pulser

HV tests have been repeated with the same set up when a prototype of the 50kV pulser has been delivered at LNF.

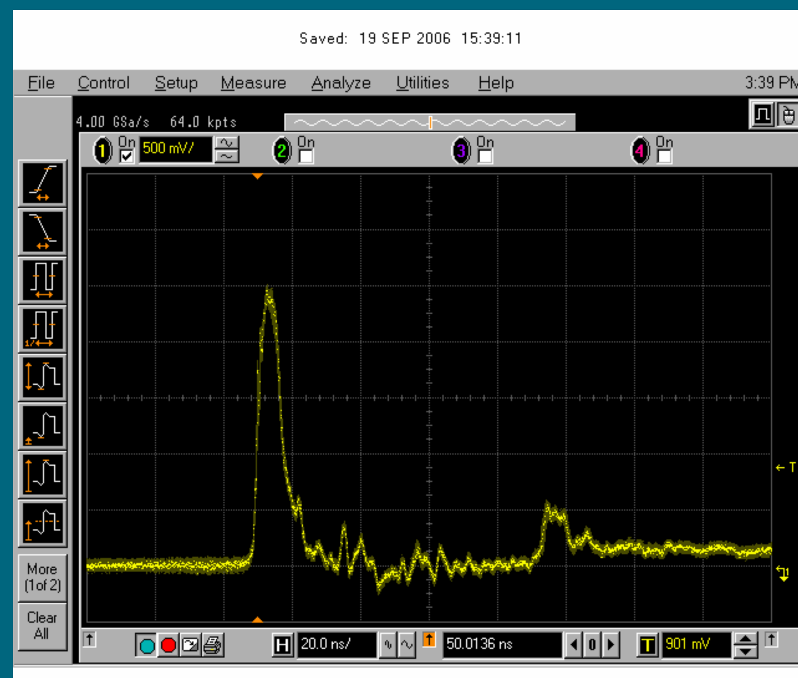


Test results:

• even at maximum output voltage (50 kV) there are no discharges along the stripline.

• after few pulses (some hundreds) there has been a breakdown of the ceramic of one feedthrough which lost its vacuum tight.

• a modification in the feedthrough housing was done; but, after some thousands of pulses with the voltage set at 48 kV, discharges occured in the air side of the feedthrough. It has been irreversibly damaged.



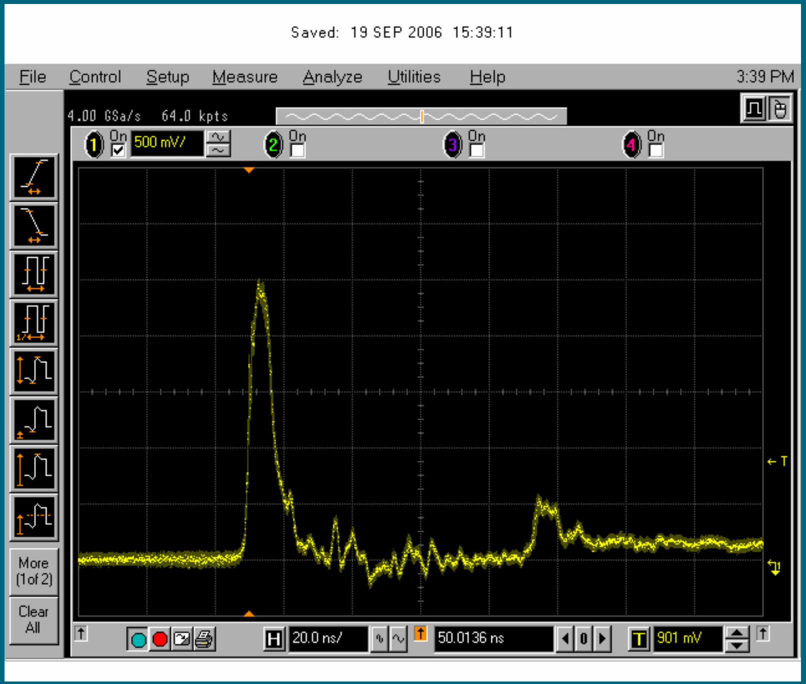
Grabbed waveform of the pulse (V_{OUT}=48kV) before the feedthrough damaging

R&D and HV tests:
the FPG 50-01SP pulser

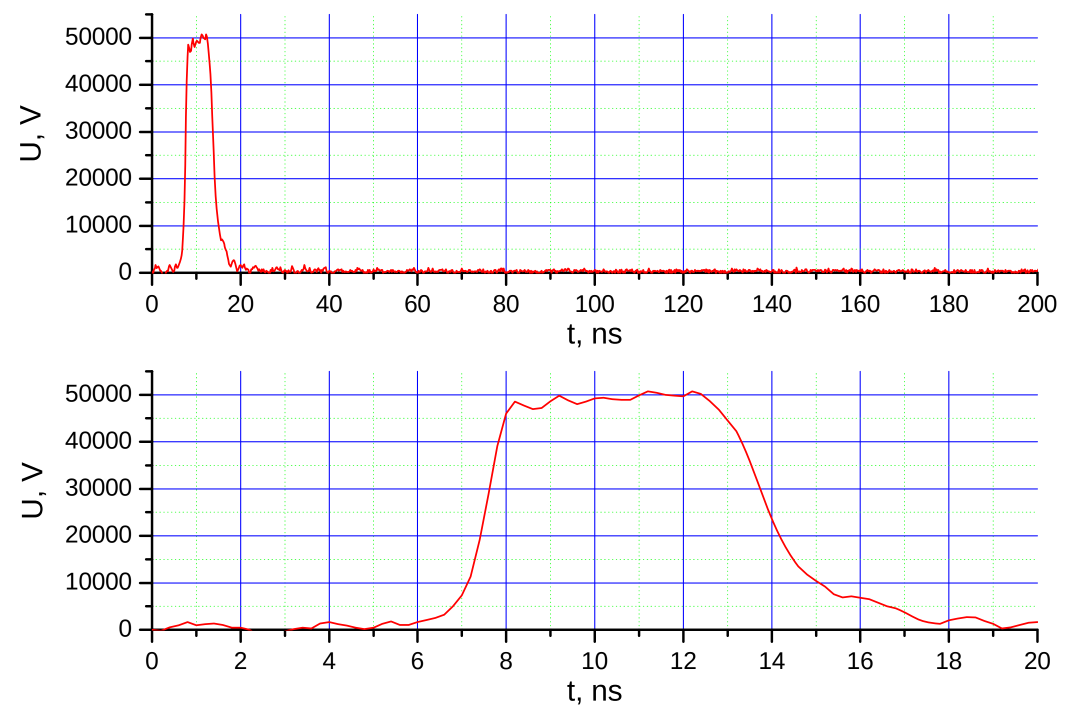
A second version of the 50kV pulser has been developed by FID to improve the pulse shape:

•Fall time shortened
•No secondary pulses
•Improved flatness of the pulse.

We are waiting for the delivering of this improved version of the pulser.



Waveform of the first version of the 50kV pulser measured at LNF



Waveform of the improved 50 kV pulser measured by FID

CONCLUSIONS

Different typologies of devices for injecting and extracting the beam in combiner or damping rings has been studied, designed and realized in the last years at LNF.

An original RF deflector system and a TW RF deflector have been constructed for the CTF3 DL and CR respectively. Both of them have been already and successfully commissioned.

The possibility to use TW structures powered in a multi-frequency mode has been investigated for the ILC DR.

Finally a strip-line electrode fast pulse kicker has been designed for the upgrade of the DAFNE injection system and it is now under construction. The same design criteria are valid to implement a fast kicker for the ILC DR.