Italian National Agency for New Technologies, Energy and Sustainable Economic Development

IBIC 2019
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Malmö, Sweden
8-12 September 2019

Development of a Passive Cavity Beam Intensity Monitor for Pulsed Proton Beams for Medical Applications

IBIC'19, 9 September 2019, Malmö, Sweden

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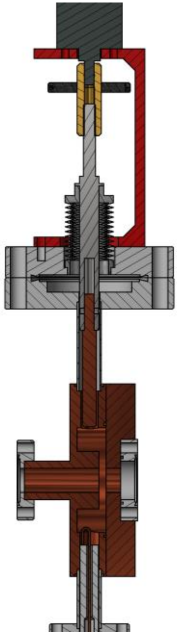
Agenda of the presentation

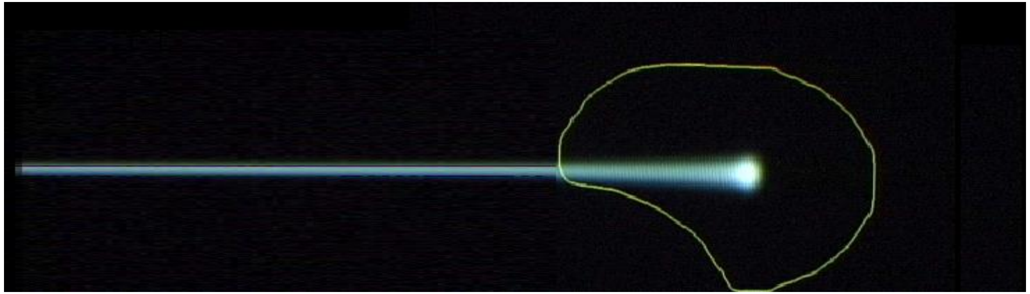


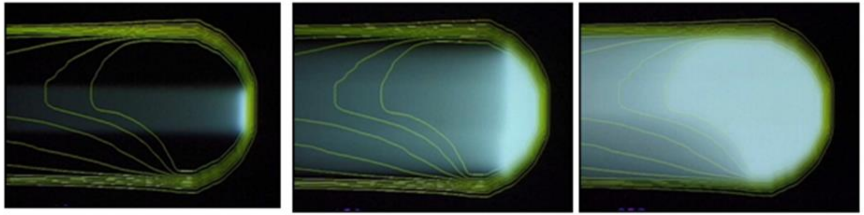
- **INTRODUCTION TO HADRON-THERAPY AND TO THE TOP-IMPLART LINAC**
  - Proton therapy overview
  - The TOP-IMPLART project and accelerator
    - TOP IMPLART proton beam characteristics
- **RESONANT CAVITY AS BEAM INTENSITY MONITOR**
  - Analytical model
  - Prototype cavity design and realization
- **PRELIMINARY MEASUREMENTS ON THE PROTON BEAM**
  - Amplification electronics
- **CONCLUSION**

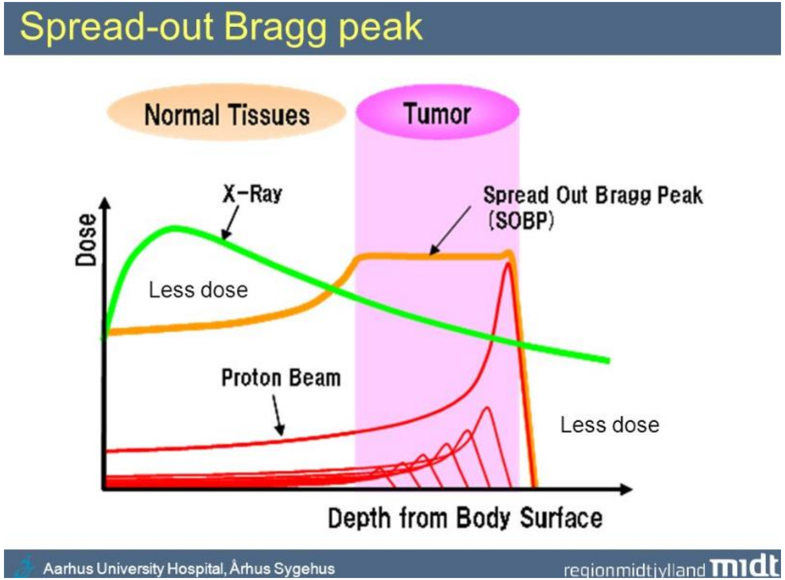
Proton Therapy Overview

Tumor treatment with protons

- Protons damage tissue cell DNA beyond their repair capability, causing their death
- Most damage occurs at Bragg's peak where protons lose the major part of their initial energy



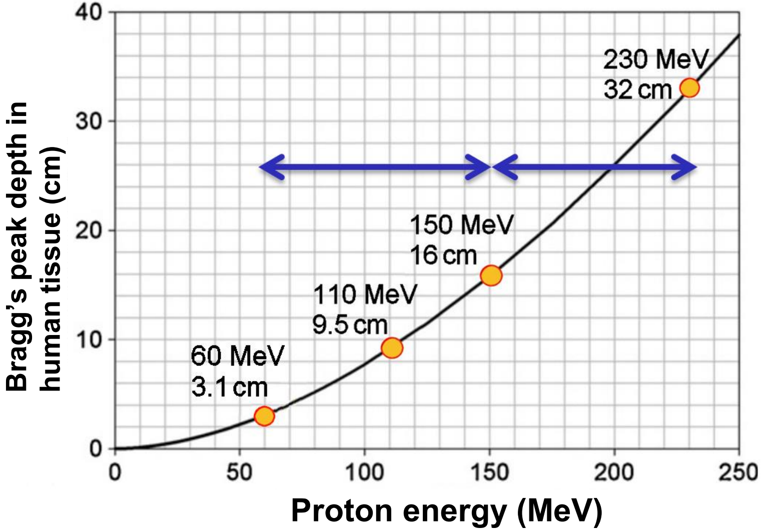


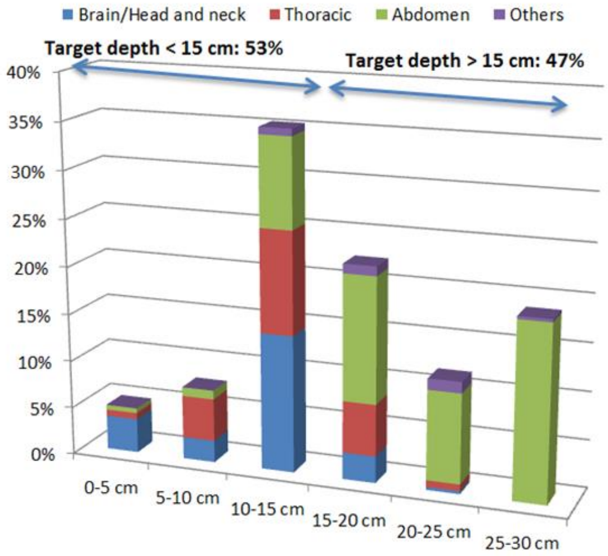


SOPB: extended uniform dose region in depth formed by optimal stacking of multiple dose curves

Proton Therapy Overview

Proton energies for treatment

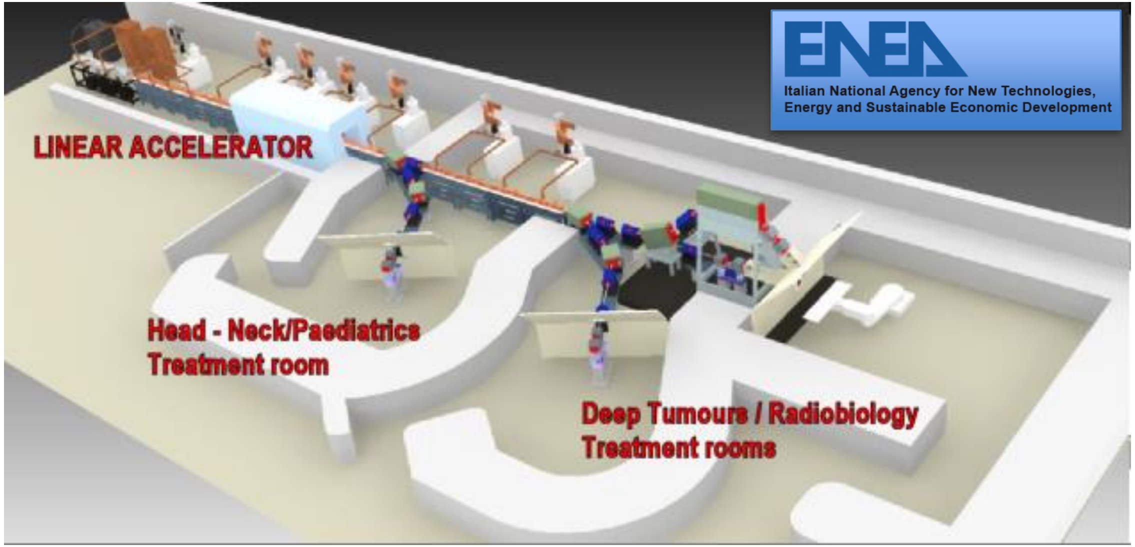




- ❖ More than 50% of tumors develops at depths between 3 cm and 16 cm and can be treated with 60 -150 MeV protons
- ❖ 230 MeV protons (32 cm) can treat the totality of tumors eligible for proton-therapy

TOP-IMPLART Program

Terapia Oncologica con Protoni - Intensity Modulated Proton Linear Accelerator for RadioTherapy



Program partners

ISTITUTO SUPERIORE DI SANITÀ

IRE ISTITUTO NAZIONALE TUMORI REGINA ELENA

ISG ISTITUTO DERMATOLOGICO SAN GALLICANO

ISTITUTI DI RICOVERO E CURA A CARATTERE SCIENTIFICO

Funding agency

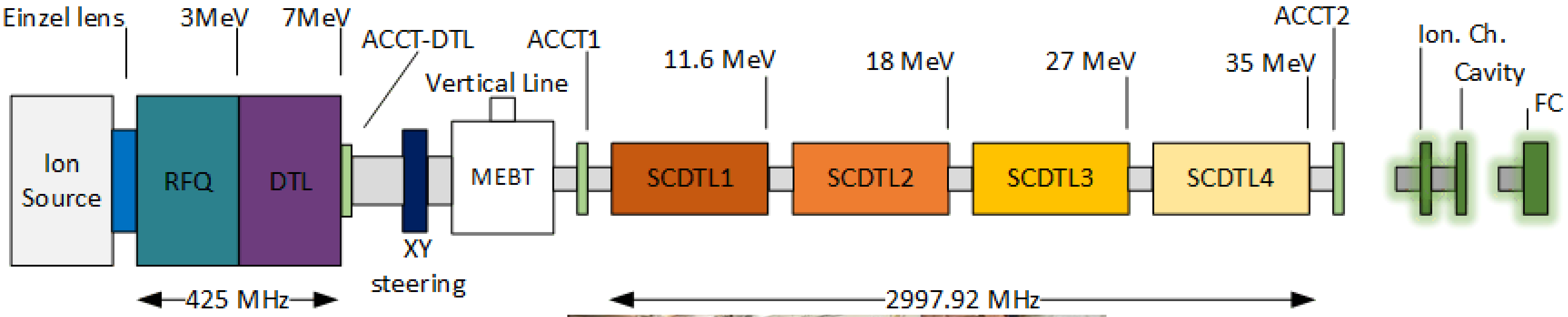
REGIONE LAZIO

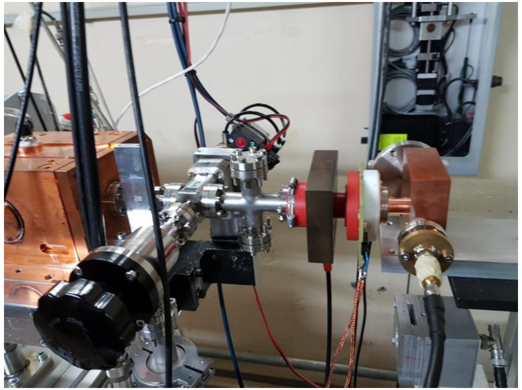
LAZIO INNOVA

Development of a technology demonstrator of an high-performances, low cost, and manageable fully linear accelerator for proton-therapy

TOP-IMPLART linac

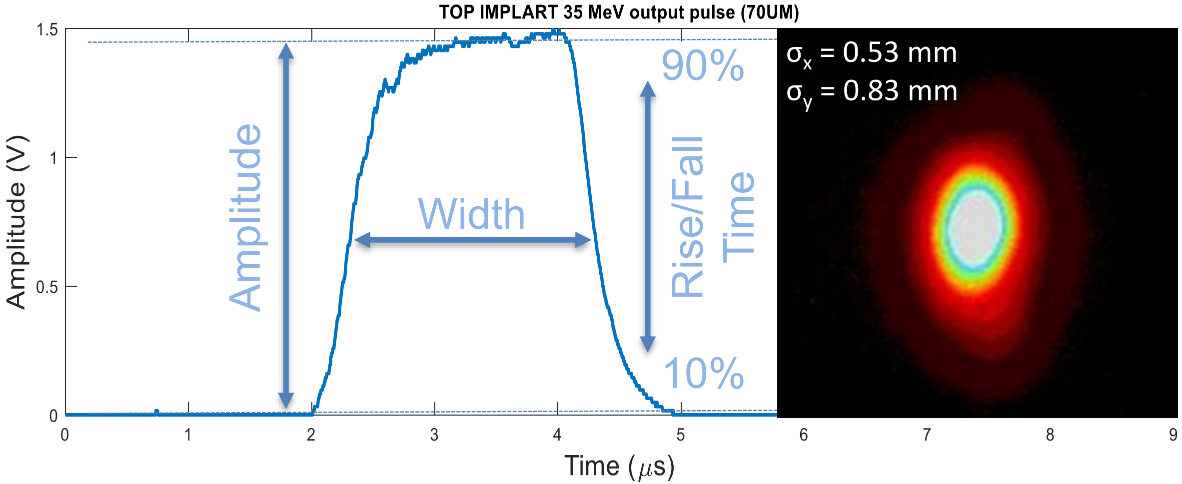
Layout





TOP-IMPLART Proton beam @35 MeV

Pulse characteristics



Parameter	Value	Notes
Width	1 – 4 μs	2.7 μs typ.
Rise time	~ 500 ns	
Fall time	~ 500 ns	
PRF	100 Hz (max)	25 Hz typ.
Current	≤ 50 μA	
Charge	135 pC (max)	
h^+/pulse	$8.4 \cdot 10^8$ (max)	
Beam size	<1 mm (x)	
	<2.5 mm (y)	
Stability	~ 3%	

- ❖ TOP IMPLART pulse characteristics at the output of the 35 MeV section

TOP-IMPLART beam diagnostics

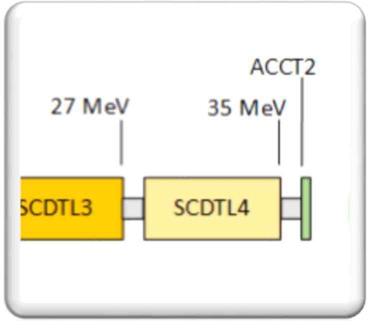
Medical applications beam

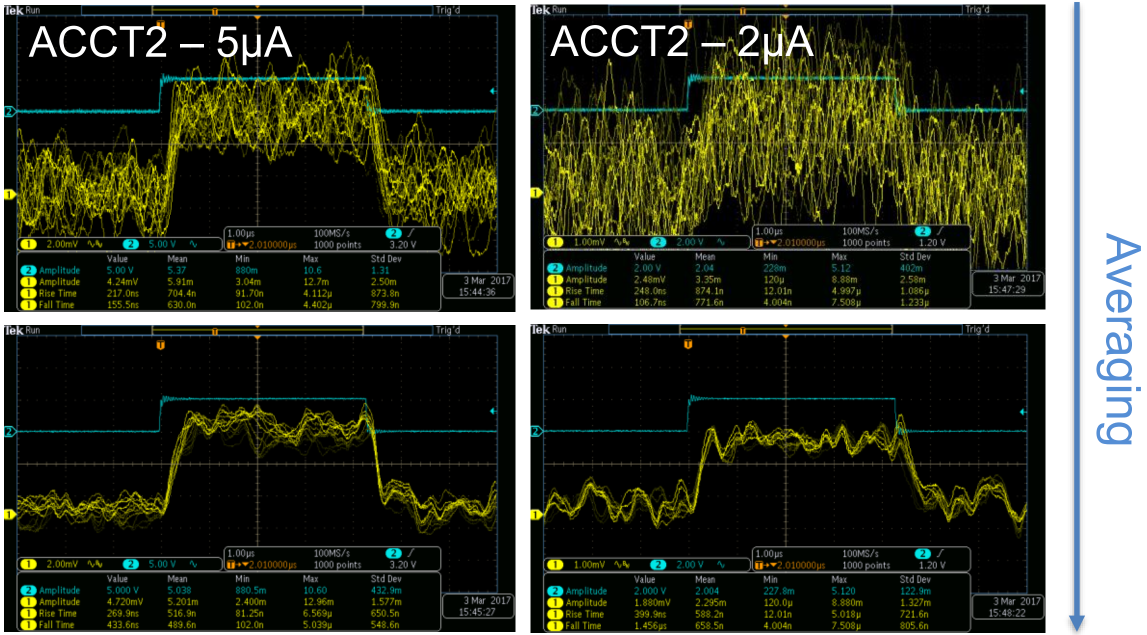
- Proton-therapy typical dose-rate is 2Gy/min:
  - this corresponds to an average beam current a few nA
  - Constant dose-rate scaling for TOP-IMPLART pulsed beam requires 1.0 – 2.0 pC per pulse
  - This is obtained with pulse currents around 1 μA
  - Pulse current diagnostics is essential during commissioning and machine operation (not for dose delivery)

  - We installed AC current transformers as non interceptive diagnostics

TOP-IMPLART Pulse Current Measurement

Measure the pulse current signal for each pulse at the output of sections



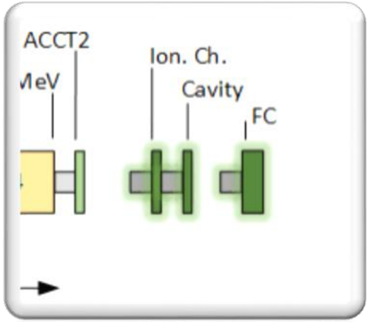


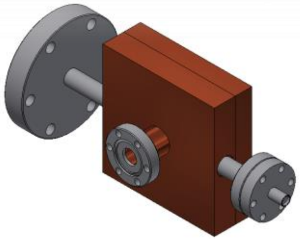
- ❖ Current transformers are not sensitive enough
- ❖ Averaging is necessary to extract signal from noise but we lose single pulse information

We need a sensitive, compact, non interceptive detector between sections

Passive Cavity

... as beam intensity monitor





- Commissioning of the 35 MeV section relied on a ionization chamber for low current (<10 μA) pulse characterization
- *Ionization chambers cannot be easily installed and operated under vacuum (between accelerating sections)*
- Resonant cavities have been proposed as beam intensity (and position) monitors
- A dual cavity monitor has been introduced in medical linacs (*for dose delivery control*)[1]
- Resonant cavities in fundamental mode (TM010) are short and can be installed in vacuum
- *Are they sensitive enough ?*

[1] A. Leggieri *et al.*, "Real-Time Beam Monitor for Charged Particle Medical Accelerators", *IEEE Trans. on Nuc. Sci.*, vol.63, no.2, p.869.

Passive Cavity

Analytical model

An compact analytical model has been developed in (2), to compute the RF power extracted from a resonant cavity

$$P = \underbrace{(a_1)^2}_{\text{Beam}} \underbrace{(R_s/Q_0)T^2 Q_{load}}_{\text{Cavity}} \underbrace{\frac{\beta}{(1+\beta)}}_{\text{Coupling}} \underbrace{\cos^2\varphi}_{\text{Detuning}}$$

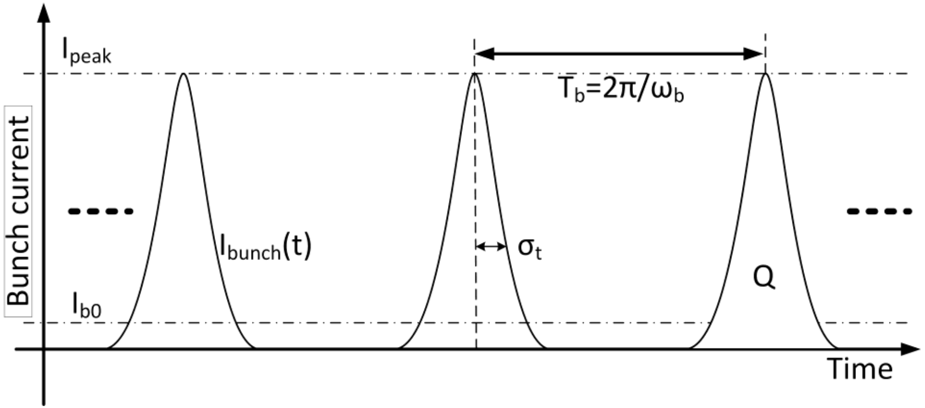
- RF output power «P» is proportional to beam current through «a_1», the first term of Fourier series expansion of the beam current signal,
- to the cavity shunt impedance «R_s», transit time factor «T», quality factors «Q_0» and «Q_{load}», RF coupling «β»
- *Extracted power is also sensitive to the detuning of the cavity (cosine term)*

[2] T. R. Pusch *et al.*, "Measuring the intensity and position of a pA electron beam with resonant cavities", *Phys. Rev. Accel. Beams*, vol. 15, p. 112801, Nov. 2012.

Passive Cavity

Analytical model (2)

$$I_{bunch}(t) = I_{peak} \exp \frac{t^2}{2\sigma_t^2} = \frac{Q}{\sqrt{2\pi}\sigma_t} \exp \frac{t^2}{2\sigma_t^2}$$



Fourier series expansion

$$I_{bunch} = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(n\omega_b t)$$

$$a_n = 2I_{peak}\sqrt{2\pi}\,\sigma_t/T_b \exp\left(-\frac{n^2\omega_b^2\sigma_t^2}{2}\right) = 2\mathrm{I_{b0}}\exp\left(-\frac{\mathrm{n}^2\omega_b^2\sigma_t^2}{2}\right); n = 0,1,2,3,\ldots$$

If $\left(\frac{1}{\mathrm{n}\omega_b}\right) \gg \sigma_t, \exp\left(-\frac{n^2\omega_b^2\sigma_t^2}{2}\right)$ $\quad I_{b0} = I_{peak}\sqrt{2\pi}\,\sigma_t/T_b$

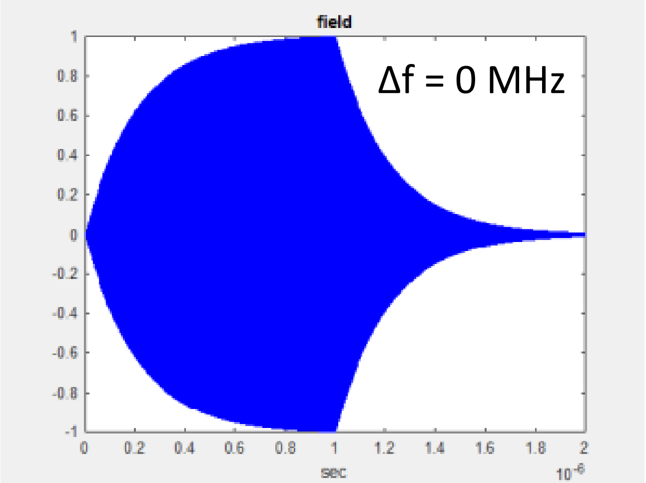
$$\boxed{a_1 = 2I_{b0}\exp(-\frac{\omega_b^2\sigma_t^2}{2})}$$

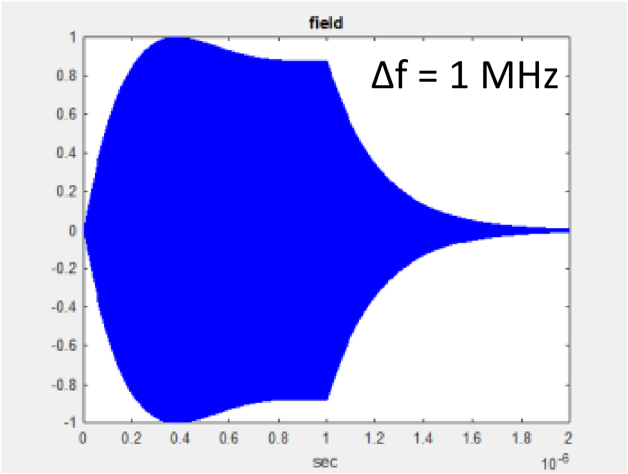
Passive Cavity

Time response from analytical model

Passive cavity response to a 1 μs pulse with T_b = 333.6 ps and σ_t = 8.5° RF
(Cavity parameters: Q_0 = 4000, β=1, f_0 = 2997.92 MHz)

$$G = \frac{\frac{\omega_0}{Q_{load}} s}{s^2 + \frac{\omega_0}{Q_{load}} + \omega_0^2}$$





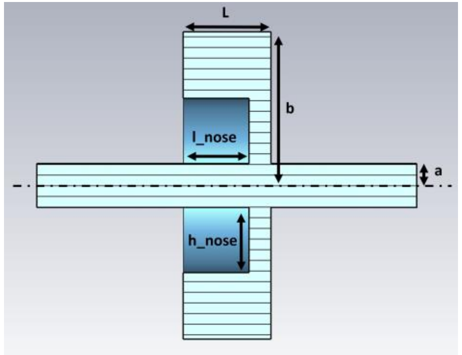
$$\cos^2 \varphi = 1[(1 + 4Q_{load}^2 \left(\frac{\Delta f}{f_0}\right)^2]$$

Passive Cavity - Design and Simulation

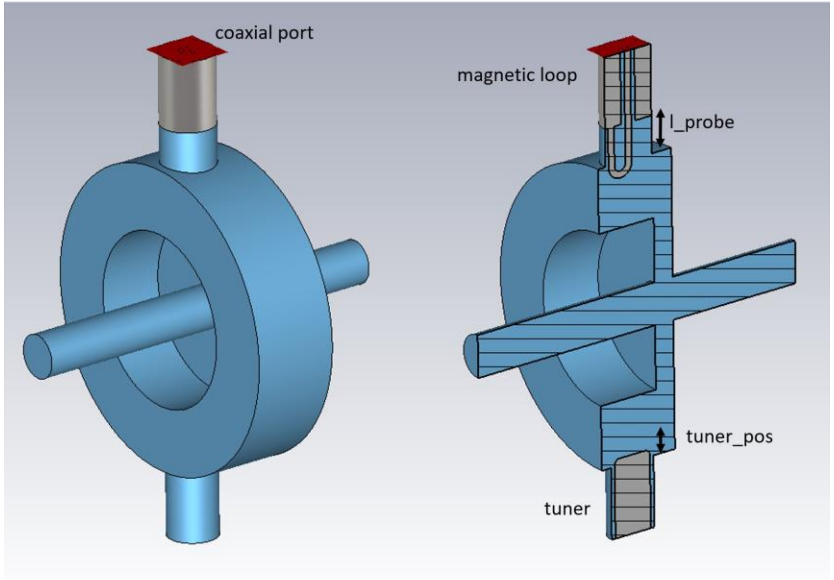
Reentrant cavity (CST MWstudio)

Design goal: reentrant cavity 12 mm long with t_{fill} between 100 and 200 ns, maximizing shunt impedance and transit time factor

- Simulations used eigenmmode and frequency domain solvers
- Tuning screw and coupling loop are included in the simulation. Material is copper

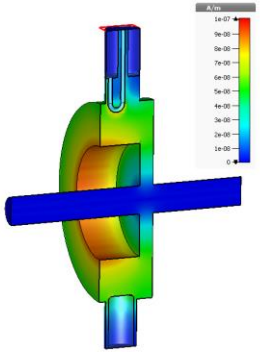


Param.	Value	Notes
a	3 mm	Beam pipe radius
b	21 mm	Cavity radius
l_nose	9 mm	Reentrant depth
h_nose	9 mm	Reentrant height
L	*12 mm*	*Cavity Length*



Passive Cavity - Design and Simulation

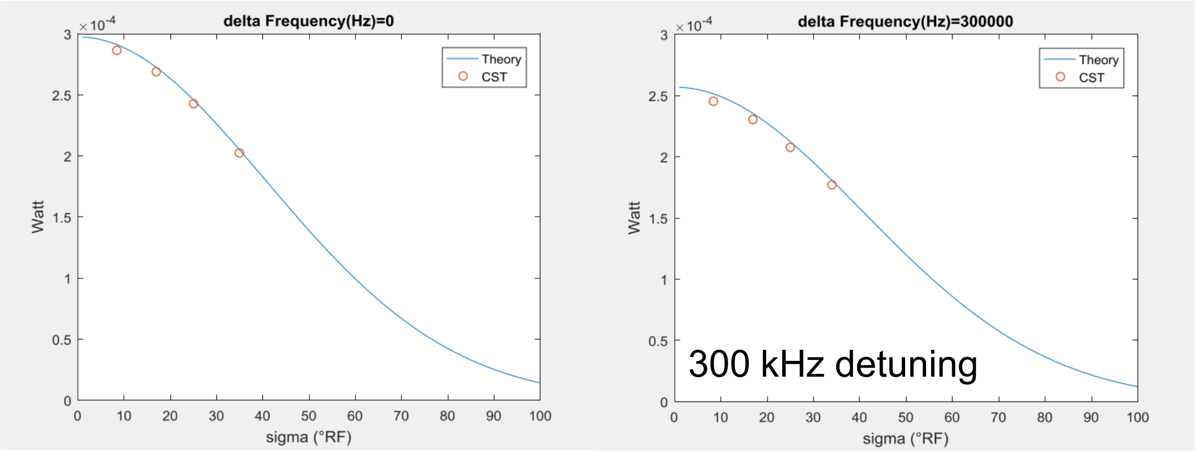
Reentrant cavity (CST PIC solver)



PIC solver has been used to compare validate the analytical model

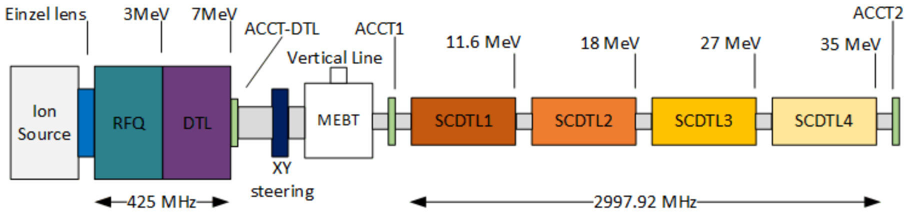
- Beam input: gaussian pulse train with T_B = 1 / (2998 MHz)
- Simulation of 300 kHz detuning

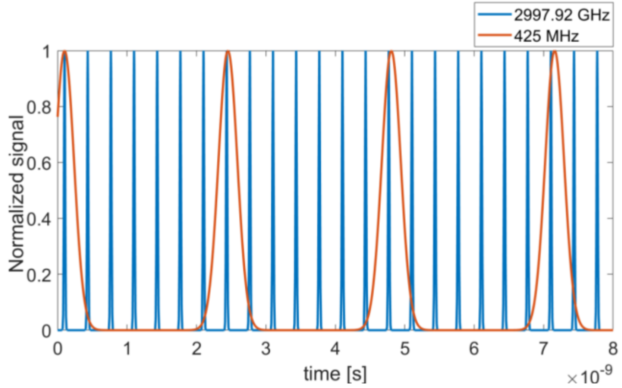
Parameter	Value
Frequency	2998 MHz
Q_0	4261
R_S/Q	63
R_S	270 kΩ
T	*0.87*

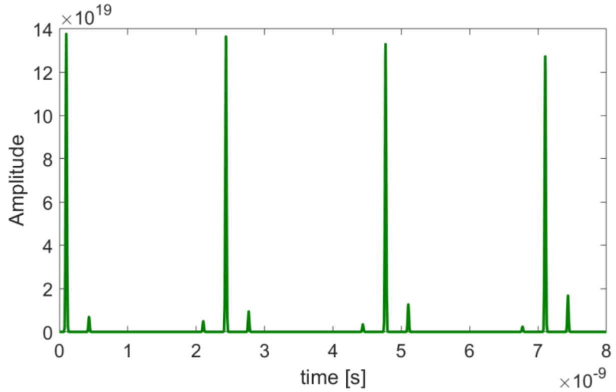


Passive Cavity - Design and Simulation

Effect of micro-bunch irregularities





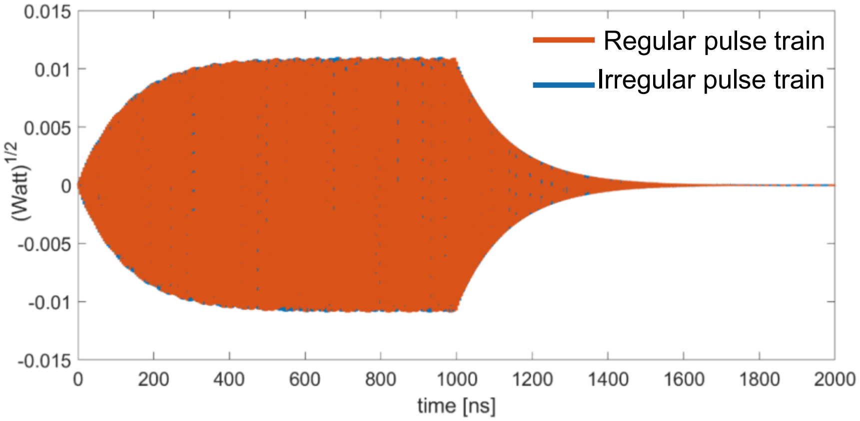


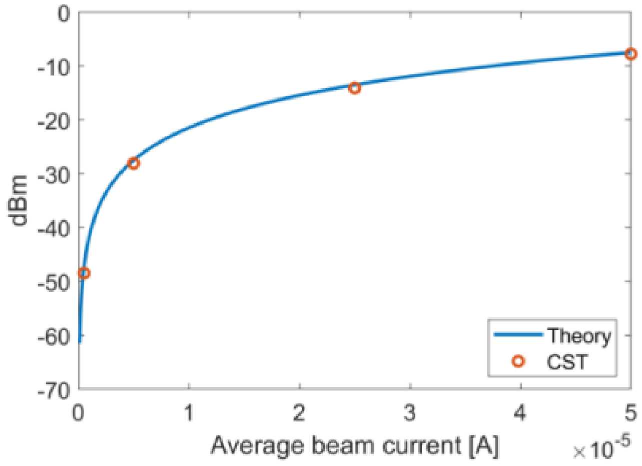
- ❖ The analytical model was developed for a regular pulse micro-structure (all bunches equal)
- ❖ TOP-IMPLART pulse microstructure reflects the non integer relation between the 425 MHz injector frequency and the 2997.92 MHz booster frequency
- ❖ RF phase between injector and booster slides continuously
- ❖ Charge contents in each micro-bunch is different
- ❖ *Will the cavity still measure correctly pulse current in this condition ?*

Passive Cavity - Design and Simulation

Simulation of irregularities

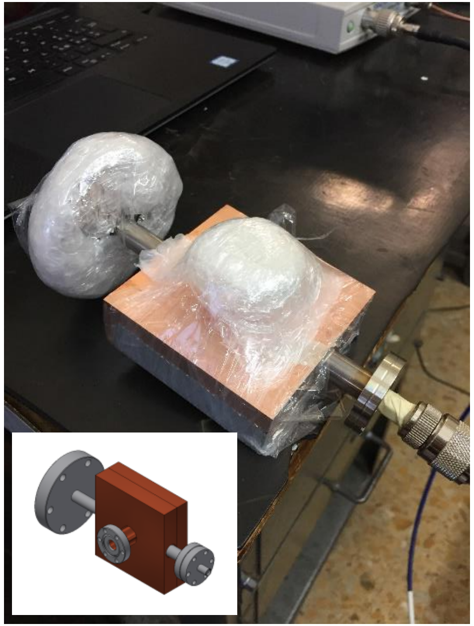
- Cavity response to a beam with empty bunches has been simulated (irregular gaussian pulse train)
- Cavity output signal is still proportional (as described by the analytical model) to the average beam current



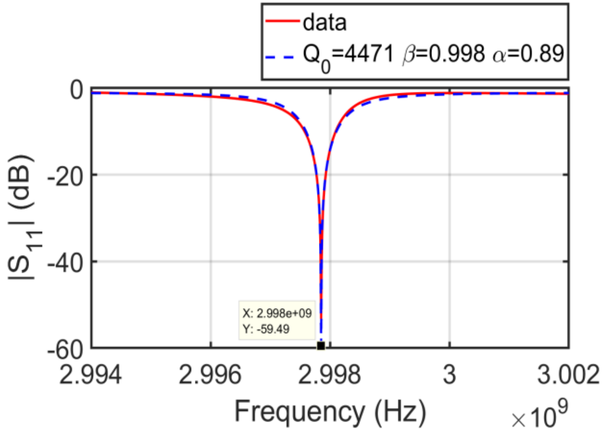


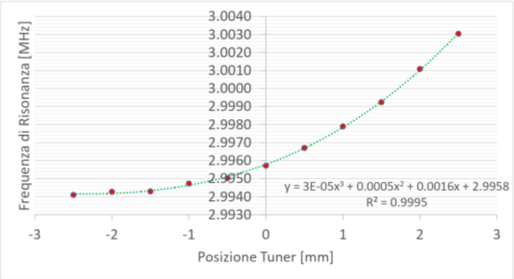
Passive Cavity - Prototype

S11 Mesurement (VNA)



Parameter	Value (sim)	Value(proto)
Frequency	2998 MHz	2997.85 MHz
Q_0	4261	4471
R_S/Q	63	-
R_S	270 kΩ	-
T	*0.87*	-
β	*0.994*	*0.997*





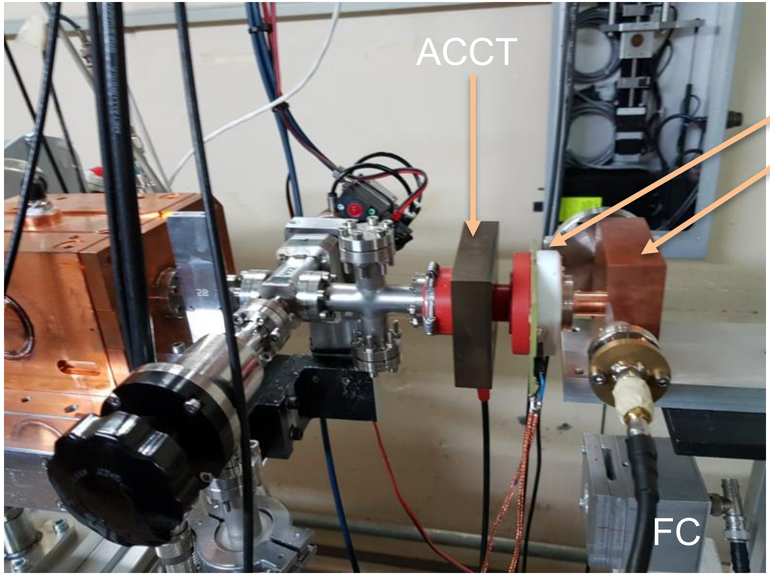
- Prototype measurements matches simulations
- Frequency tuning exceed 10 MHz

Passive Cavity installation

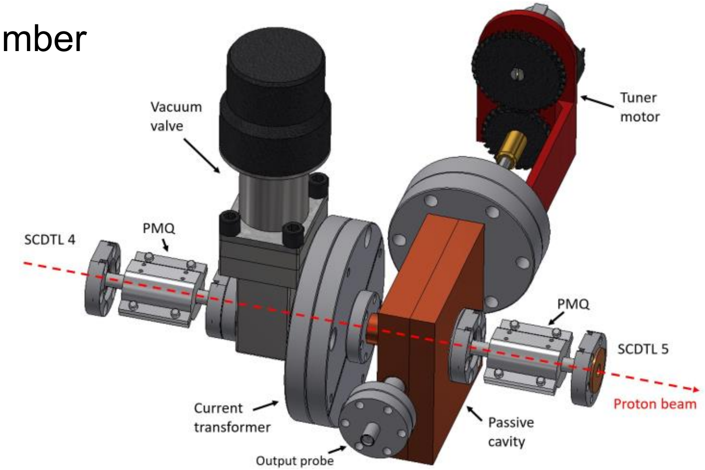
Testing the cavity on TOP IMPLART beam

The cavity has been tested on the proton beam at the output of the 35 MeV section in air

Layout of the inter-section beam current diagnostics under review: ACCT followed by a passive cavity



Ionization Chamber
Passive cavity

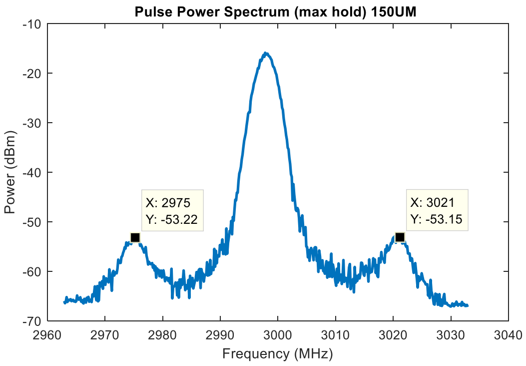


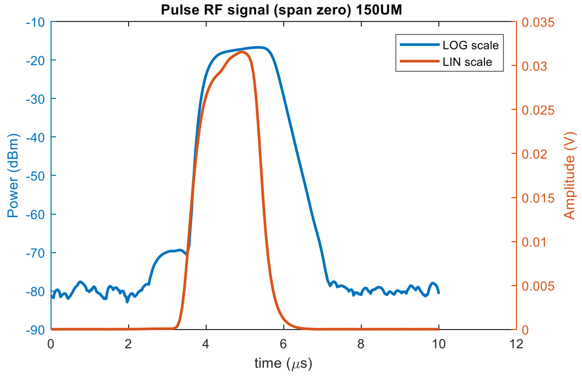
Passive Cavity Measurements

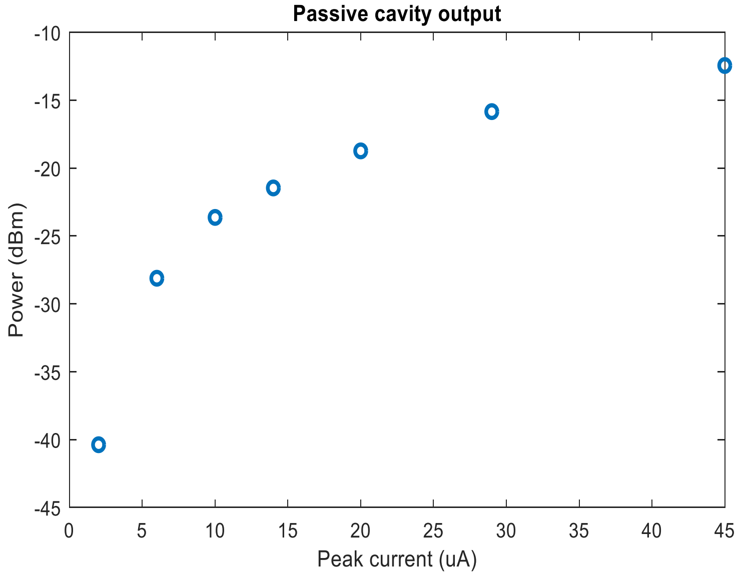
Characterization on Spectrum Analyzer

Two measurement classes have been carried out:

- ❖ Spectrum of the output signal (max-hold). The spectrum contains two side-lobes due to the 425 MHz component in the beam (also predicted by simulations)
- ❖ RF pulse power (span zero)





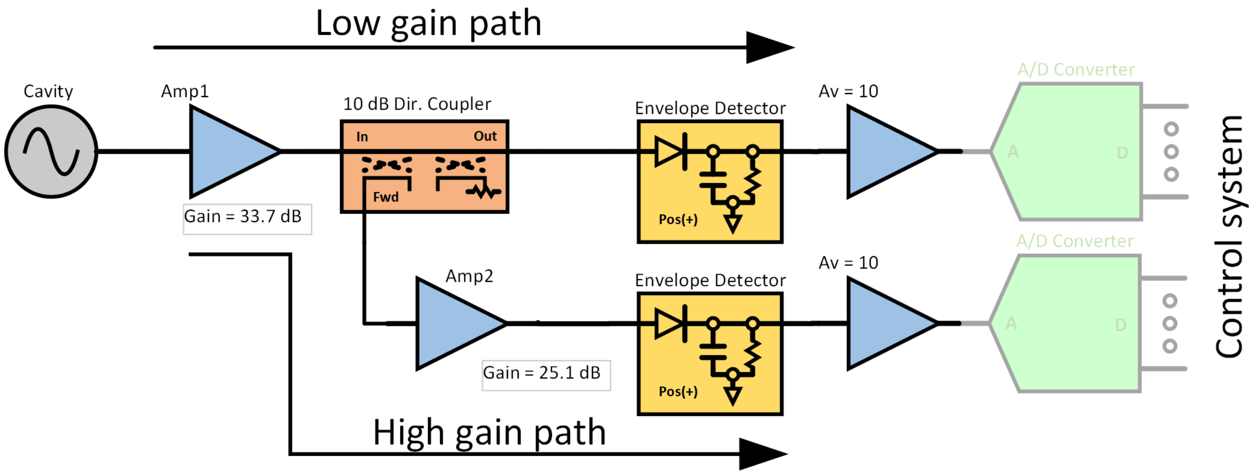


Pulse current is computed from the charge measurement obtained with the ionization chamber

Passive Cavity signal amplification

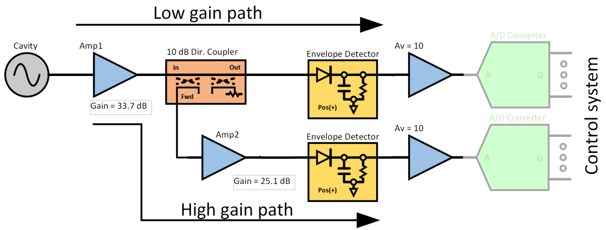
Dual gain envelope detector

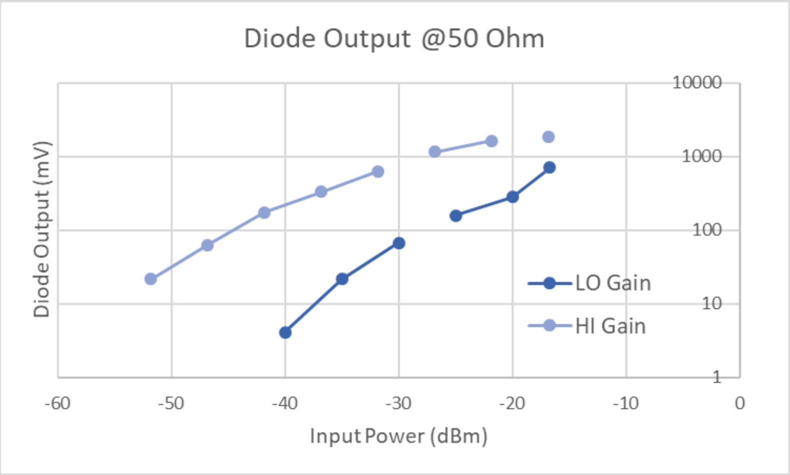
- Cavity signal is detected using Zero Bias Schottky Diodes (CPDETLS-4000)
- Detector diodes have a dynamic range of 20 dB
- Two amplification paths are needed to cover the 40 dB signal range

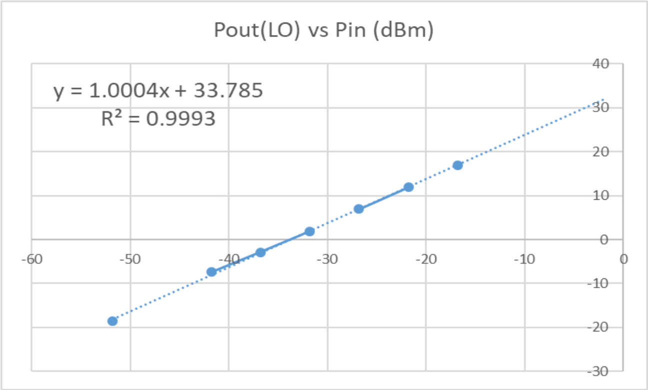


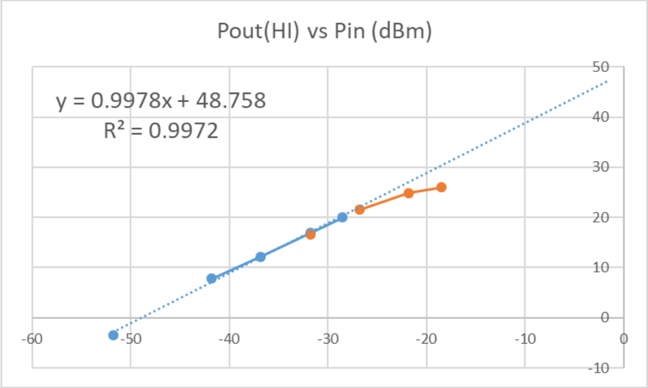
Passive Cavity signal amplification

Detector characterization





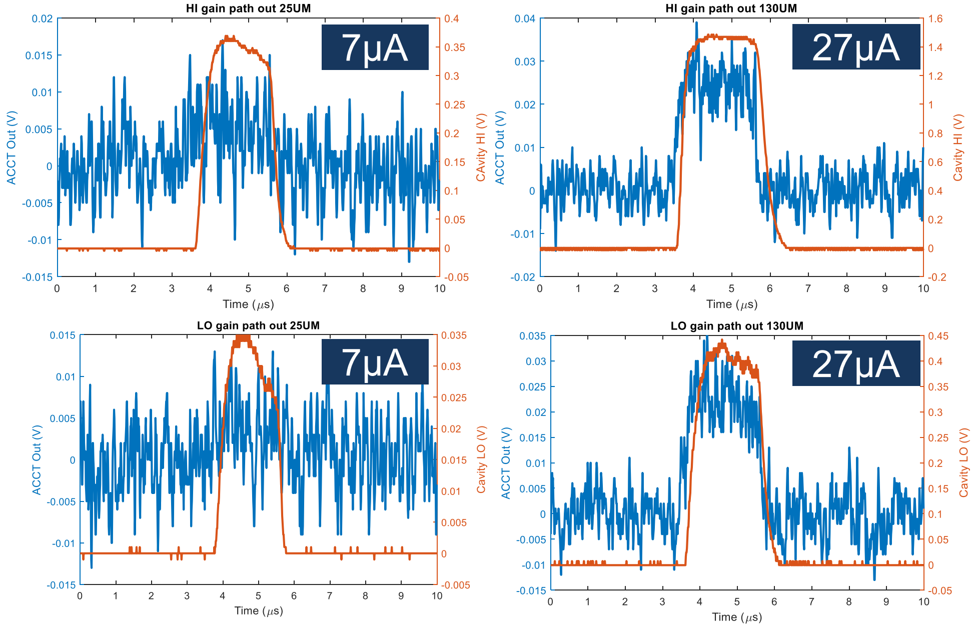


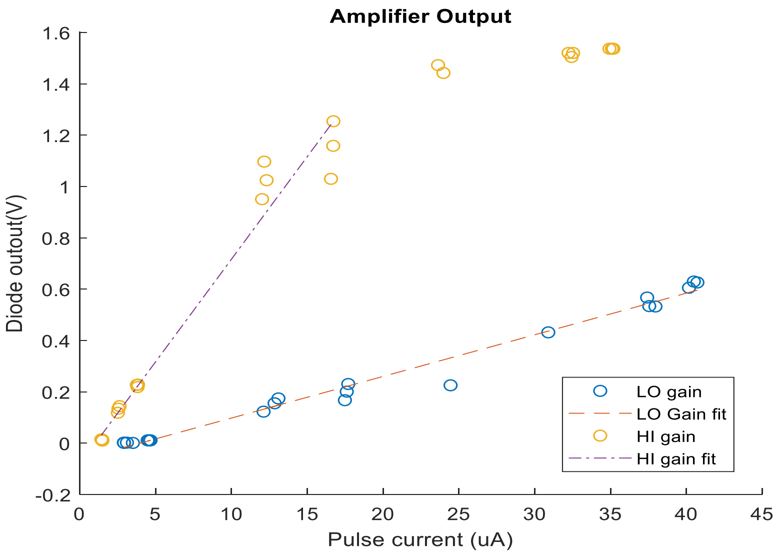


Complete system measurements

Diode outputs connected to a dual channel 8 bit digitizer (50 Ω)

The amplifying chain has been tested (10x amplifiers are not yet available)

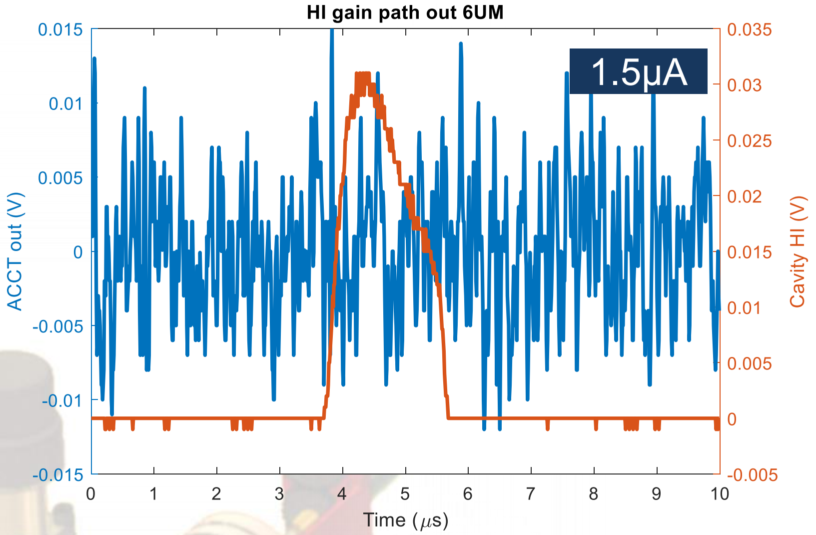




f(x)=p1x+p2	LO	HI
p1	0.016	0.080
p2	-0.06	-0.08

Conclusion

- Pulse currents in the order of 1 µA are needed for TOP-IMPLART medical beam
- A non-interceptive, compact and vacuum-compatible diagnostics is needed
- A beam current intensity monitor based on a resonant cavity has been designed and realized
- Preliminary measurement have been presented
- *Cavity tests under vacuum with upgraded electronics are underway*



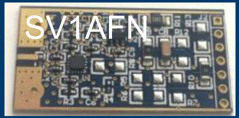
Thank you for attention

Q&A

TOP-IMPLART Program

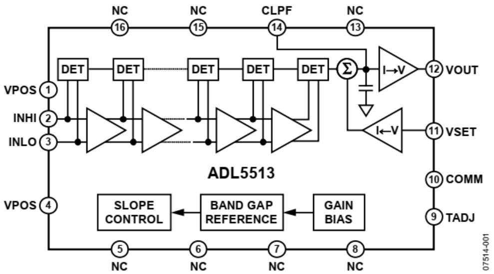
Support material

New Electronics – Sneak Peek



Under evaluation ADL5513 Power Detector

FUNCTIONAL BLOCK DIAGRAM



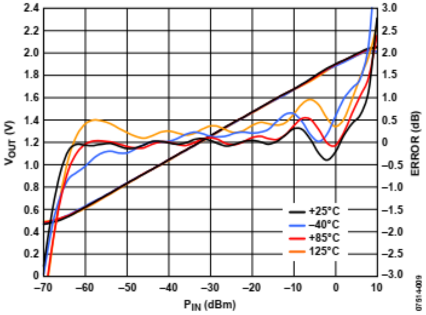
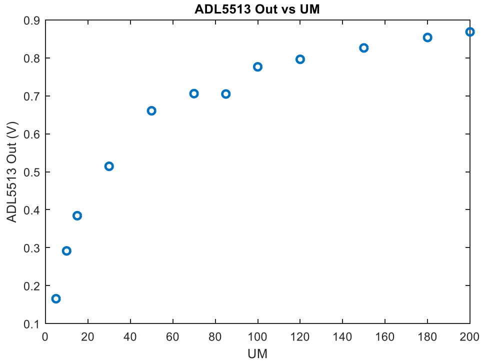
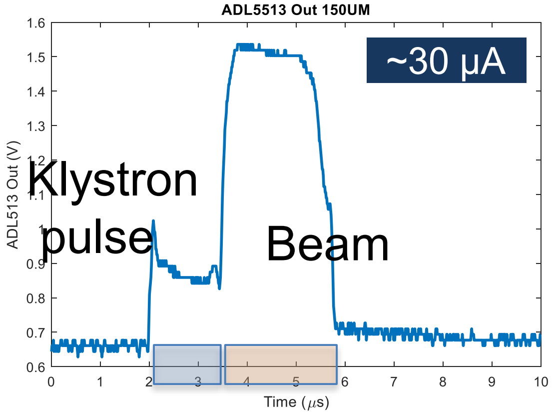


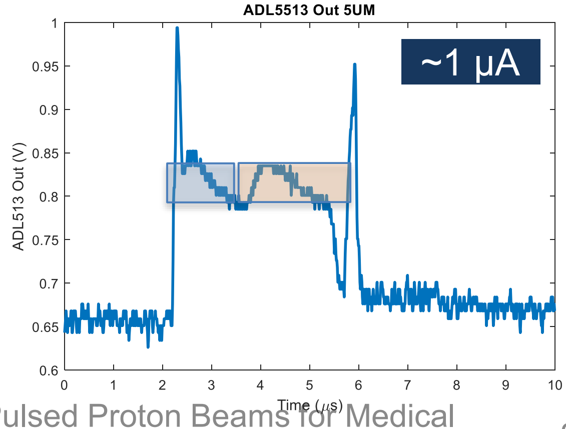
Figure 10. V_{OUT} and Log Conformance vs. Input Amplitude at 2600 MHz, Typical Device, V_{TADJ} = 0.83 V

FEATURES

Wide bandwidth: 1 MHz to 4 GHz
80 dB dynamic range (±3 dB)
Constant dynamic range over frequency
Stability over –40°C to +85°C temperature range: ±0.5 dB
Operating temperature range: –40°C to +125°C
Sensitivity: –70 dBm
Low noise measurement/controller output (VOUT)
Pulse response time: 21 ns/20 ns (fall/rise)
Single-supply operation: 2.7 V to 5.5 V at 31 mA
Power-down feature: 1 mW at 5 V
Small footprint LFCSP
Fabricated using high speed SiGe process

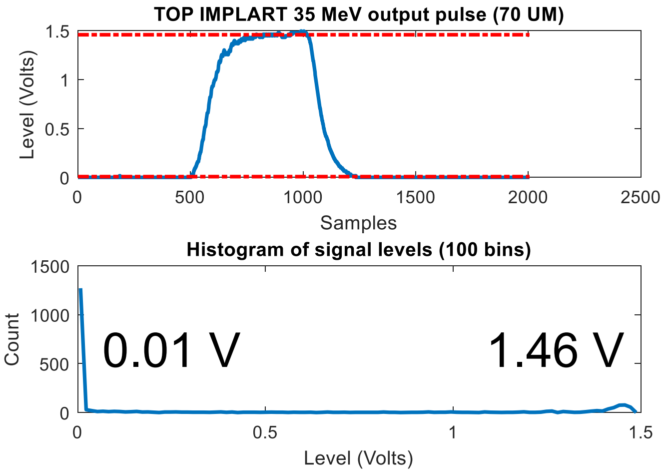


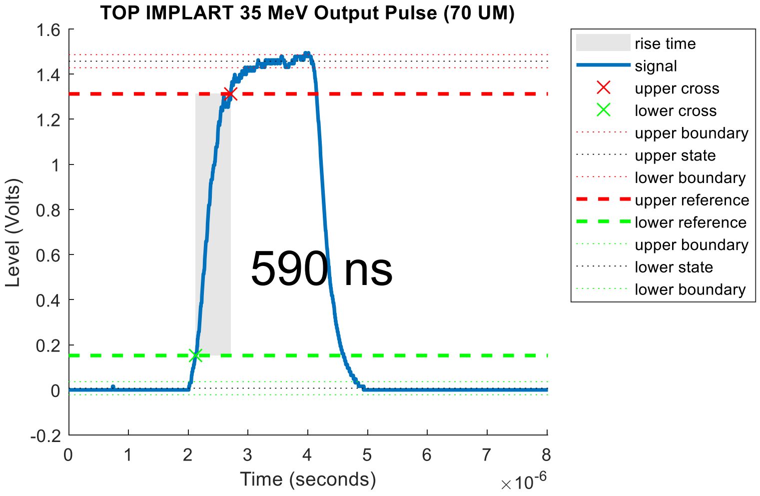




TOP-IMPLART Proton beam

Pulse analysis methods (1)





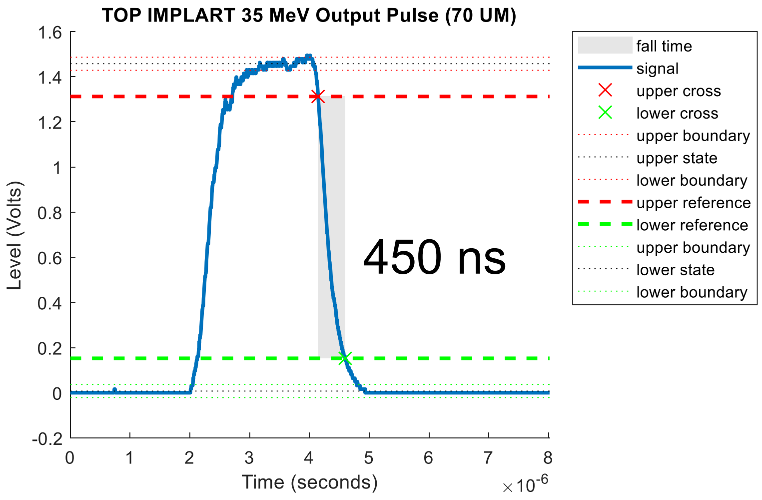
Pulse height (V, A) determined using the histogram method(1).

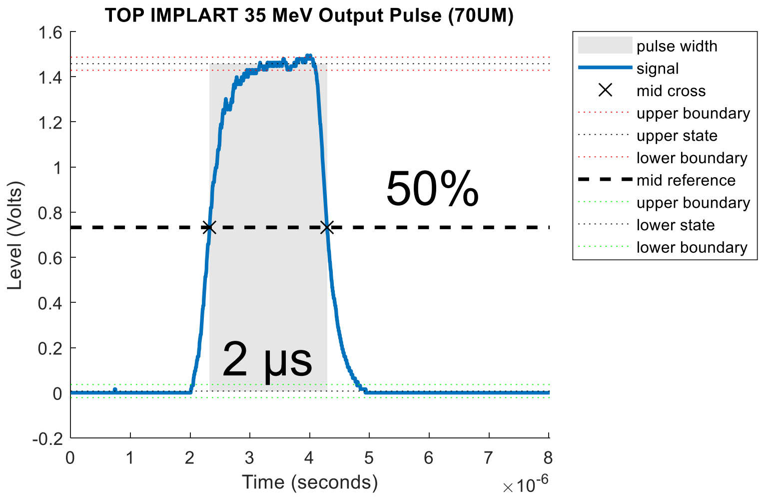
Rise time is time difference between 10% and 90% of amplitude.

[1] *IEEE® Standard on Transitions, Pulses, and Related Waveforms*, IEEE Standard 181, 2003, pp. 15–17.

TOP-IMPLART Proton beam

Pulse analysis methods (1)



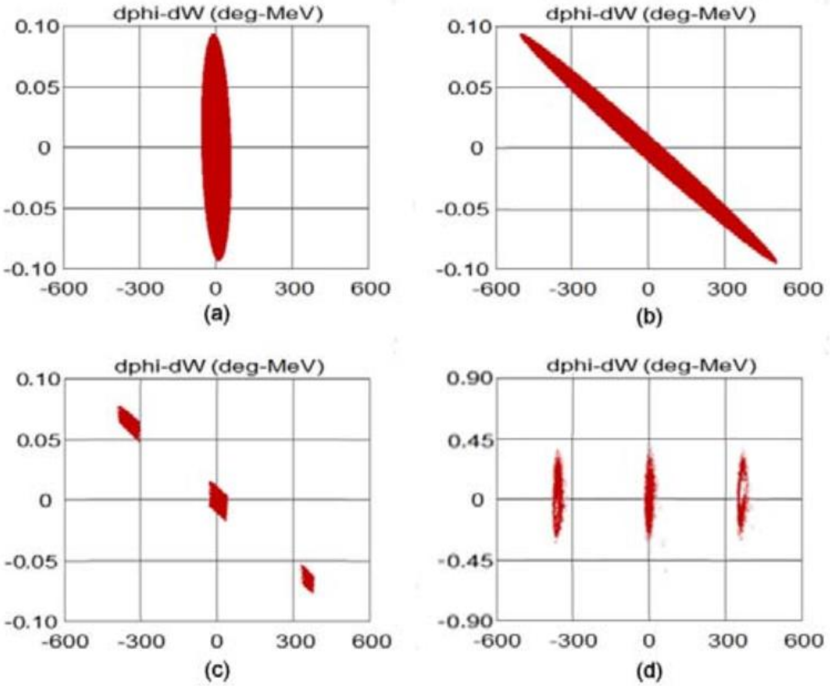


Fall time is time difference between 10% and 90% of amplitude.

Pulse width is computed at 50% of amplitude.

Passive Cavity - Design and Simulation

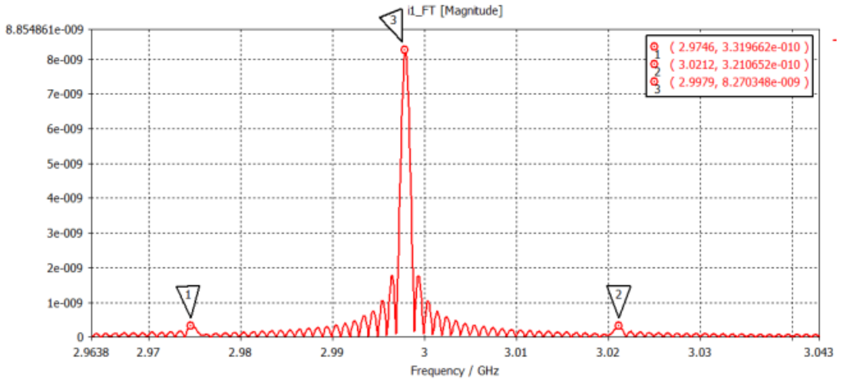
Bunch lenghtnening



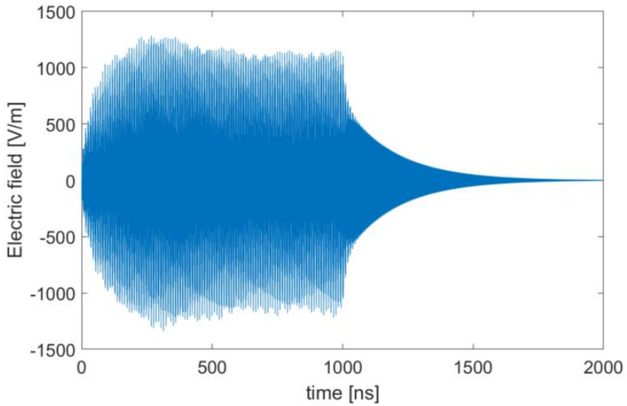
Passive Cavity - Design and Simulation

Transient simulation – field induced by particle beam

The cavity output to the TOP-IMPLART beam has been indirectly simulated. The spectrum of the electric field generated by the particles has been computed and given as input to CST.



Input spectrum

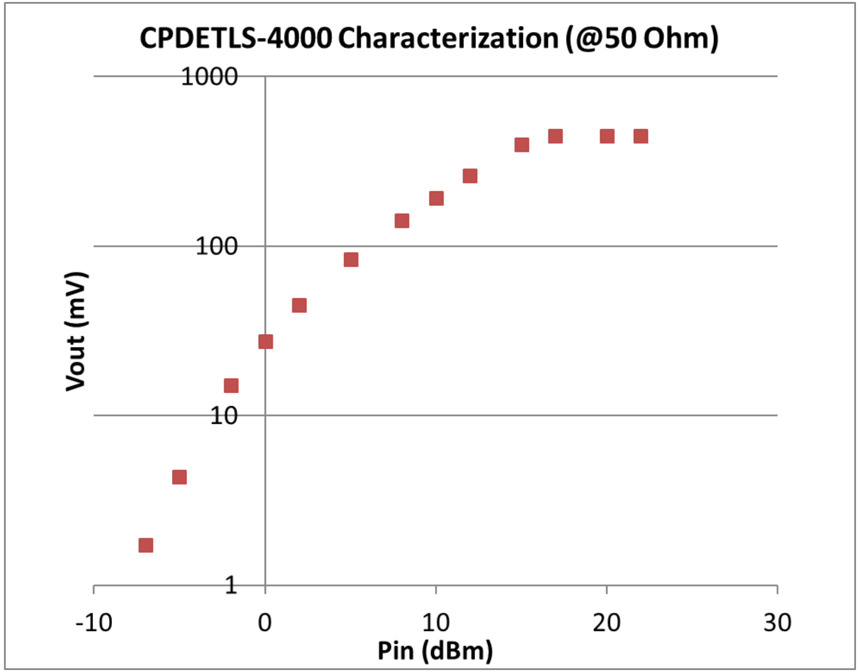


Cavity Output

CPDETLS-4000 Calibration

On a 50 Ohm load

- CPDETLS-4000 diode datasheet does not reports diode output for 50 Ohm load.
- The input power usable range for this diode is -7 dBm – 15 dBm.



<u>Features:</u>

- 10 MHz to 4 GHz Frequency Range
- Zero Bias Schottky
- Large Signal Power Detector, greater than -10 dBm
- +30 dBm Max Input Signal
- 100 pF Video Capacitance
- Operating Temperature: -20°C to 70°C
- Storage Temperature: -40°C to 85°C

Passive Cavity - Design and Simulation

Bunch lenghtnening in the MEBT