A Next Step in Proton Therapy:
Boosting to 350 MeV
for Therapy and Radiography Applications

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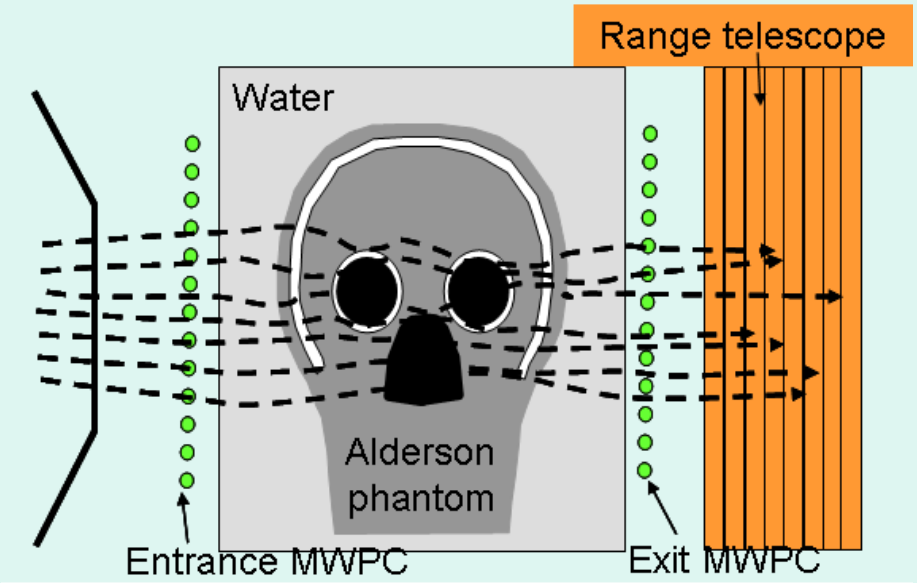
TERA
Fondazione per Adroterapia Oncologica

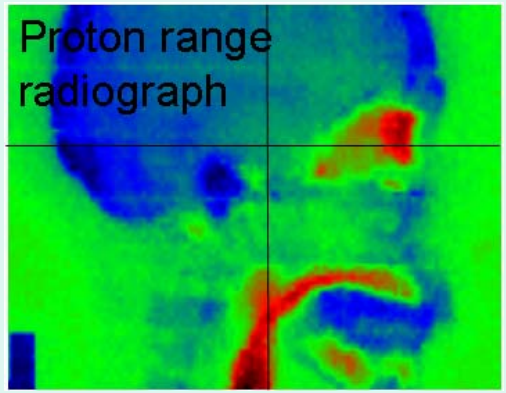
Current limitations in proton therapy:

- Where is the tumour ? → imaging
- What is the range ? → **radiography** (PET, prompt γ,…)
- Sharpen the dose distribution: → **high energy**

Proton radiography



U.Scheider and E.Pedroni Med. Phys. 22(1994), 353



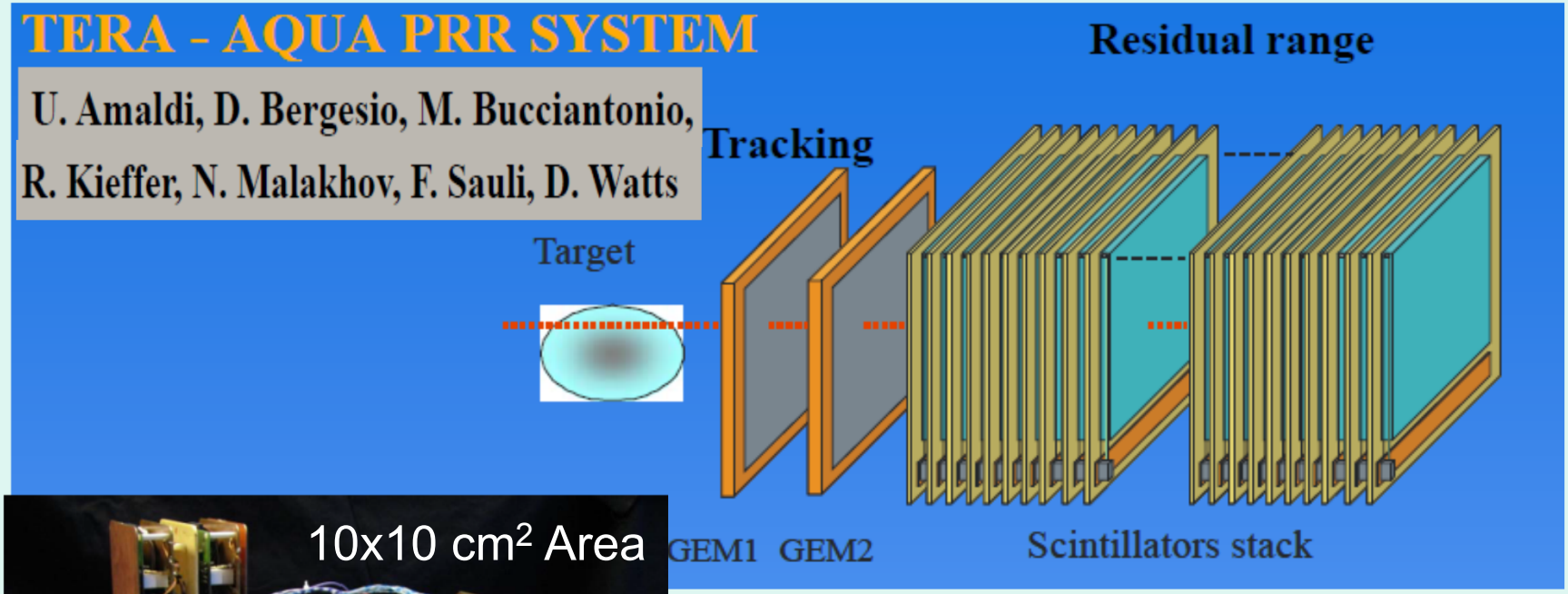
Note:

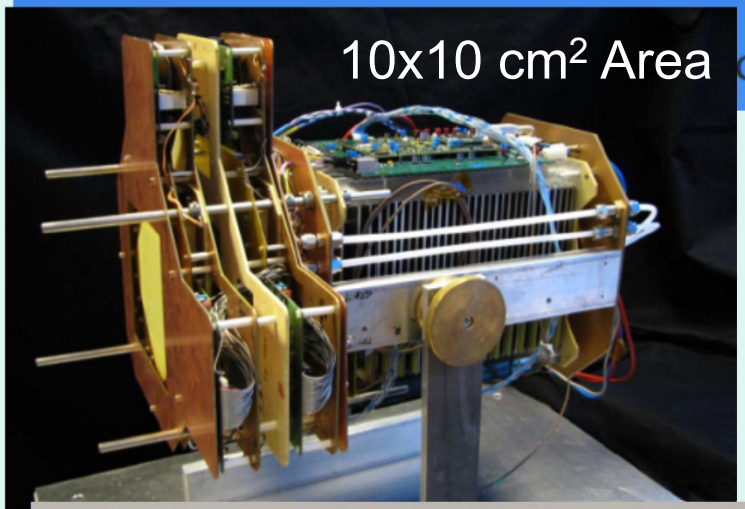
Higher energy gives sharper images

(Simulated proton radiograph from:

Jao Seco, Nick Depauw, Marta Dias, MGH)

Proton radiography



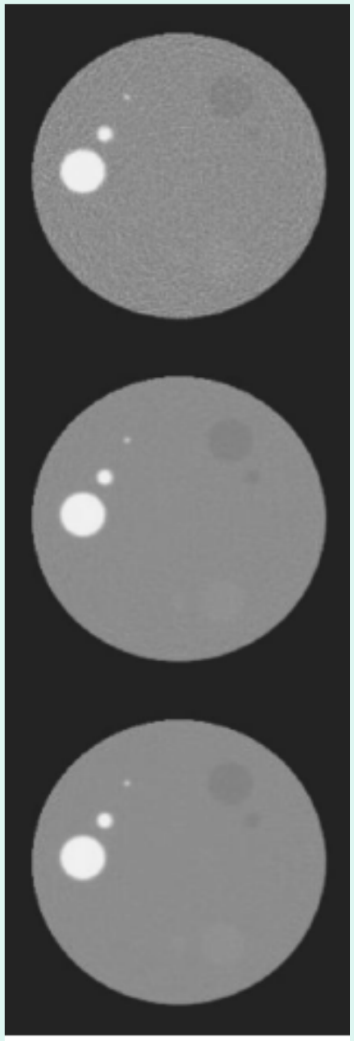


U. Amaldi et al, Nucl. Instr. and Meth. A629(2011)337

In construction:

- Larger area: 30x30 cm^2
- 48 scintillators
- Faster readout

Proton radiography



0.16 mGy

1.6 mGy

3.1 mGy

Proton tomography

Schulte et al., Med Phys 32 (2005) 1035

- Directly measures proton stopping power
- Very low dose to patient
- Many beam directions needed

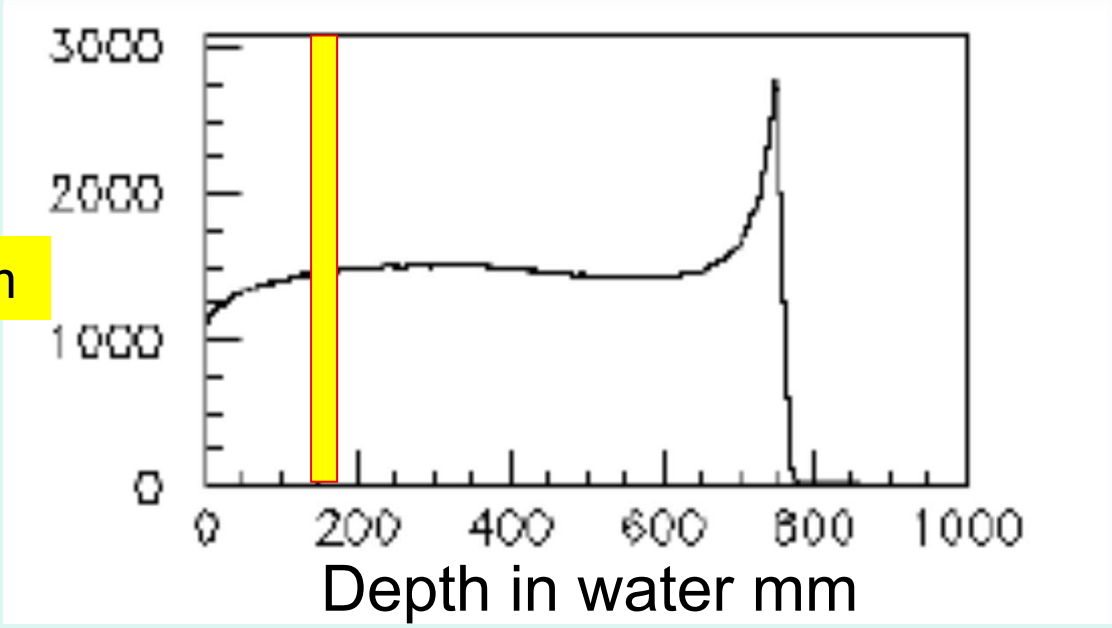
  => high energy needed

  => gantry needed

sharp lateral penumbra

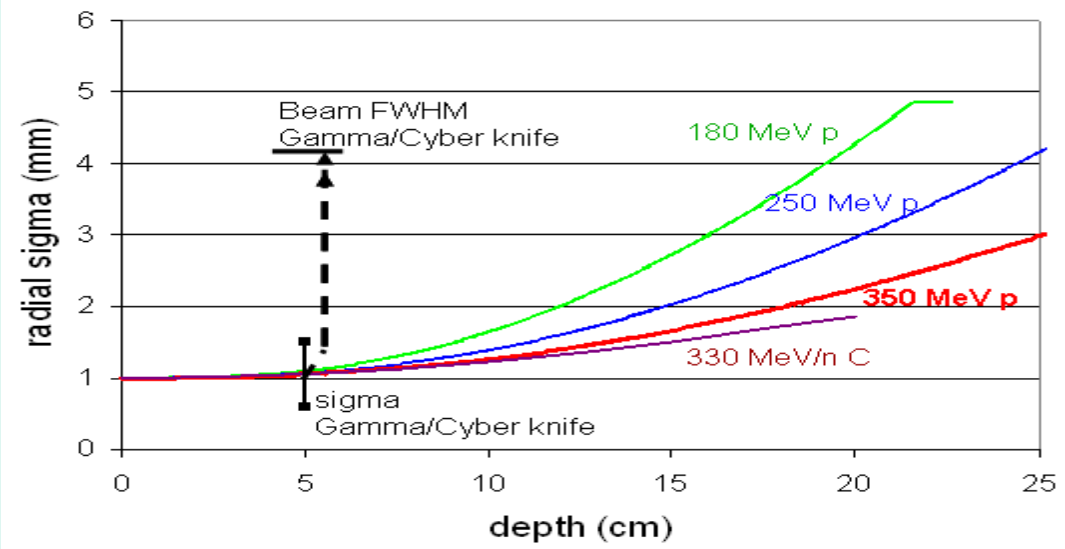
Depth dose curve, 350 MeV protons

$dE/dx \approx 3.5$ MeV/cm



- Shoot-through technique
- Stereotactic treatment
- At small target volumes, the integral dose to NT is not worse than of photons (work in progress)

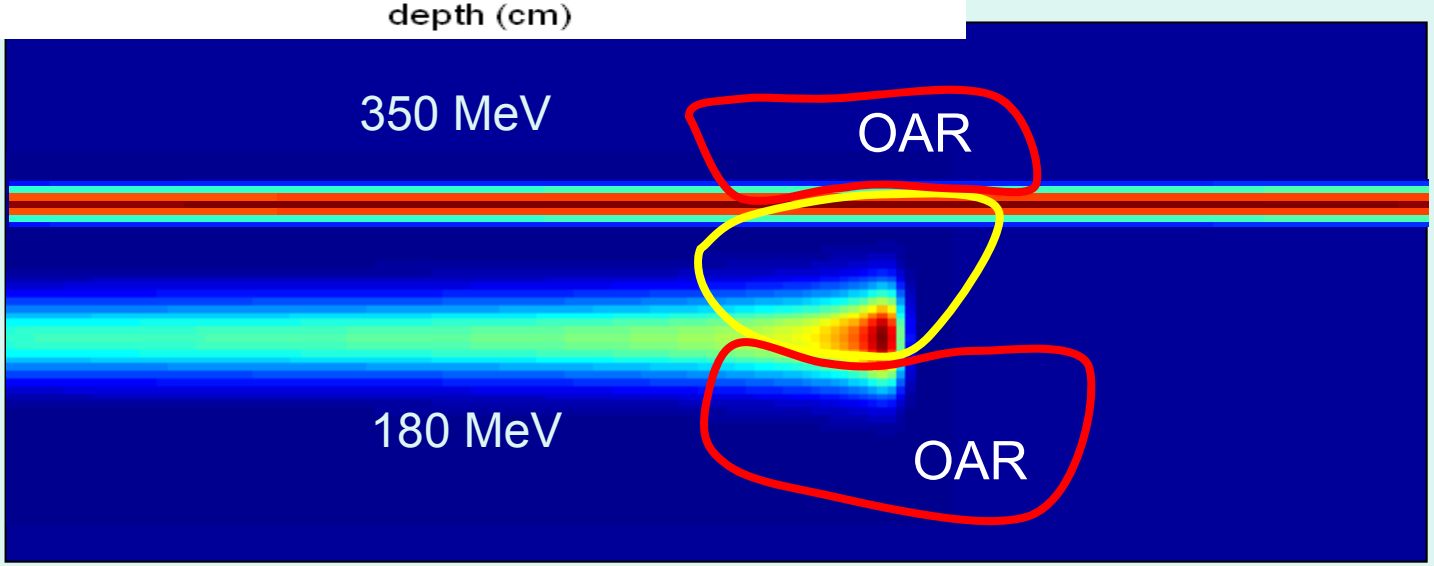
sharp lateral penumbra



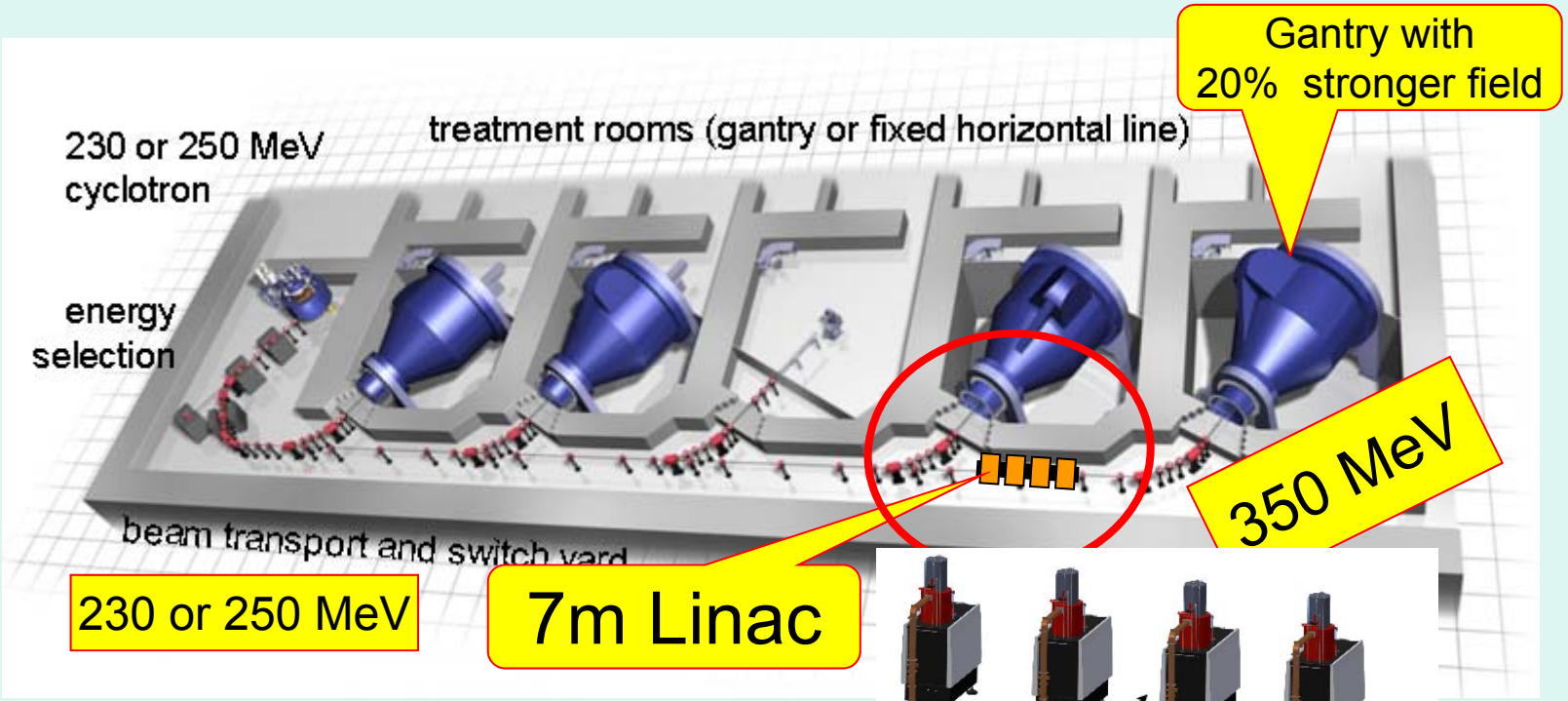
Therapy applications:

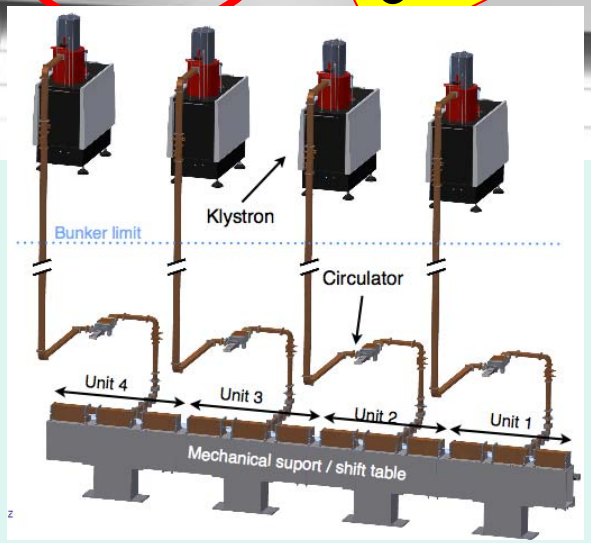
-(stereo tactic) treatment of **small lesions** (few cc)

-**sharpen edge** of dose distrib.



Upgrade for high energy





Linac based on existing
TERA design of CCL linac

Gradient: 25 MV/m
=> 100 MeV needs effectively 7 m

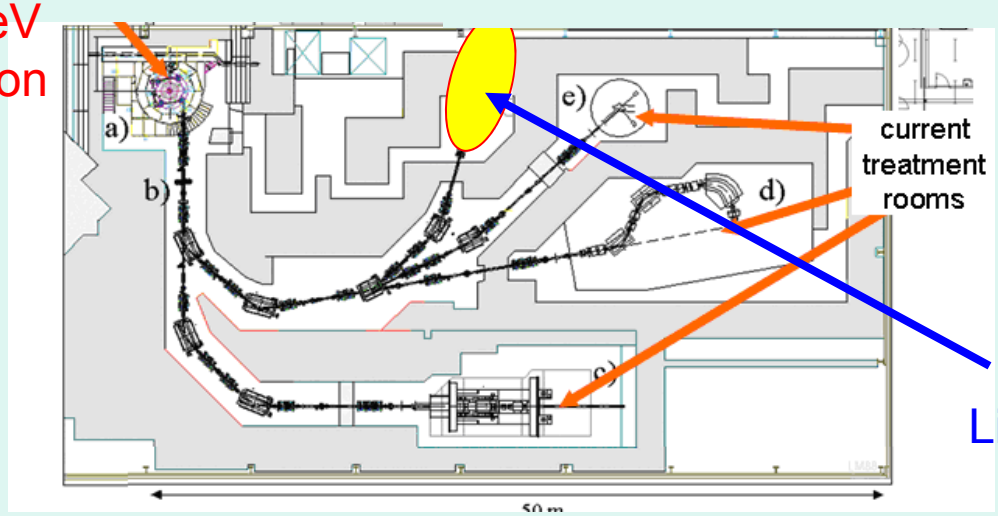
Boosting to 350 MeV at PSI

ImPulse project PSI:

In collaboration with TERA

Linac for boosting from 250 to 350 MeV

250 MeV cyclotron

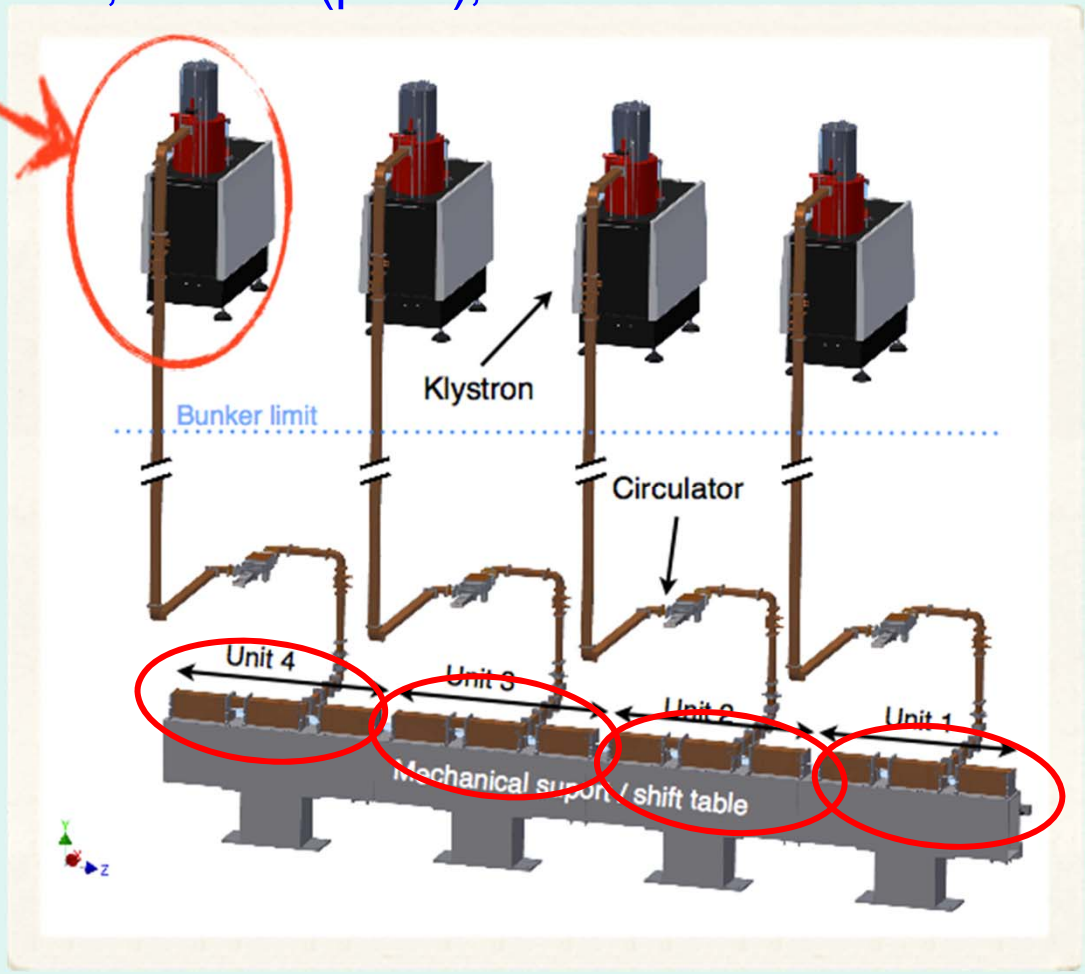


Linac location if gantry-3 accepts 350 MeV

Linac 250-350 MeV

4 independent units of 25 MeV

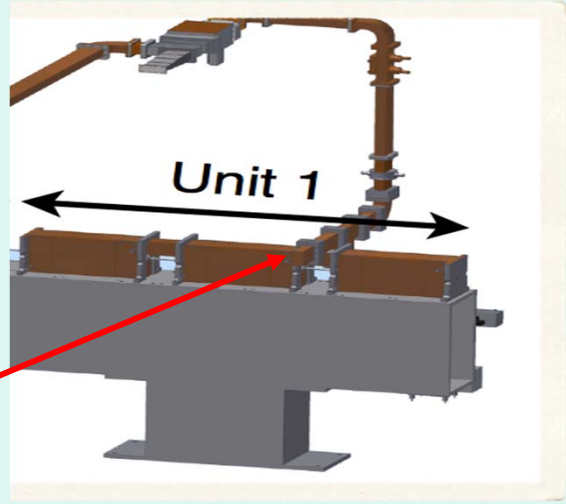
RF pro unit: 3 GHz, 10 MW (peak), 120 kVA



Linac 250-350 MeV

LInear **BO**oster concept from TERA:

4 independent units of 25 MeV:

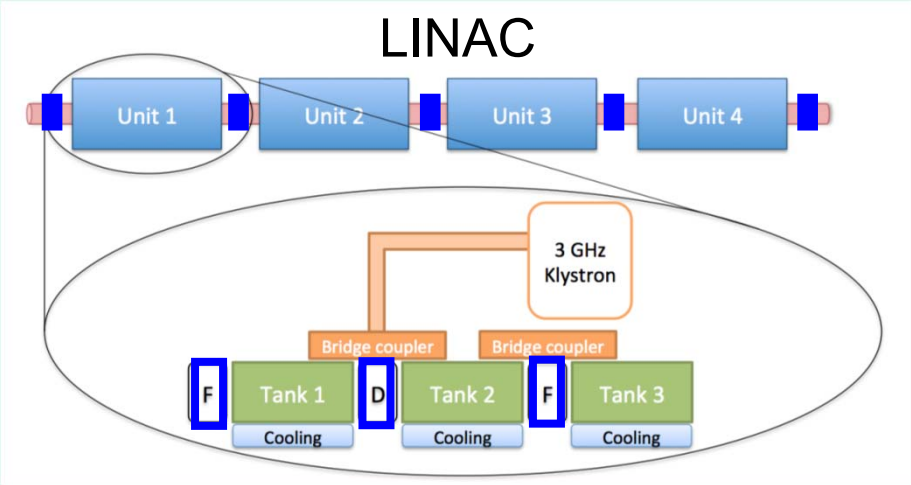


Per unit:

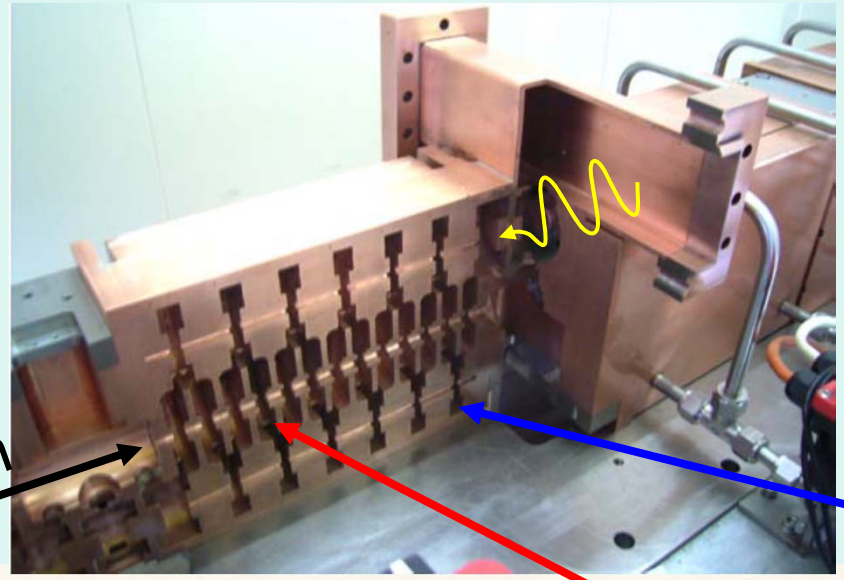
3 Tanks

Bridge coupler

Focusing in between tanks



Coupled Cavity Linac

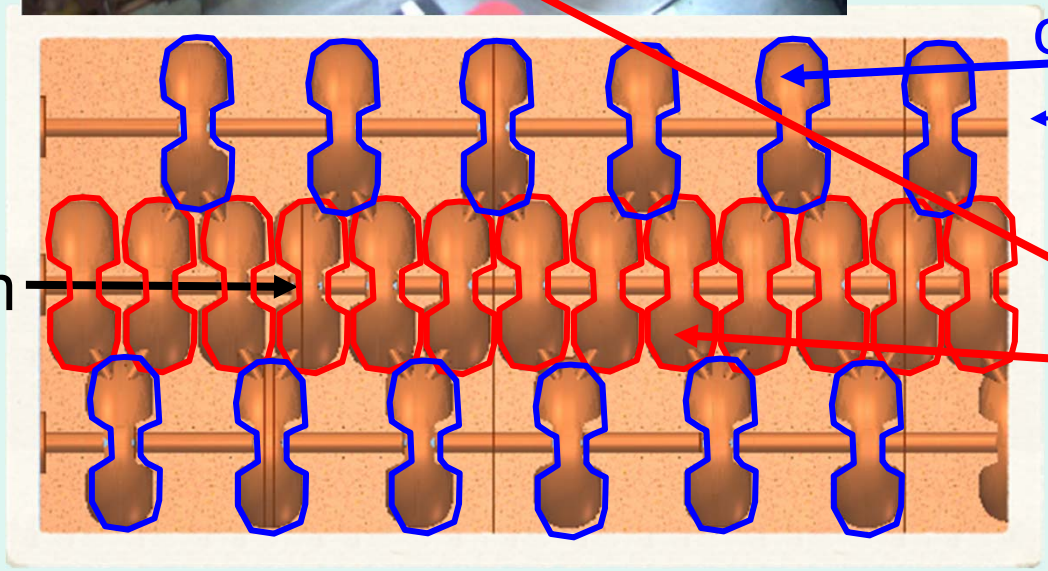


Beam

1 tank:

Normal conducting copper
Standing wave
π/2 mode
3 GHz: strong E field possible

coupling cavities



Beam

Accelerating Cavities (12)

Experience with 3 GHz CCL

C. De Martinis et al. , Nim A 681 (2012) 10–15

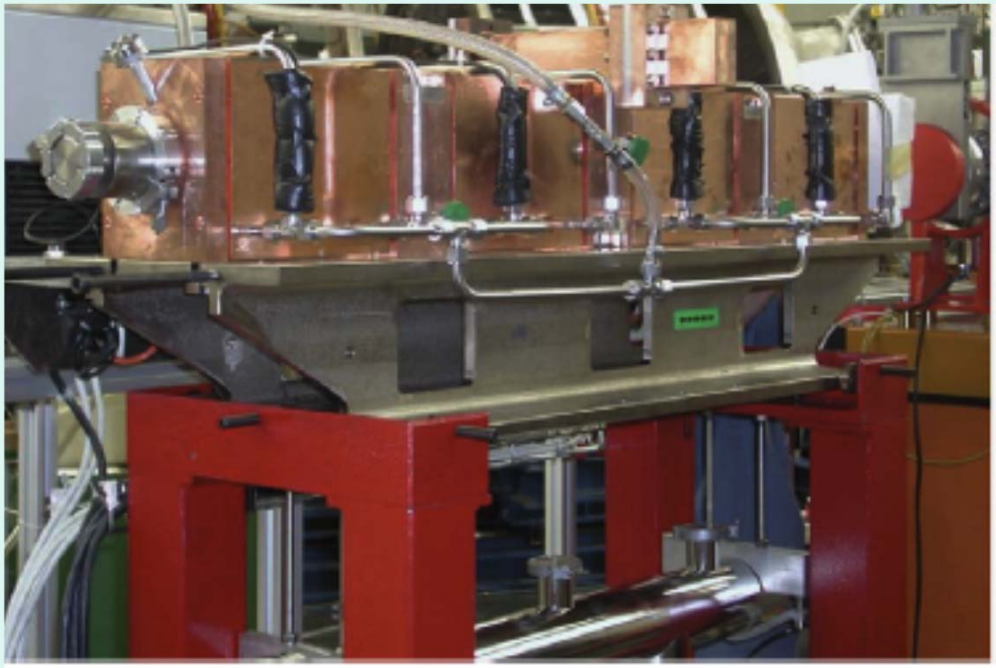


Fig. 4. The LIBO module installed in the LNS beam line.

Feasibility of proton acceleration (62 → 72 MeV) at 3 GHz in 1.3 m CCL has been demonstrated.

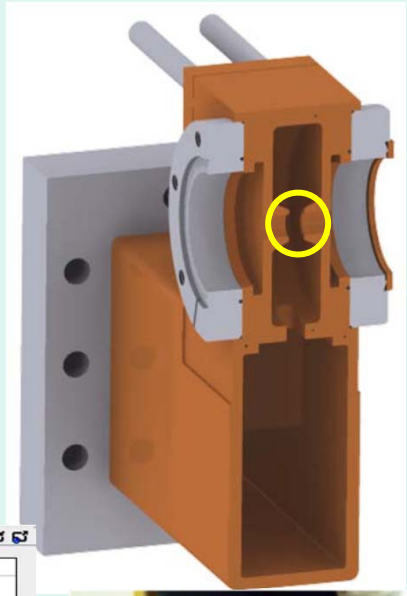
Used acceleration field:
E_0 = 27.5 MV/m
Needed peak power: 55 kW/cell

LIBO = LInac BOoster

Experience with 3 GHz CCL

3 GHz Test Cavity to find max E_0

- Single accelerating cell
- H-coupled to waveguide

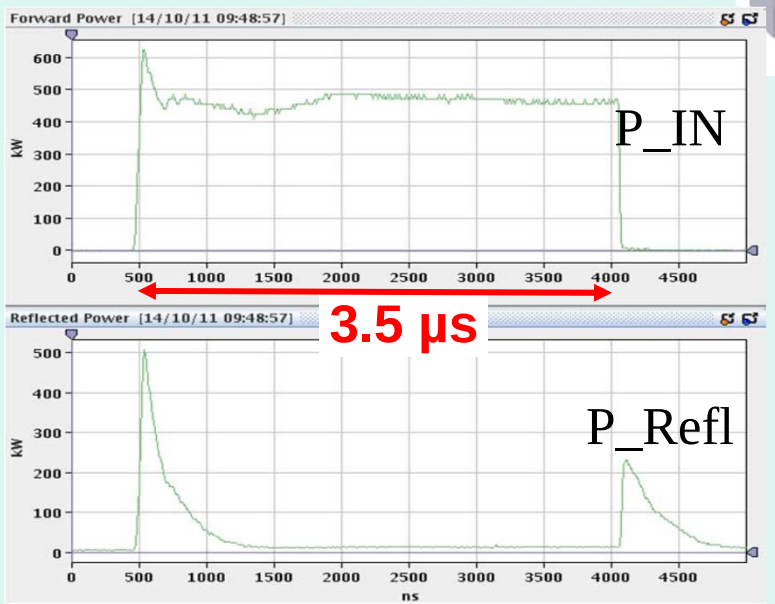


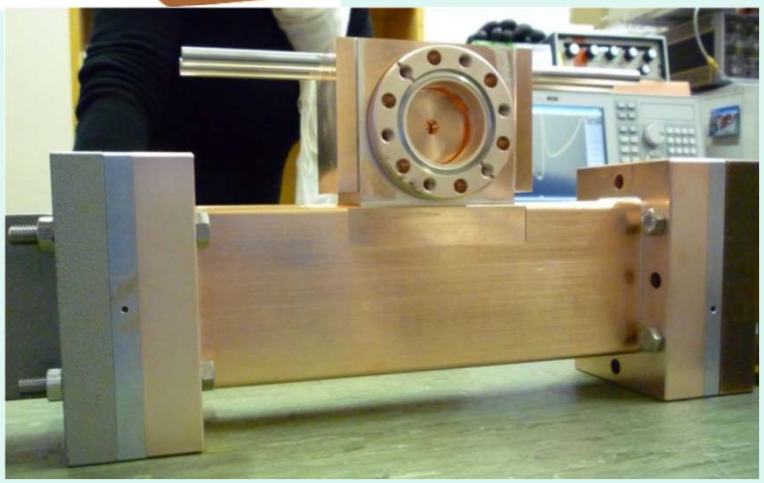
$\Rightarrow E_0 > 45$ MV/m

At:

1 MW / cell peak and

max $E_{surface}$ 175 MV/m





Garlaschè , Degiovanni , Verdú.A , Bonomi (TERA)

Cavity design for 250→350 MeV

Optimize the geometry using *LINAC–code* from *TERA*

Maximize the acceleration effectiveness:

Effective shunt Impedance:

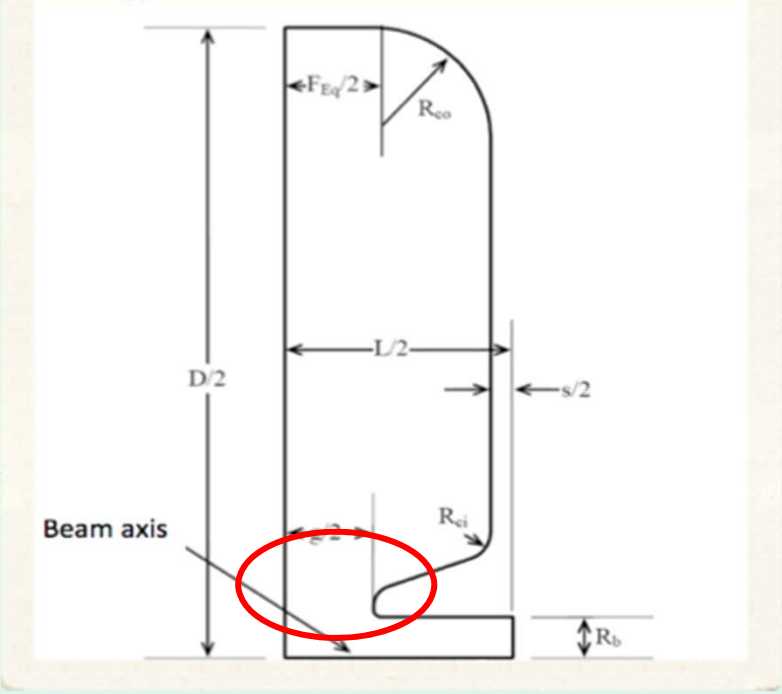
$$ZTT = \frac{E_0^2 T^2}{P/L}$$

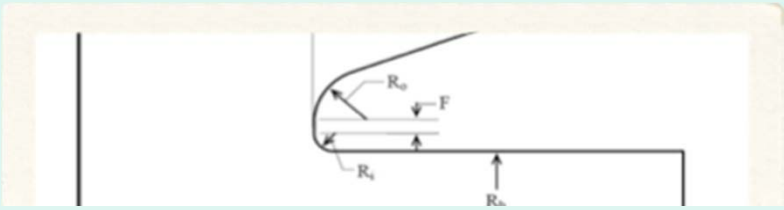
Minimize power losses

Minimize the E_{max} (break down)

Adapt cavity cell-length per tank to particle speed:

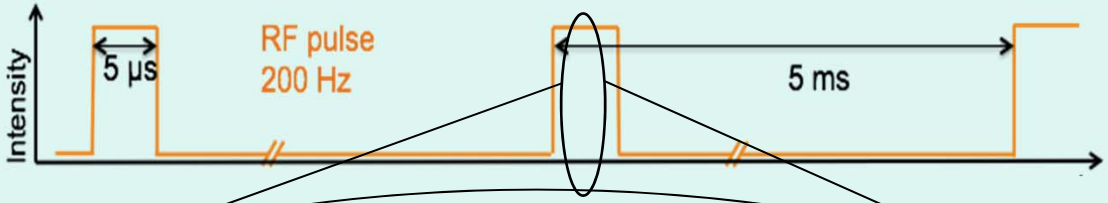
$$L = \beta c/2f \qquad \beta: 0.61 \rightarrow 0.71$$



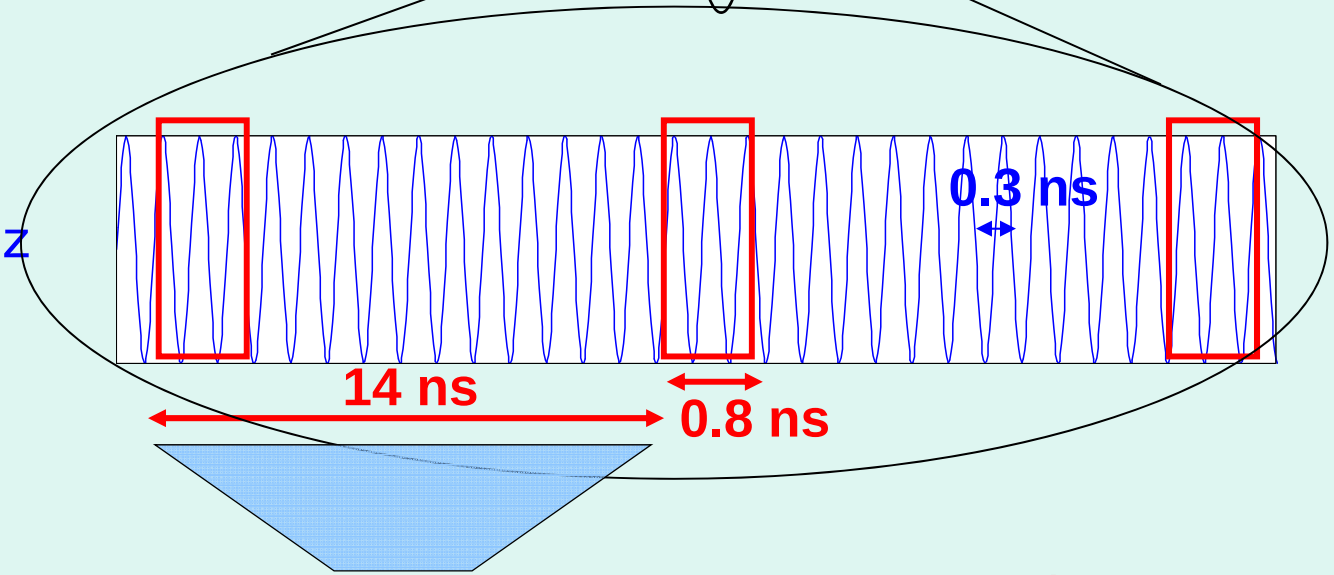


Some frequencies

LINAC **pulses**: 200 Hz

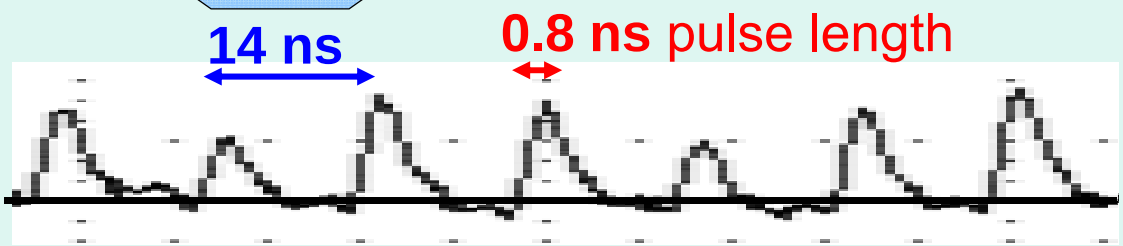


LINAC **RF**: 3 GHz

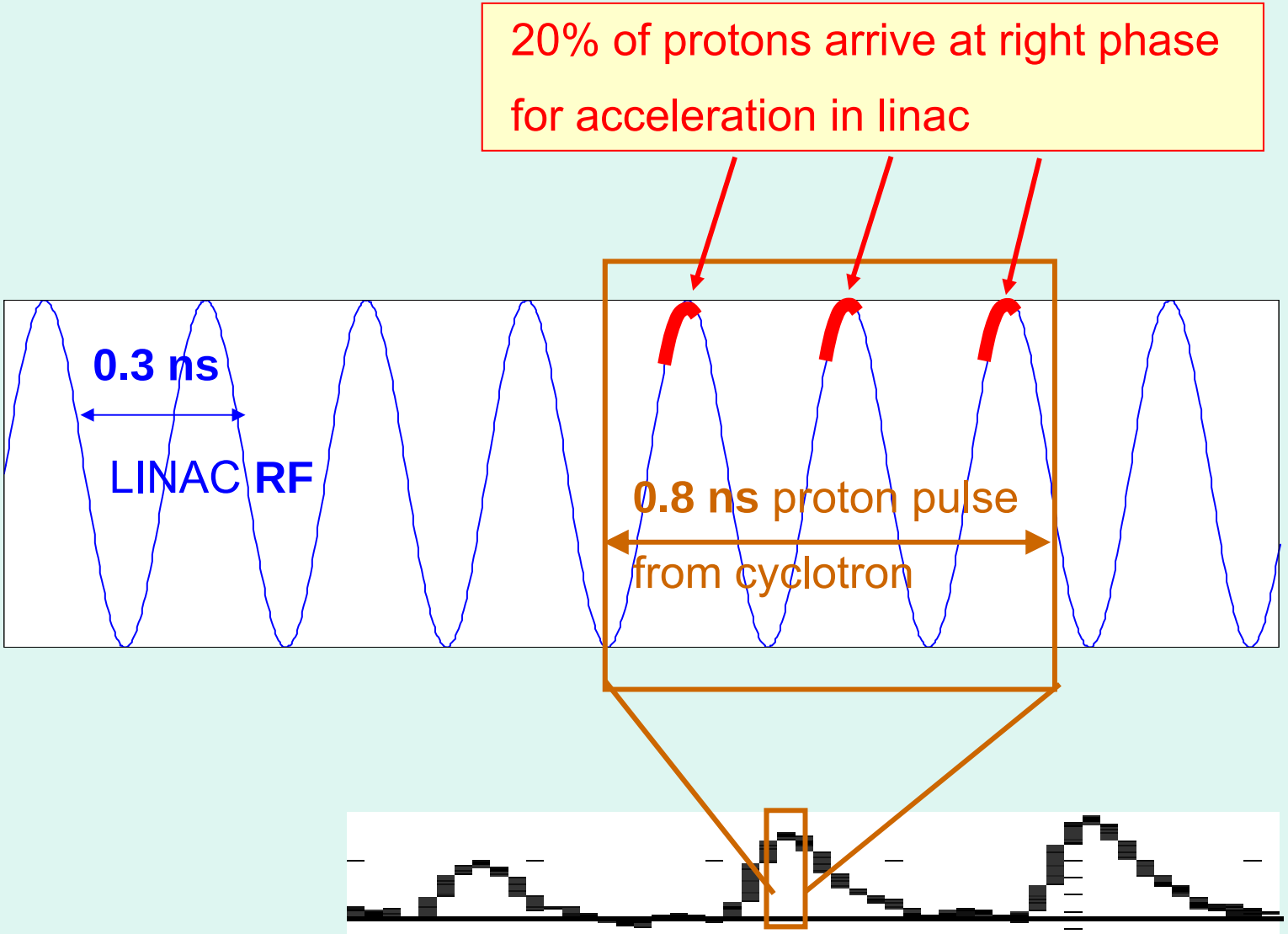


CYCL. RF: 72 MHz

Proton intensity:



Some frequencies

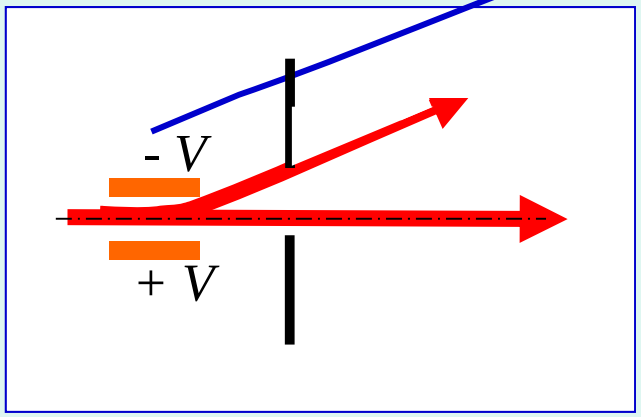


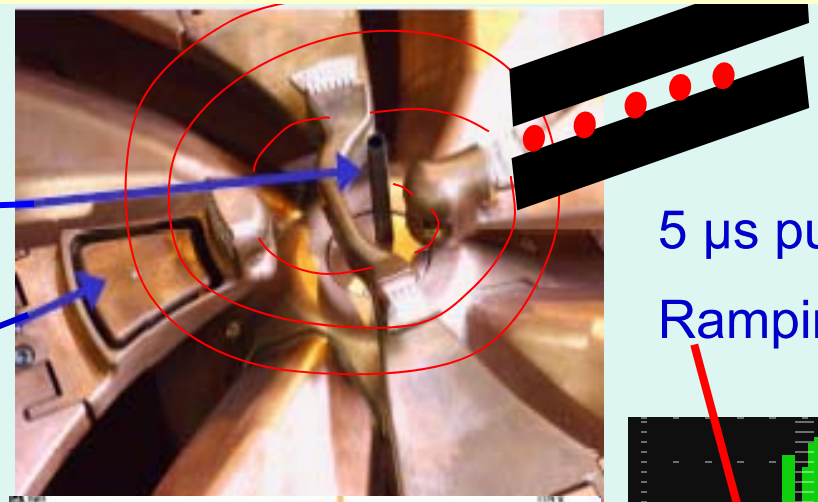
Beam chopping in cyclotron

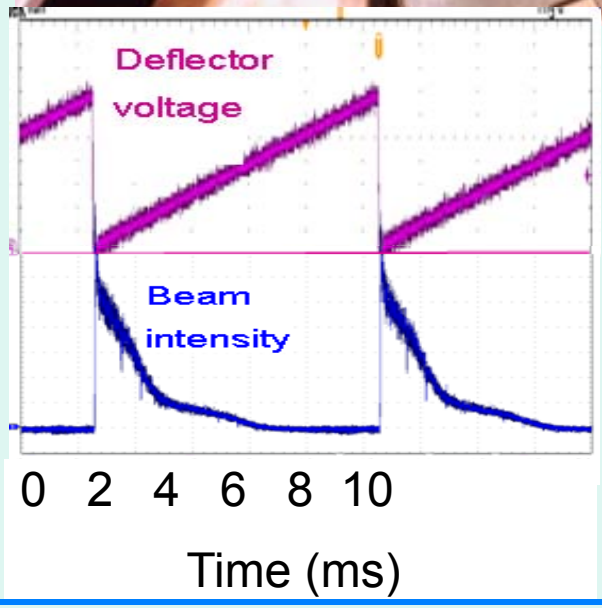
99.9% of Cyclotron beam is **not used** between the 200 Hz RF pulses

proton source

Vertical Deflector plate

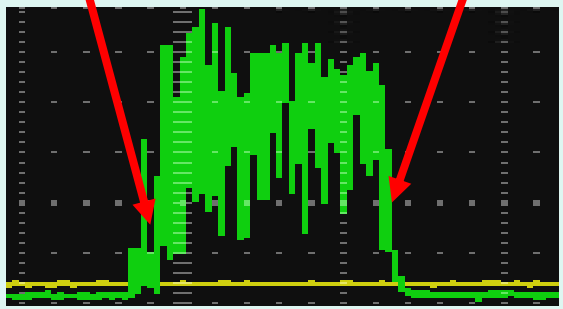


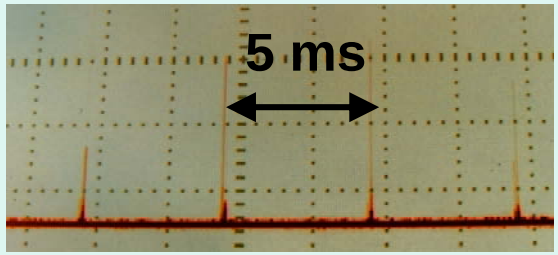




5 µs pulses

Ramping time < 1-2 µs

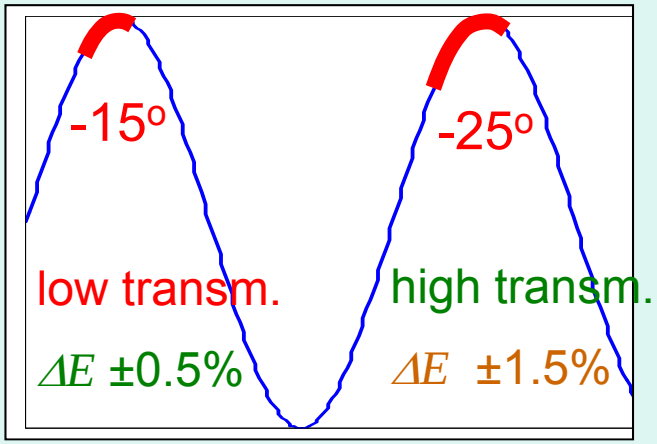


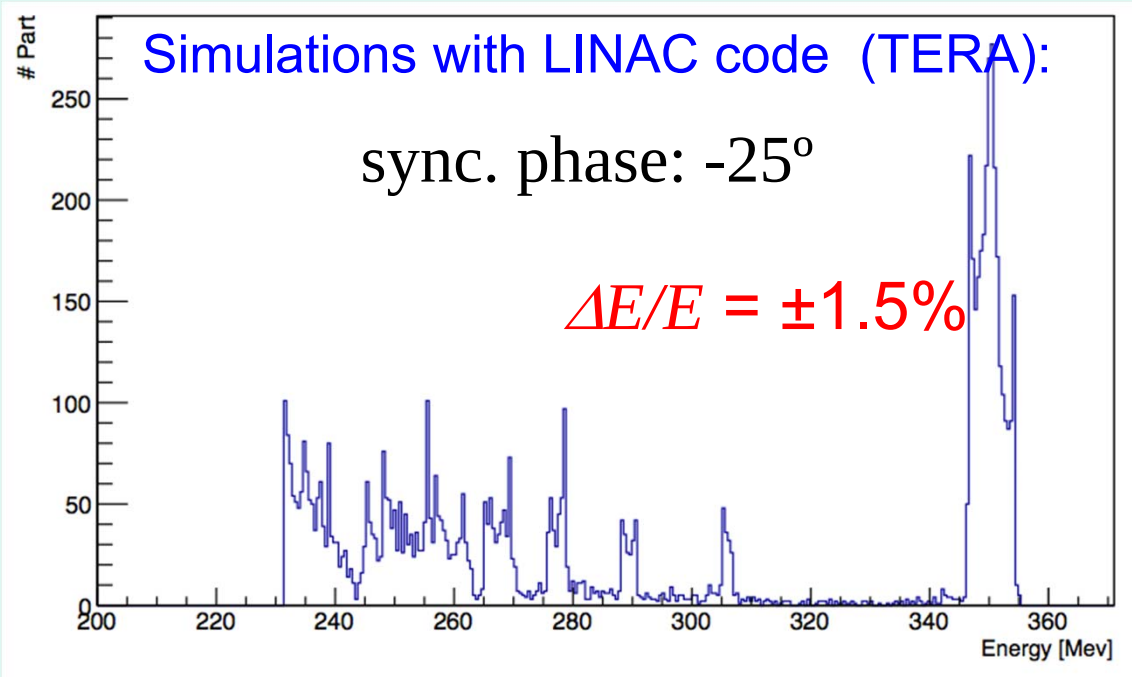


Pulse at 200 Hz

energy spectrum

Choice of synchronous phase





- OK. for High energy therapy
- Beam analysis needed for proton-radiography
- (analysis needed anyway to remove <300 MeV)

Results of simulations

- Longitudinal acceptance at 350 MeV: 25-30%
- Transverse acceptance (4 mm bore radius): 9.2π mm.mrad

  Typ. beam emittance : **3 - 4π mm.mrad**
- Energy Acceptance 250 ± 4 MeV

  Energy spread and max deviation of cyclotron : **1 MeV**

=> Total transmission from cyclotron exit to linac exit:

If cyclotron CW: 0.02 %

If cyclotron is pulsed: 15 %

Includes 3x higher losses in Analysis

1 μA from cyclotron in 200 Hz pulses of 5 μs:

Radiography: tomogr. 10 lit. needs 10^9-10^{10} protons => **takes 3-30 sec**

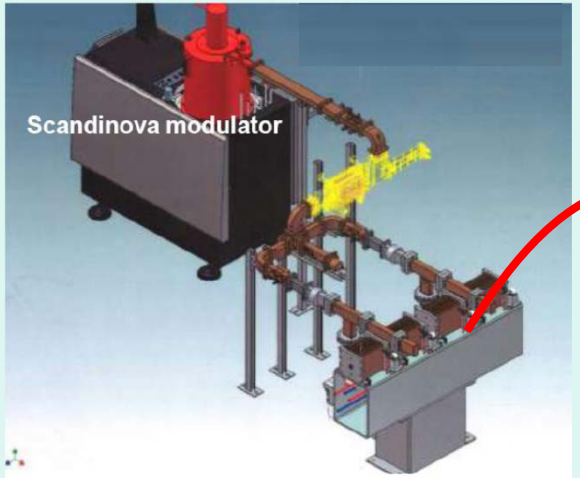
Therapy: 10 Gy in 10 cm^3 needs 10^{12} protons => **takes 100 sec**

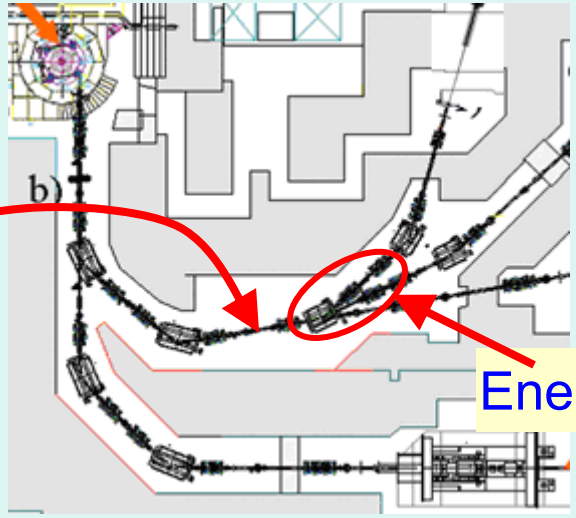
Conclusion

Study for facility upgrade with booster 250 → 350 MeV:

- **7m long** , 3 GHz (S-band) CCL, 40 MW peak
- **Enough beam intensity** for radiography and special therapies
- **Fits** in standard facilities

250→275 MeV test unit is planned at PSI:





total length 1.5 m

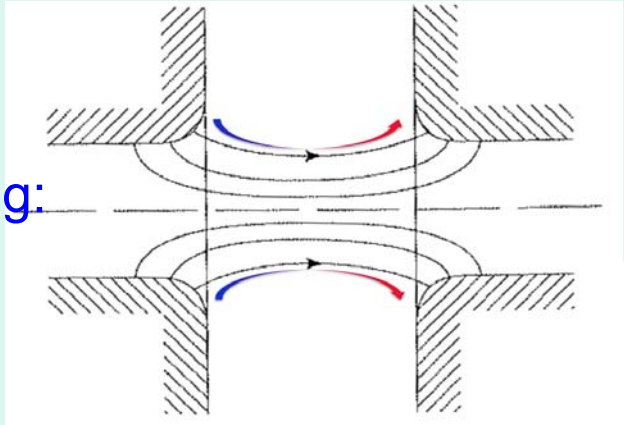
in existing beam line

Energy measurement

Thank you !

Quadrupoles

Transverse defocusing:



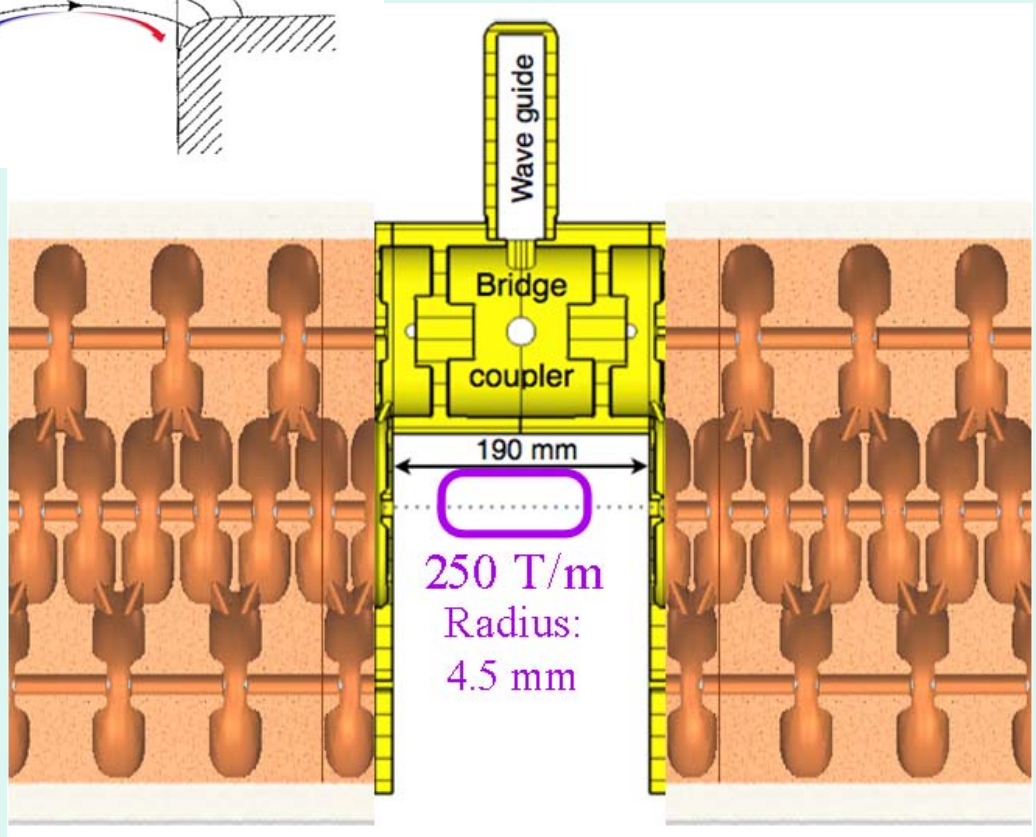
Compact

Easy to operate

Permanent Qpoles:

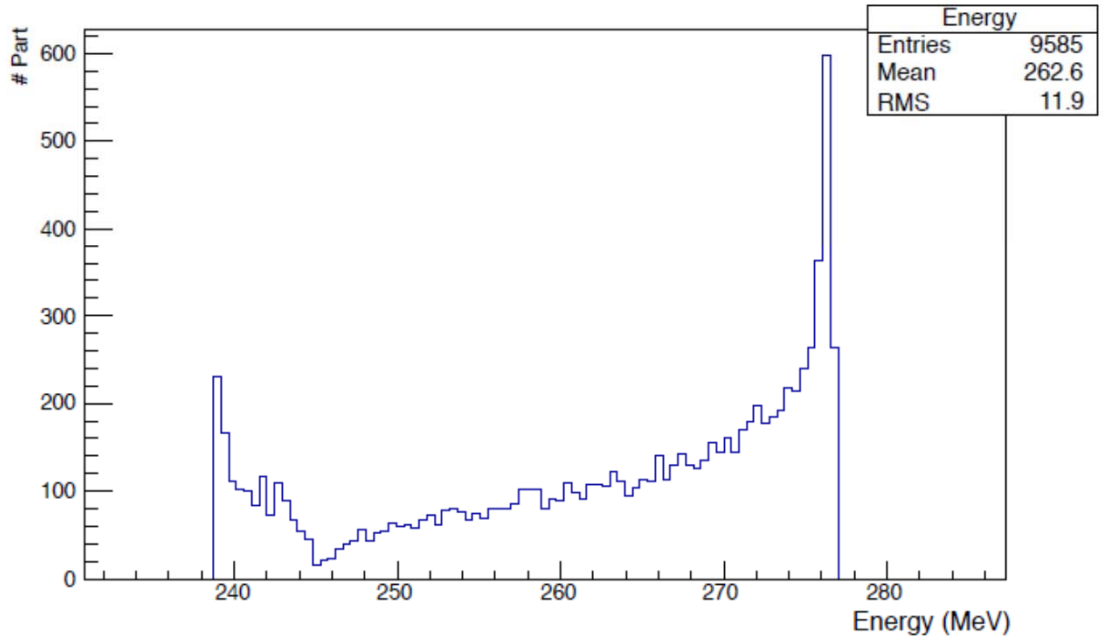
Alignment ?

Irradiation damage ?

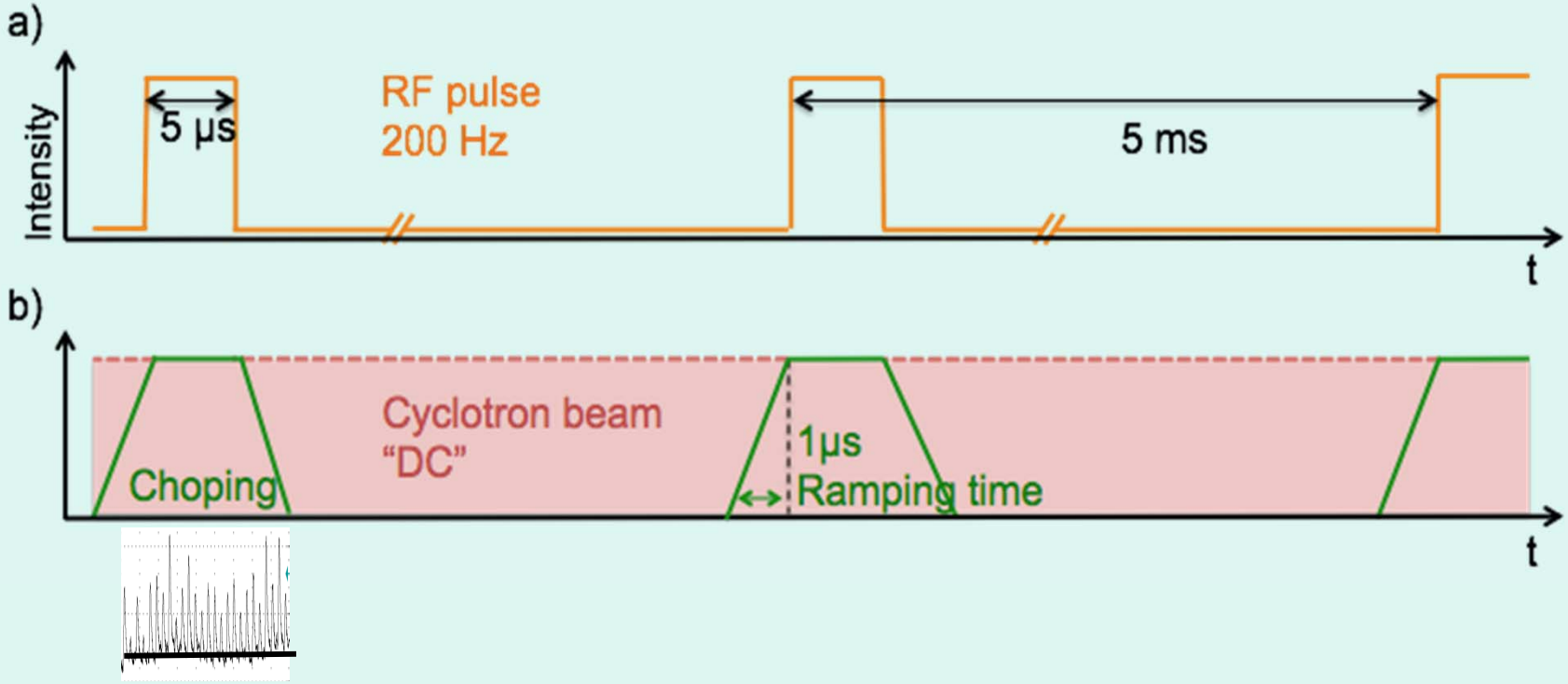


25 MeV test unit (1th unit of 100 MeV linac)

Due to the short size of the linac there is no time to bunch the beam, and the energy spectrum, shown in figure 5.23, is almost continues with a maximum energy of 275 MeV.



Some frequencies



99.9% of Cyclotron beam is not used between the 200 Hz RF pulses

=> to reduce activation cyclotron beam must be chopped