PMB ALCEN

PHENIICS DOCTORAL SCHOOL DAYS, LAL, 11/05/2016

Laboratoire de l'Accélérateur Linéaire LAL

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HIGH-GRADIENT S-BAND ELECTRON LINAC FOR THOMX

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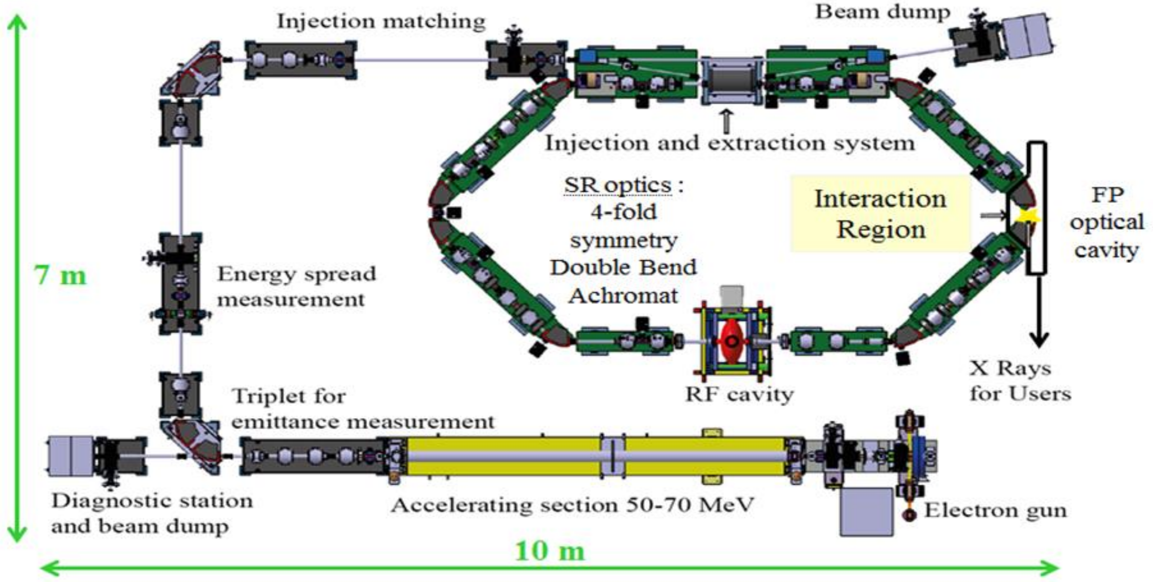
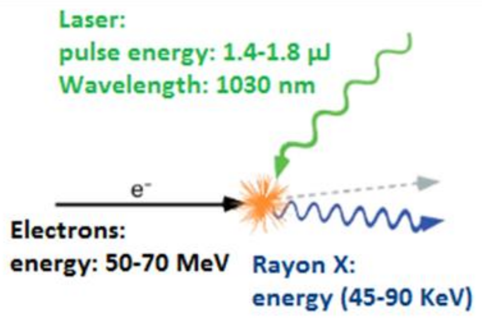
Outline

- **ThomX project;**
- **LINAC main specifications respect to the ThomX layout;**
- **Beam dynamics simulations of the photo-injector;**
- **PMB-LAL research collaboration for LINAC upgrade:**
  - High gradient S-band accelerating structure (HGAS) for THOMX LINAC,
  - Single cell geometry optimization and 3D simulations results,
  - Prototypes design and 3D simulations results,
  - Quasi-constant field high gradient accelerating structure (preliminary configuration);
- **Conclusions and prospects;**

ThomX project



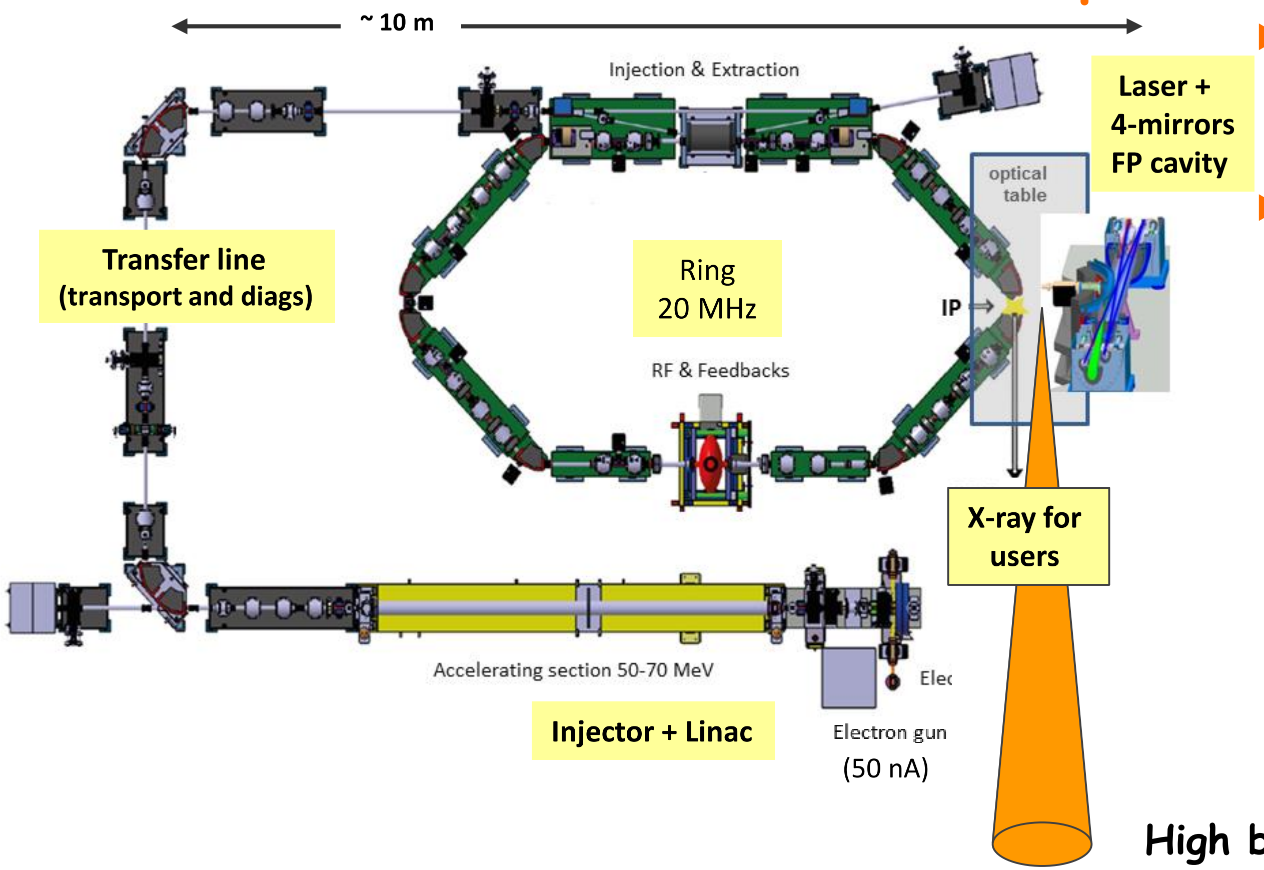


Principe d'interaction Compton

- French project led by LAL (budget: 12 M€, 10 M€ TTC facility & 2 M€ TTC operation).
- Compton backscattering compact hard X-rays (45-90 keV) source with high flux (10^{11}-10^{13} ph/s).
- Relatively low energy machine (50-70 MeV) which allows installation in hospitals or museums.
- A demonstrator was recently funded and it is under construction in the Orsay University campus.
- Application domains:
  - Cultural heritage (collaboration with LAMS, Paris): imaging, structural & chemical studies of artefacts,
  - Medical science (collaboration with ESRF, Grenoble): imaging, high energy radiotherapy (specific tumors),

Industrialisation phase (Thales): ThomX demonstrator can be commercialised as an integrated product.

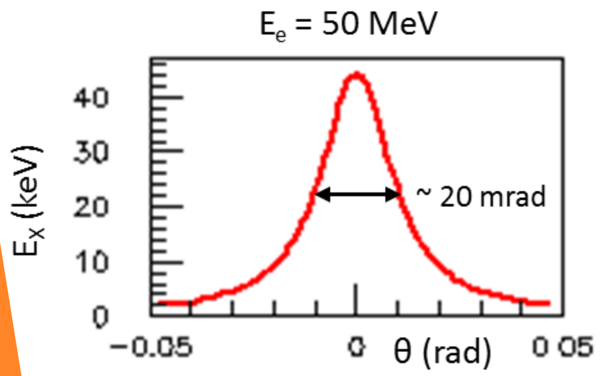
LINAC main specifications



- To fulfill the accelerator specifications, the LINAC has to be carefully designed, especially the photo-injector.
- LINAC requirements
  - Energy: 50 MeV,
  - Bunch charge: 1 nC,
  - Repetition rate: 50 Hz,
  - Rms norm. emittance: $\varepsilon_N \sim$ 4 mm mrad π
  - Rms energy spread: < 1%
  - Rms bunch length: < 5 ps

$$Br \sim \frac{Flux \,.\, \gamma^2}{\varepsilon_N^{\,2}}$$

High brightness small e^- beam emittance ε is required



Conical beam

E_e = 50 MeV

θ ~ 10 mrad → 22 keV

On axis photons → 45 keV

Courtesy of M. Jacquet

X-ray beam

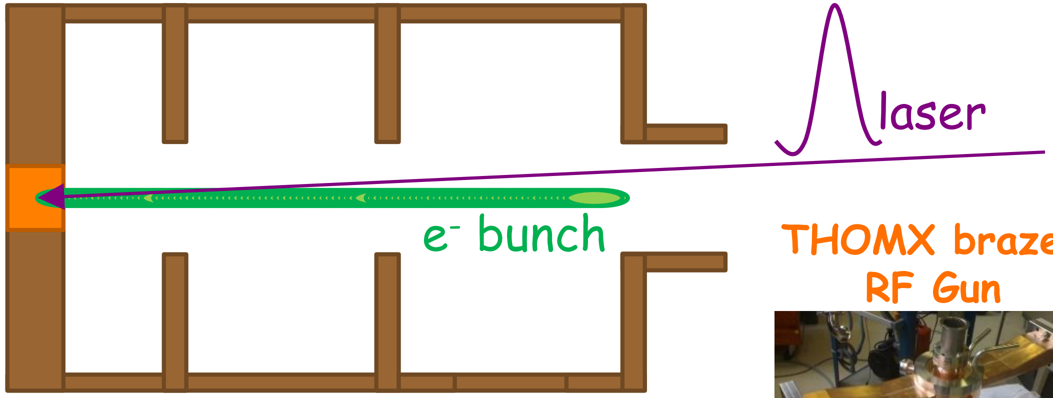
Flux	10^{13}
Brigthness	10^{11}
Transv. size	70 µm
E_X	30-90 keV
σ_t	10-20 ps

Photo-injector

- Long experience achieved from LAL in the RF Gun fabrication.
- The RF Gun design is almost the same as for the Probe Beam Photo-Injector (PBPI) at CLIC Test Facility 3.
- To avoid vacuum constraints with high efficiency, a metallic magnesium photocathode has been chosen.

RF Gun

Photo cathode



THOMX brazed RF Gun

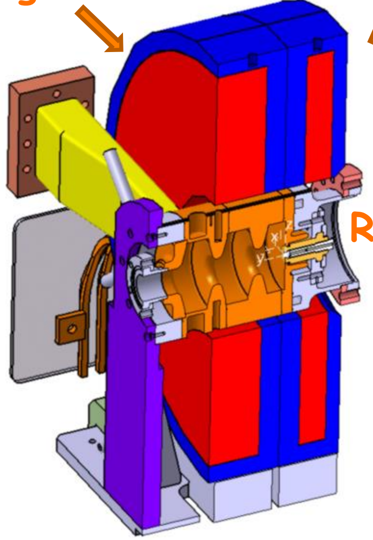
Specifications

Laser wavelength	266 nm
Laser pulse duration & energy	5ps, 100 μJ
Q – factor	15000
Shunt Impedance	50 MΩ/m
RF input power	5 MW, 3 μs
Peak Accelerating gradient	80 MV/m
Energy gain	~ 5 MeV

2.5 cells RF Gun

focusing coil

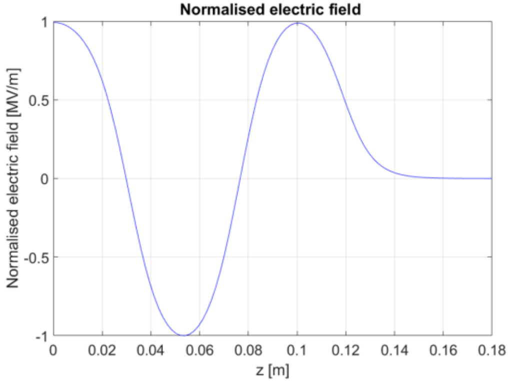
bucking coil



RF Gun

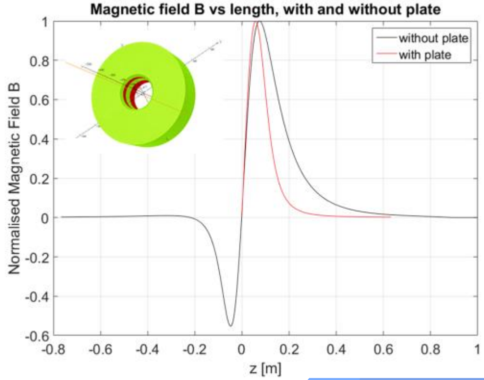
E field along beam axis

- 2D-field profile obtained by SUPERFISH,
- Frequency & $\Delta\Phi$: 2998.55 MHz, π-mode,
- Good field flatness achieved,



B field along beam axis

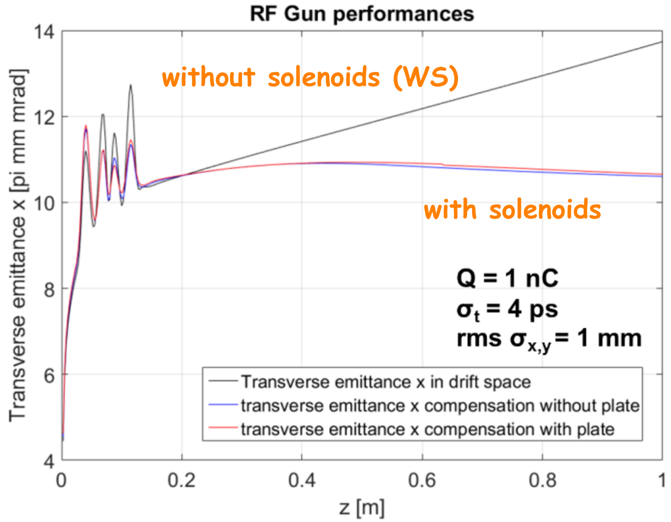
- 2D-field profile obtained by OPERA,
- B strength without & with shielding plate,
- B = 0 T @ z = 0 m (photocathode position),



Beam Dynamics Simulations of the Photo-injector

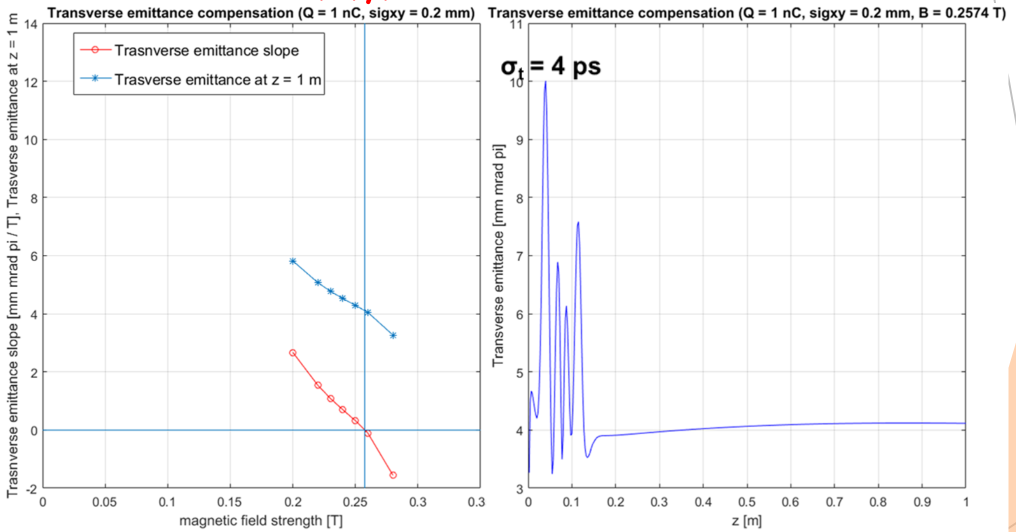
- Transverse normalized total beam emittance in RF Gun ➡ dependence of RF field (ε_{RF}), space charge (ε_{SC}), thermal photoemission (ε_{th}). $\epsilon_{n,x,y,tot} = \sqrt{\epsilon_{RF}^2 + \epsilon_{SC}^2 + \epsilon_{th}^2}$
- Beam dynamics simulations has been performed using A Space charge TRacking Algorithm (ASTRA).
- Electron bunch distribution setting in ASTRA: 10000 particles, bunch charge Q, laser pulse duration σ_t, rms size $\sigma_{x,y}$.
- Shielding plate is much more effective on the beam size ($\sigma_{x,y}$ = 9.7 mm without shielding, ~ 3 mm with shielding).
- Transverse emittance compensation: $\varepsilon_{x,y}$ =13.7 mm mrad π without shielding, 10.6 mm mrad π with shielding.

Solenoids effect



- WS: emittance growth is linear.
- The effect of the shielding plate is effective on the transverse beam size.

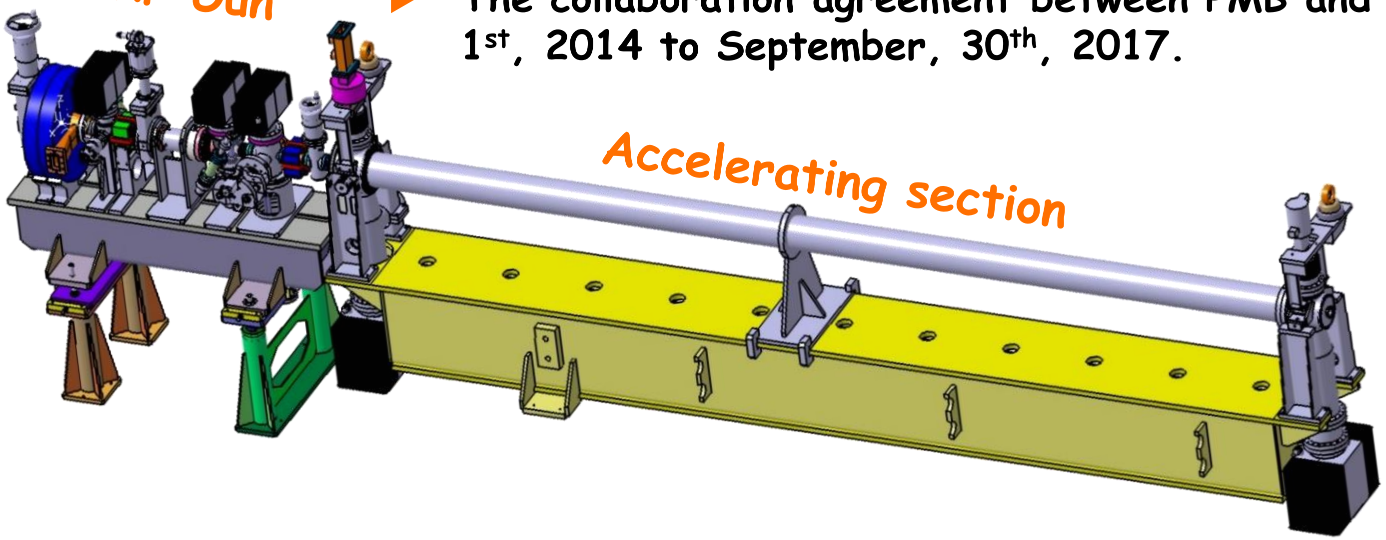
$\varepsilon_{n,x,y,tot}$ vs B strength



- $\varepsilon_{n,x,y,tot}$ function of z is calculated for different magnetic field strengths.
- Intersection with the zero cross line gives the right value of B.

L. Garolfi et all., "BEAM DYNAMICS SIMULATIONS OF THE THOMX LINAC", Proceedings of IPAC2016, Busan, Korea.

PMB ALCEN-LAL Research Coll.: High Gradient Structure



- The collaboration agreement between PMB and LAL has been established from October, 1st, 2014 to September, 30th, 2017.

- S-band Linac :
  - f_{RF} = 2998.55 MHz @ 30 ° C under vacuum,
  - Repetition rate max = 50 Hz,

Commissioning phase: LIL structure

- Total length: 4.5 m (135 cells),
- Travelling wave section (TW),
- Quasi-constant gradient structure,
- Phase advance per cell: 2π/3-mode,
- Average acc.field: 14.6 MV/m @ 18 MW,
- Filling time ~ 1.35 µs,

Upgrade →

Upgrade phase: PMB-LAL

High gradient & compact structure (HGAS)

- Total length: 3.2 m (96 cells),
- Travelling wave section (TW),
- Quasi-constant gradient structure,
- Phase advance per cell: 2π/3-mode,
- Average acc. Field: 18.5 MV/m @ 18 MW,
- Filling time ≤ 1 µs,

Direct impact on X-rays energy:
50 MeV → γ ~ 45 keV
70 MeV → γ ~ 90 keV

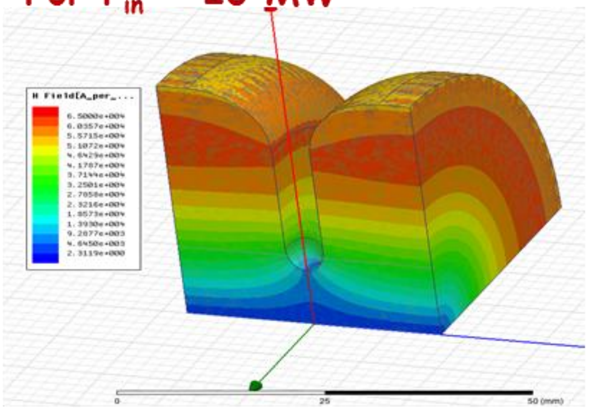
PMB ALCEN-LAL Research Coll.: Single cell geometry optimisation

- Optimization of the cell shape (HFSS & CST MWS) ⇨ Improvement of the main RF figure of merit: r/Q, vg, α, $<E_a>$, $E_{speak}/<E_a>$, $S_c/<E_a>^2$, etc.
- Single cell has been designed exploring the different TW cell parameters as a function of the iris aperture (a), iris thickness (t), ellipticity ratio (r_2/r_1) and radius ρ.
  - Irises with elliptical shape (r_2/r_1=1.7): reduce the peak surface field of 10-15%
  - Rounding of the cell edge (ρ=10 mm): improves the quality factor more than 10% and reduces the wall power consumption.
- Minimum power consumption and the minimum risk of breakdown ⇨ modified Poynting vector S_c

$$\eta \equiv \frac{P}{<E_a>^2} \cdot \frac{S_c}{<E_a>^2} = \frac{v_g}{\omega} \cdot \frac{S_c/<E_a>^2}{r/Q}$$

Surface Magnetic Field

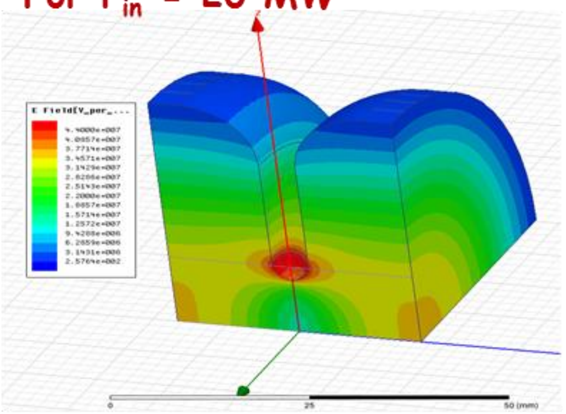
For P_{in} = 20 MW



$H_{s\ peak}$ = 65 kA/m

Surface Electric Field

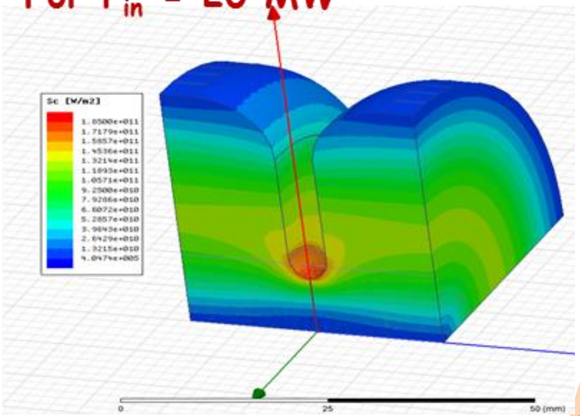
For P_{in} = 20 MW



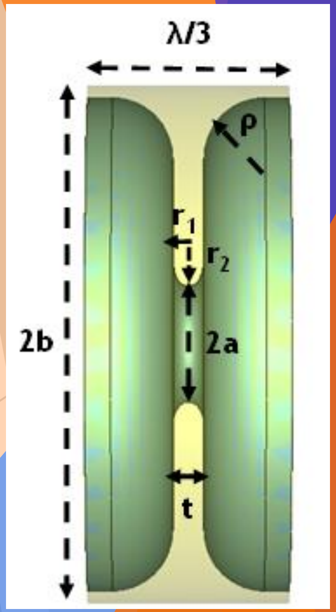
$E_{s\ peak}$ = 44 MV/m

Modified Poynting Vector

For P_{in} = 20 MW



$S_{c\ max}$ = 0,185 MW/mm²



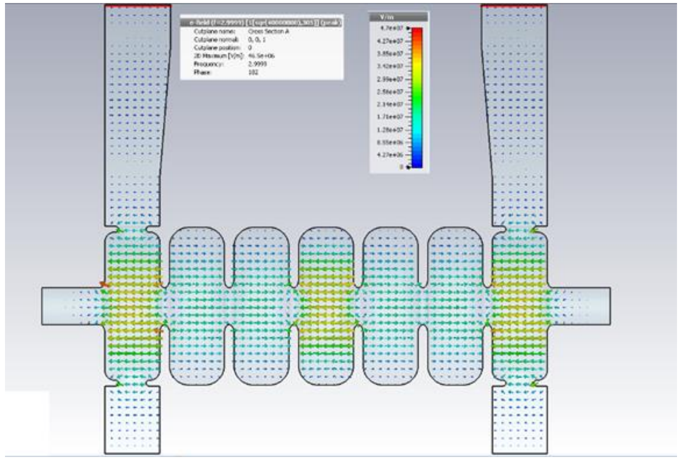
Both $E_{s\ peak}$ and S_c are localized in the iris area

L. Garolfi, M. El Khaldi, "3 GHz SINGLE CELL CAVITY OPTIMIZATION DESIGN", Proceedings of IPAC2015, Richmond, VA, USA.

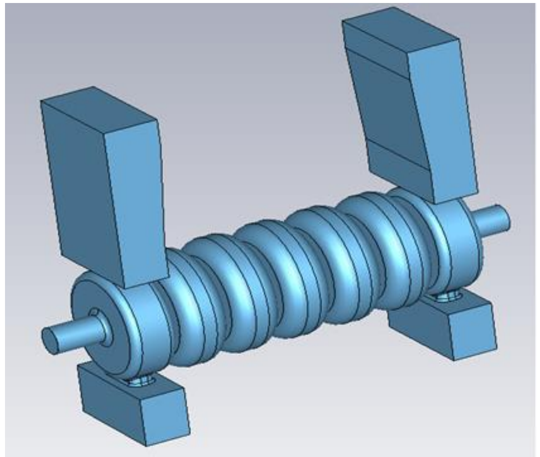
PMB ALCEN-LAL Research Coll.: prototype design

- Constant Impedance (CI) prototypes with a reduced number of cells (7 cells): design, fabrication & high power tests.
- Goals: analysis of RF, mechanical issues, improving the machining of cells and brazing processes.

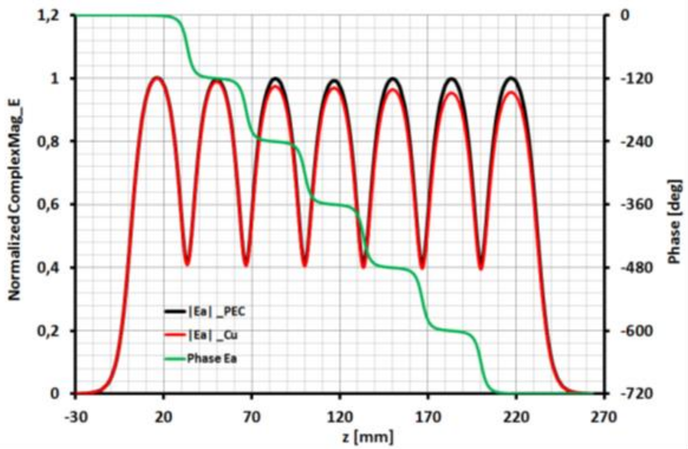
Accelerating field $TM_{010\_2\pi/3}$ mode



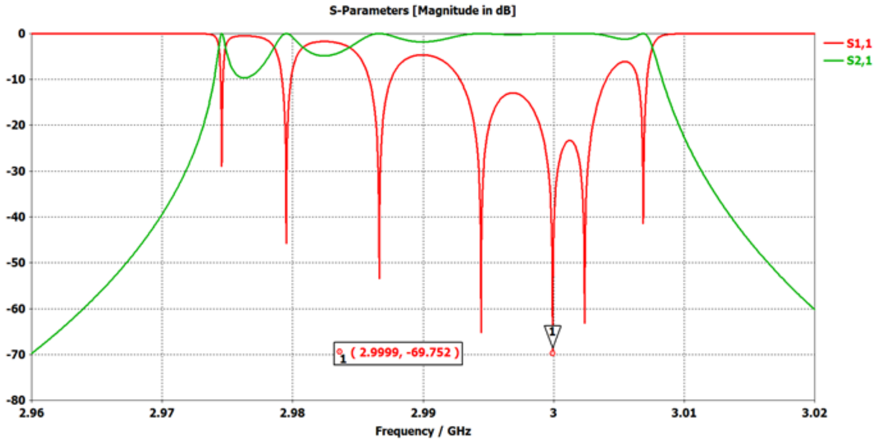
Constant Impedance (CI) prototype design



Electric field amplitude & phase advance per cell



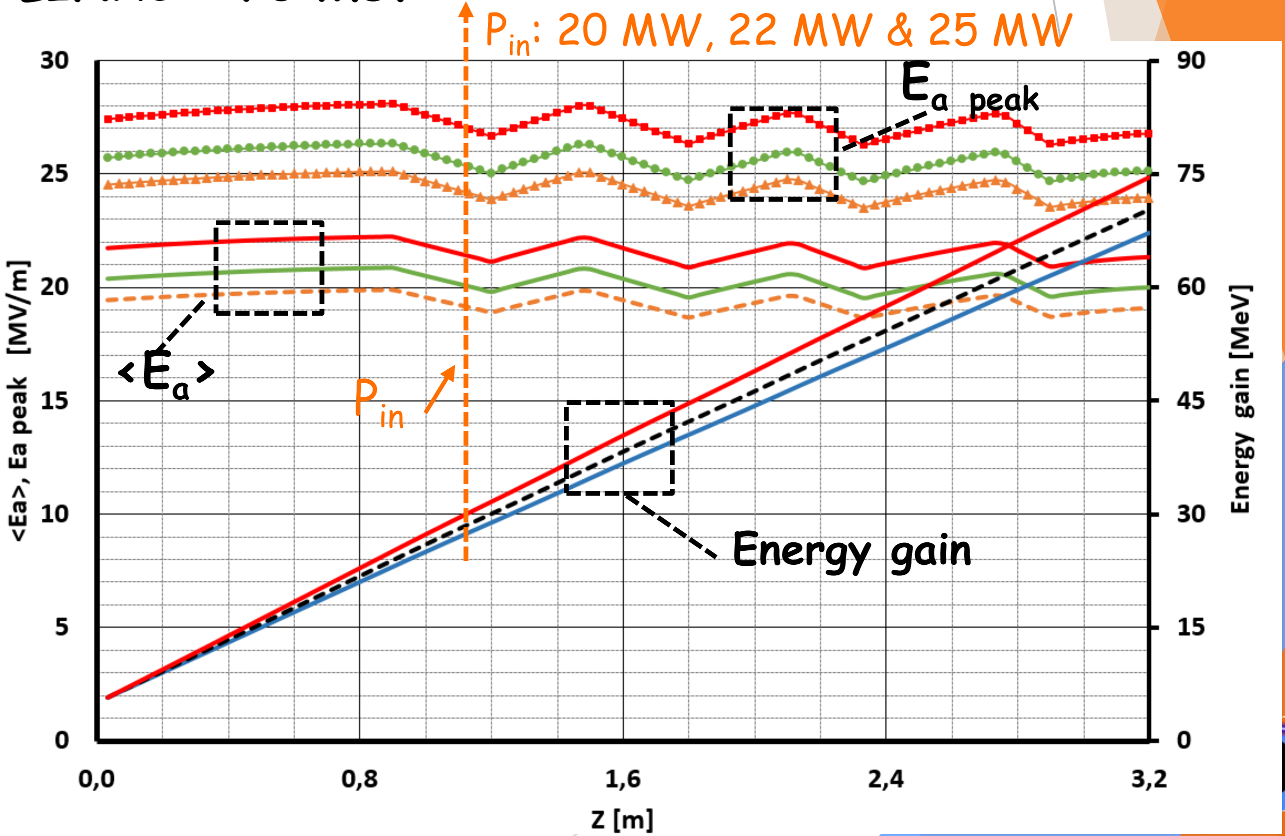
S parameters



M. EL Khaldi, L. Garolfi,"RF DESIGN OF A HIGH GRADIENT S-BAND TRAVELLING WAVE ACCELERATING STRUCTURE FOR THOMX LINAC", Proceedings of IPAC2015, Richmond, VA, USA

PMB ALCEN-LAL Research Coll.: Final Structure Design

- Preliminary configuration of the whole HG accelerating section 3.2 m:
  - Electric field & energy gain along the structure for P_{in} = 20, 22 & 25 MW,
  - 5 MeV energy at the entrance of the accelerating section (provided by the RF Gun),
  - For P_{in} = 22 MW:
    - $\langle E_a \rangle \approx$ 20.5 MV/m average accelerating field acting on the particles.
    - Energy gain at the end of the LINAC: 70 MeV
    - 73,5 MΩ/m ≤ rs ≤ 89,3 MΩ/m
    - 0.13 ≤ α (Neper/m) ≤ 0,43
    - 0.005 ≤ v_g/c ≤ 0,016
    - Filling time ~ 1 μs



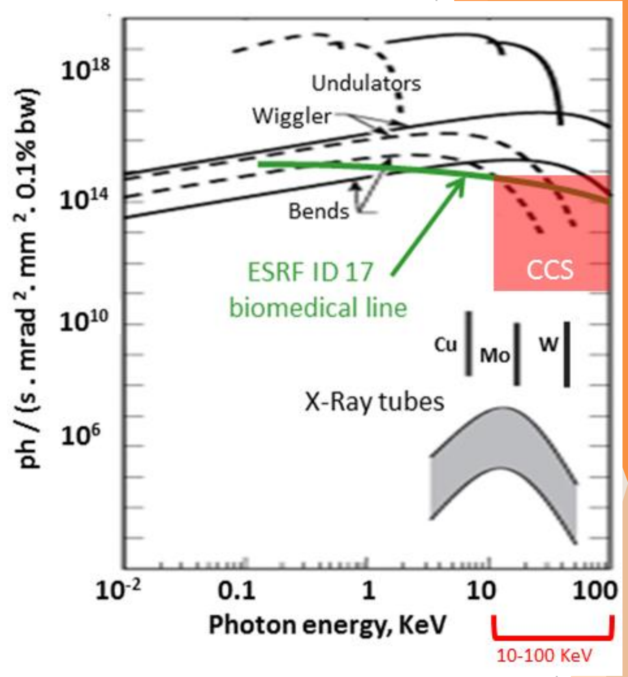
- Other configurations are under study for energy gain optimisation & filling time reduction, considering for example an iris diameter in the range 17 mm $\leq \emptyset\, iris \leq$ 22,6 mm.

Conclusions et perspectives

- Normalised transverse beam emittance compensation of the THOMX RF Gun has been estimated by means of ASTRA code.
- The nominal transverse emittance value ($\varepsilon_{n,x,y,tot}$ = 4 π mm mrad) is fulfilled for a transverse laser spot of $\sigma_{x,y}$ = 0.2 mm.
- RF design has been performed & main requirements accomplished,
- Prototype mechanical drawing (reduced number of cells) are completed,
- Aluminium prototype fabrication is finished (check out & validation of all technical choices),
- Low power tests will be expected on May, 2016,
- Thermal analysis of the RF Gun has been performed,
  - M. EL Khaldi, J. Bonis, A. Camara, L. Garolfi, A. Gonnin, "ELECTROMAGNETIC, THERMAL AND STRUCTURAL DESIGN OF A THOMX RF GUN USING ANSYS", Proceedings of IPAC2016, Busan, Korea.
- Thermal analysis of the 7 cells prototype is underway,
- To get the final beam parameters at the end of the LINAC, beam dynamics simulations of the accelerating section are currently underway.

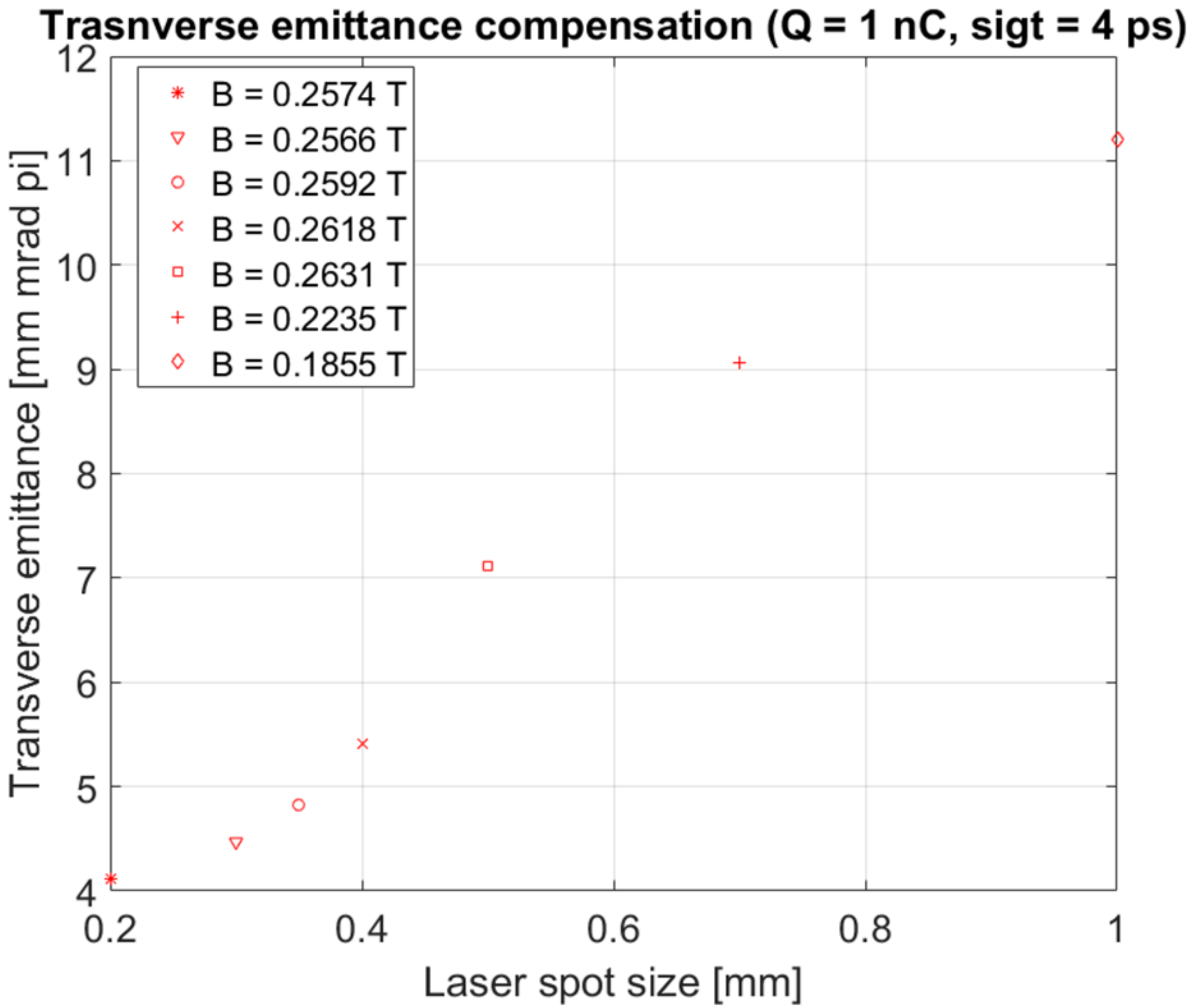
Thank you

Current panorama of the X-ray source brightnesses



- **Compact Compton Sources (CCS)**
  - **Compactness** (surface ~ 100 m^2)
  - **High intensity** (10^{12} – 10^{14} ph/sec)
  - **Tunable beam**
  - **High quality beam**
    (brightness 10^{11} – 10^{15} ph/sec/ mm^2 / 0.1% bw / $mrad^2$)

$\varepsilon_{n,x,y,tot}$ vs laser spot



PMB ALCEN-LAL Research Collaboration

- **The collaboration agreement between PMB and LAL has been established from October, 1st, 2014 to September, 30th, 2017.**

Tasks sharing

LAL	PMB
Electromagnetic study, thermal analysis, beam dynamics.	Drawing of mechanical plans according to RF design provided by LAL.
RF design and check out of mechanical plans.	Realization of Aluminium (Al) prototypes for checking out the geometry.
Realization follow up of the prototypes and complete structure at PMB.	Realization of Copper (Cu) prototypes for checking out the « standard » and « improved » fabrication processes.
High power RF tests of prototypes.	Low power RF tests of prototypes.
Conditioning process of the final accelerating section.	Fabrication of the final section: (adjustments, recovery, tests, brazing, surface treatments, etc.)
Commisionning of HGAS on ThomX machine.	Checking and testing.

S-band prototype

Energy gain in periodic structures

- The electromagnetic wave (EM) is attenuated along the structure,
- Along the accelerator, power is dissipated in the cavity walls and the electric field is attenuated:

$$\frac{d < E_a >}{dz} = -\alpha(z) < E_a > \quad \rightarrow \quad \frac{dP}{dz} = -2\alpha(z)P(z)$$

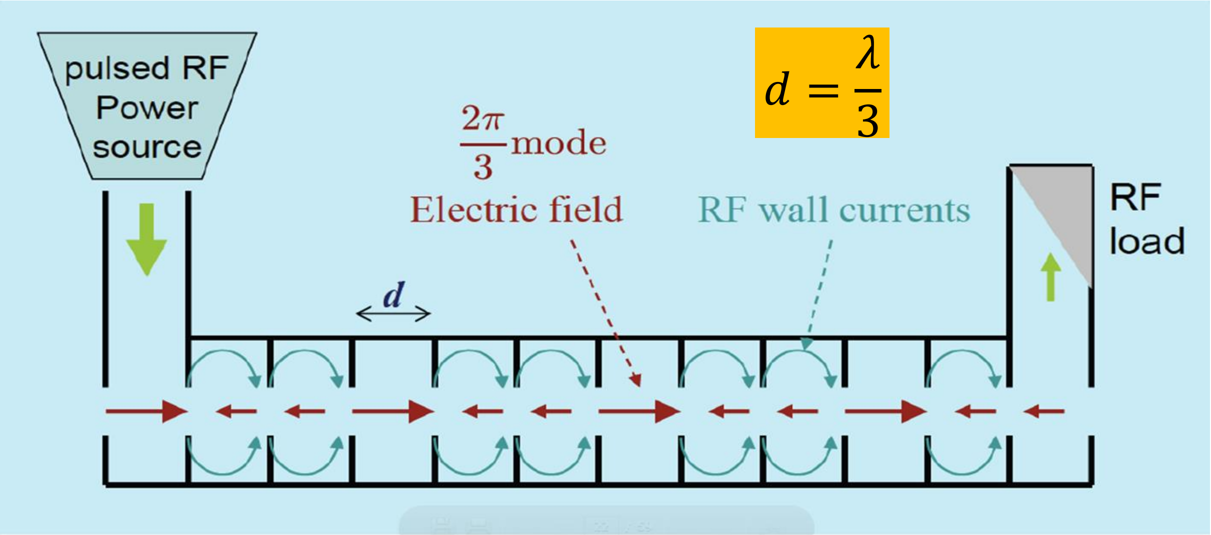
where α is the attenuation factor

- Definitions:

$$Q = \omega \frac{w}{-dP/dz}$$

$$w = \frac{P}{v_g}$$

$$-\frac{dP}{dz} = \omega \frac{w}{Q} = \omega \frac{P}{Q \cdot v_g}$$



$$\frac{dP}{dz} = -\frac{\omega}{Q \cdot v_g} P = -2\alpha \cdot P(z) \quad \rightarrow \quad \alpha(z) = \frac{\omega}{2 \cdot Q \cdot v_g(z)}$$

S-band prototype

Constant impedance section (CI)

- uniform iris aperture: a =constant,
- constant attenuation factor α(z) = constant = α,
- Q, v_g, r_s, are independent from the length z, so:

$$< E_a > (z) =< E_a >_0 e^{-\alpha z} \qquad P(z) = P_0 e^{-2\alpha z}$$

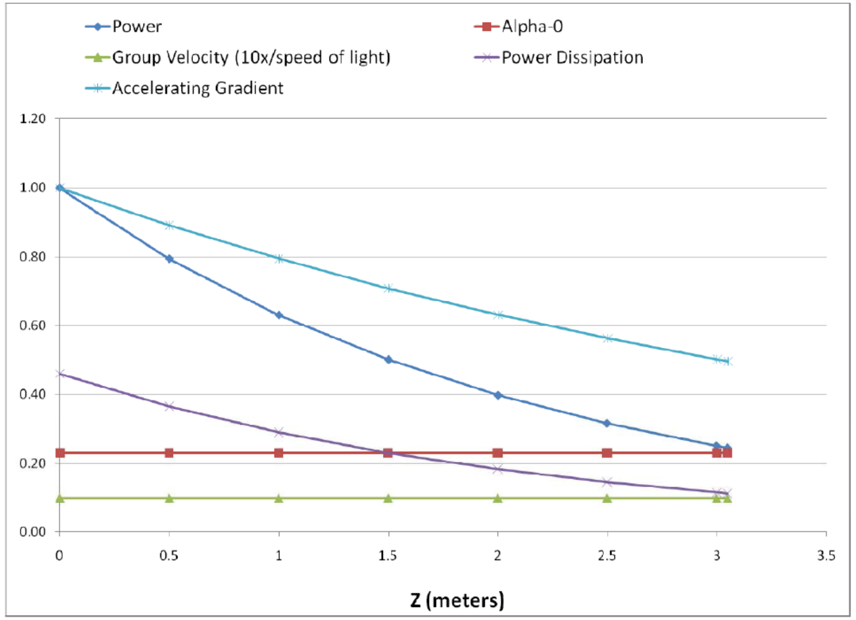
$$\alpha = \frac{\omega}{2 \cdot Q \cdot v_g} = const$$

- In the end of the structure:

$$< E_a > (L_{tot}) =< E_a >_0 e^{-\tau}$$

$$P(L_{tot}) = P_0 e^{-2\tau}$$

$$\tau = \alpha \cdot L_{tot} = \frac{\omega \cdot L_{tot}}{2 \cdot Q \cdot v_g}$$



- The energy gain is:

$$\Delta W = q \cos\theta \int_0^{L_{tot}} E_a(z)\, dz = qE_0 L \frac{1 - e^{-\tau}}{\tau} \cos\theta$$

$$\Delta W = q\sqrt{2 r_s P L_{tot}} \frac{1 - e^{-\tau}}{\sqrt{\tau}} \cos\theta$$

S-band prototype

Constant gradient section (CG)

- iris aperture varies along the structure a(z),
- attenuation factor varies along the structure α(z),
- r_s does not vary significantly with the length z,
- velocity group varies along the structure $v_g(z)$ to compensate for the power decrease by the reduction of the iris radius,

$$\frac{dP}{dz} = -2\alpha(z)P(z) = -2\alpha_0 P_0 = const \quad \text{with} \quad \alpha_0 = \alpha(0) \quad P_0 = P(0)$$

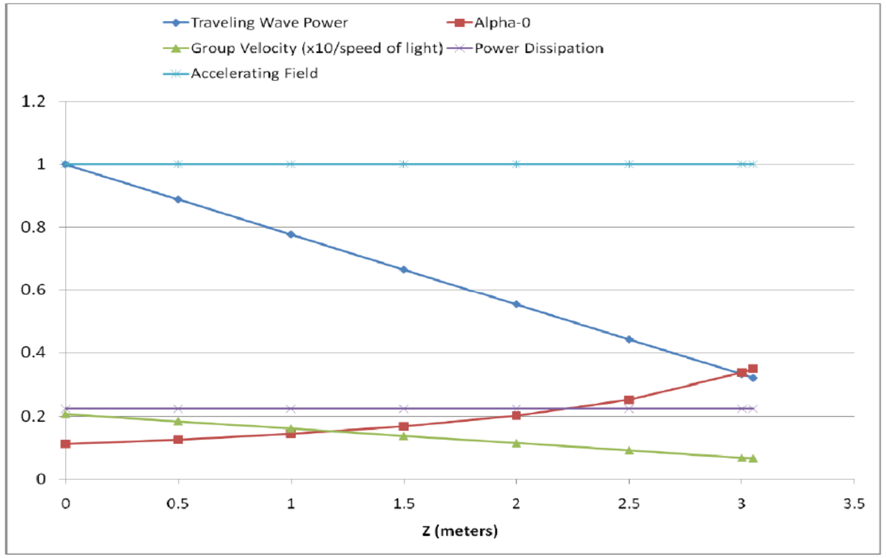
- Results that

$$P(z) = P_0(1 - 2\alpha_0 z) \qquad r_s = \frac{< E_a >^2}{-dP/dz} \sim const$$

$$\alpha(z) = \frac{\alpha_0}{(1 - 2\alpha_0 z)}$$

$$< E_a >^2 = \frac{\omega \cdot r_s \cdot P}{Q \cdot v_g} = \text{const}$$

$$v_g(z) = v_g(0)(1 - 2\alpha_0 z)$$



- The energy gain is:

$$\Delta W = q\cos\theta \int_0^{L_{tot}} E_a(z)\,dz = qE_0 L\cos\theta \qquad \Delta W = q\sqrt{2r_s P_0 L_{tot}(1 - e^{-2\tau}}\cos\theta$$