RFQ: basic considerations, achievements and criticalities

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European Spallation Source
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ESS Warm Linac Meeting, July 6th 2011, INFN-LNS, Catania, Italy

Outline

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1. Introduction
2. Beam dynamics
   - Design choices
   - Synergies
   - Main results
3. RF cavity design
   - 2D calculations
   - 3D calculations
4. The head bone's connected to the neck bone
5. Conclusions

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Forewords

The ESS linac has to provide a high power proton beam with a very high availibility (ESS total availability $> 95\,\%$)
$\Longrightarrow$ The design has to be driven by the overall reliability

Requirements

- lessons learnt from past and current projects
- labs knowlege and know-how
- margin/safety factor, conservative design
- synergies
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The RFQ design process

Beam dynamics

- voltage law
- peak surface fields
- RFQ length
- . . .

RF cavity design

- tuners
- vacuum ports
- RF coupling
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Thermo-mechanical calculations

→ internal Saclay kick-off meeting on July 8th 2011

Beam dynamics $\rightleftharpoons$ Radio-frequency $\rightleftharpoons$ Thermo-mechanical

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Pole tips design strategy

The ESS RFQ: acceleration of 50 mA (upgradable to 75 mA) proton beams from 75 keV to 3 MeV

Criticalities

1. Complex object: tuning, sparking issues, . . .
2. Impact the beam behavior throughout the full length of the linac

Pole tips design driven by:

- surface electric field below $K_p = 1.8$
- overdesign for 100 mA
- maximize the transmission:
  - long pure bunching section, adiabaticity of the process
  - longitudinal acceptance
  - focalization forces
- integrate the mechanical and RF designs in the early stage of the BD

Voltage law

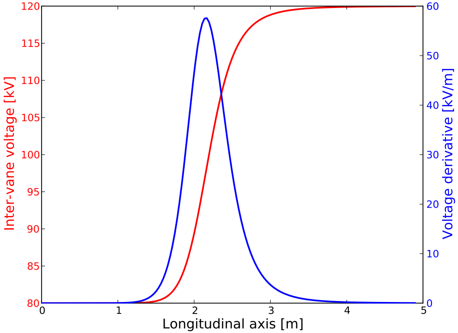

Figure: Inter-vane voltage and its derivative.

Variable inter-vane voltage

- BD goal: maintain the current limits while keeping large the value of the minimum aperture
- RF constraints:
  1. boundary conditions
  2. frequency shift:

$$\frac{\Delta f(z)}{f_0} = \frac{1}{2}\left(\frac{\lambda}{2\pi}\right)^2 \frac{1}{V(z)} \frac{\partial^2 V(z)}{\partial z^2}$$

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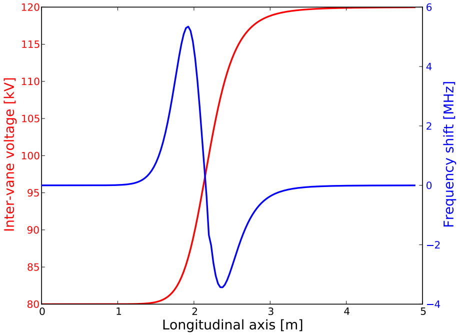

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The pole radius of curvature

Extrapolation of the Los Alamos tables

- first study with $\rho/R_0 = Const.$
- constant ρ is preferred for mechanical considerations (machining)
- Pb: some parameters used for generating the vane geometry can not be calculated from the Los Alamos tables (outside range)

→ Can we extrapolate the Los Alamos tables?

Yes: validated by 3D calculations

Figure: The IPHI RFQ.

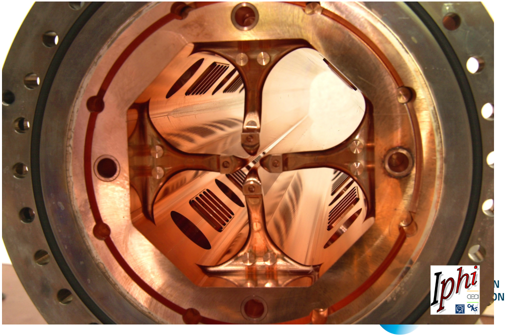

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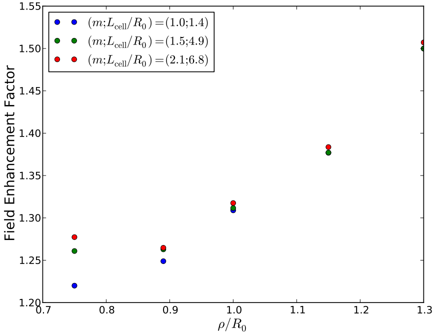
Figure: Field enhancement factor.



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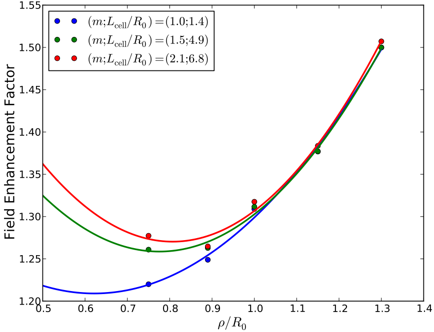

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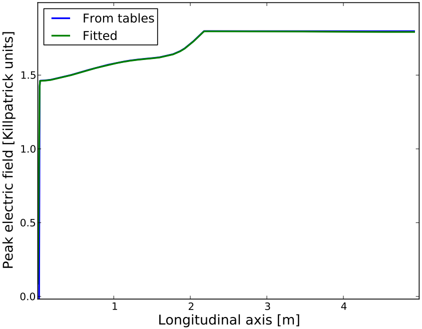
Figure: Killpatrick limit.



The pole radius of curvature

Comparative study

Results for $I = 100$ mA and 0.25 π.mm.mrad Waterbag input beam

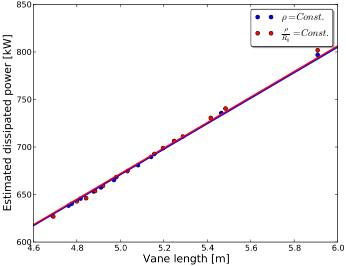


Figure: Power consumption.

1. power consumption: 135 kW/m (with $R_{\text{sh}} = 80$ kΩ.m)
2. transverse emittance
3. longitudinal emittance
4. transmission: Max. for $\rho = Const$ and $L \simeq 5$ m

Pole radius of curvature: $\rho = 3$ mm

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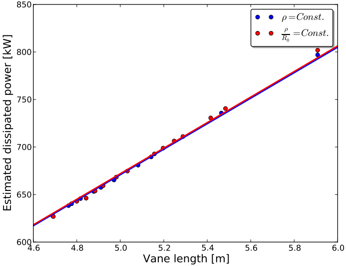

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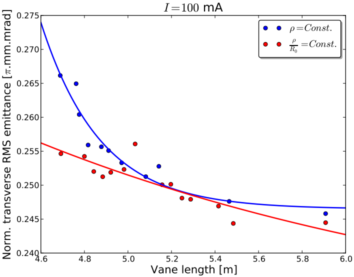

Figure: Transverse emittance.

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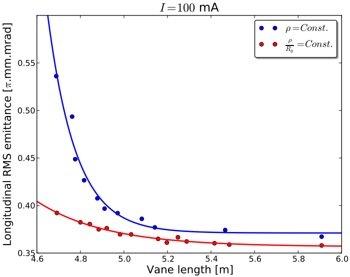

Figure: Longitudinal emittance.

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Pole radius of curvature: $\rho = 3$ mm

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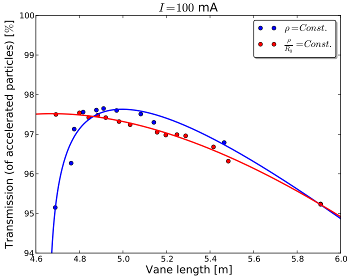

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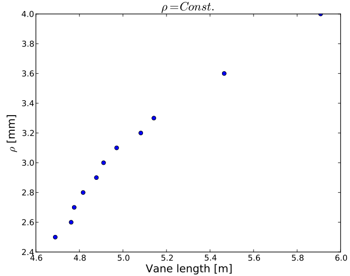

Figure: ρ as a function of vane length.

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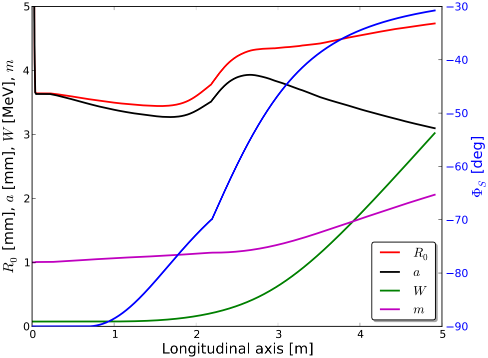
Pole radius of curvature: $\rho = 3$ mm

Geometry

RFQ pole geometry

- vane length: 4.95 m
- constant pole radius of curvature: $\rho = 3$ mm
- inter-vane voltage: from 80 to 120 kV
- max. modulation factor: $m < 2.06$
- min. aperture: $a > 3$ mm
- 5 segments of $\sim$ 1 m each

Figure: Some RFQ parameters.



Dynamics

At the RFQ output:

- no emittance growth is experienced
- very few particles are transmitted without the correct energy

Intensity (mA)	50	75	100
Trans. Em. growth [%]	~ 1	~ 1	~ 1
Long. Em. [°/MeV]	0.12217	0.1311	0.15611
Ac. Trans. [%]	99.59	98.87	97.56
Non Ac. Trans [%]	< 1	< 1	< 1
Est. klystron power [MW]	1.05	1.14	1.24

Table: Emittances and transmission (0.25 π.mm.mrad-Waterbag input beam).

Rmk: Estimated power with $P_k = 1.3 \times \left(\frac{R_{\text{sh}}}{2} \int V^2(z)\mathrm{d}z + P_{\text{beam}}\right)$

→ 3D objects to be included

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2D frequency and voltage law

- 3D RFQ frequency is set to 346 MHz without tuners
- position of the cavity back plane used to fit the 2D frequency law
- back plane width always grater than 86.9 mm $\rightarrow$ enough space to accommodate the 82 mm bore diameter tuners
- $\sim$ 1 cm excursion of the back plane with flat zones for pumping ports and tuners

Figure: 2D frequency.

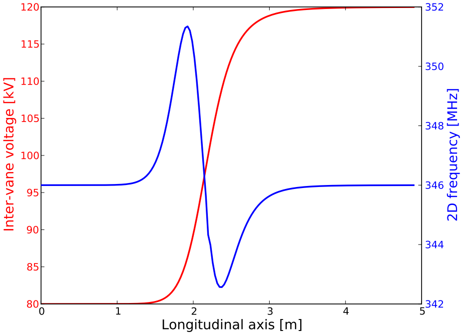

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Figure: 2D cross section of a quadrant.

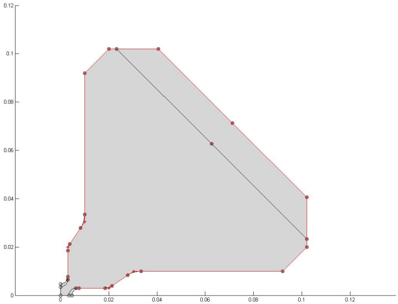

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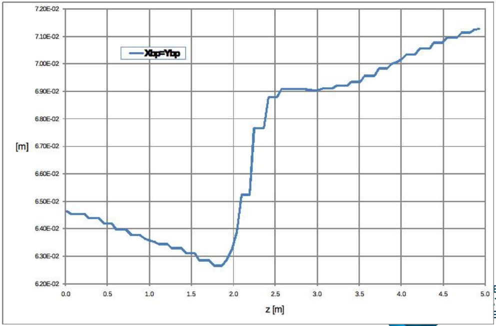
Figure: Position of the back plane vs. longitudinal axis.



End cells

Calculation tools: HFSS, Comsol and Opera

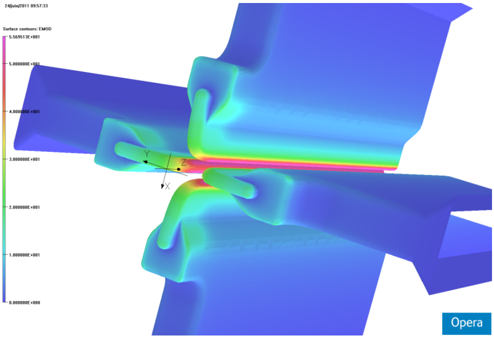


Figure: Vanes geometry at the RFQ entrance.

- RF stabilization: dipolar and quadrupolar rods
- mechanical design
- peak surface fields
- power deposition: $\sim$ 80 W/cm^2 and $\sim$ 150 W/cm^{2}at the entrance and at the exit respectively

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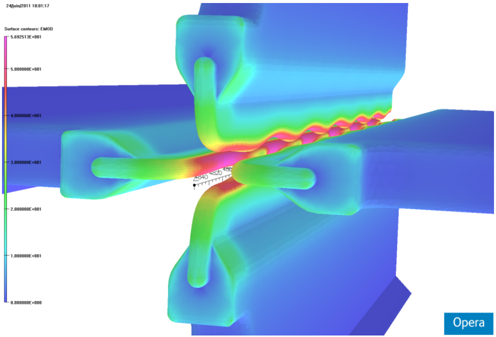

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RF coupling

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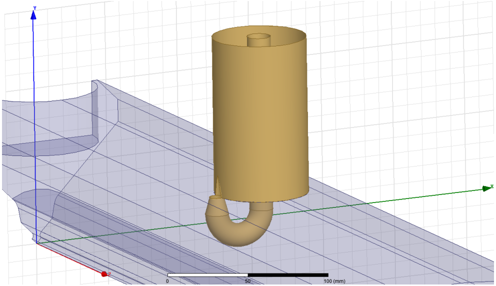

Figure: RF loop.

- RF loop (Spiral 2 and TRASCO)
- 4 couplers ×300 kW for 33.8 mm penetration (more penetration results in more coupling)
- voltage on axis unperturbed $(< 5.10^{-3})$
- final design needs a complete power evaluation

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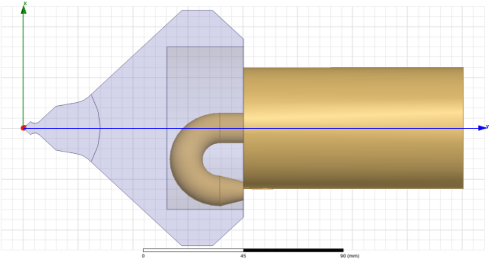

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Vacuum ports

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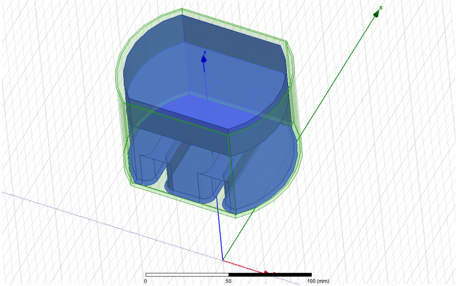

Figure: Vacuum port.

- validated CEA design for LINAC 4 RFQ
- $\sim$ 40 ports necessary
- penetration depth: very good agreement between calculations and measurements for the LINAC 4 RFQ
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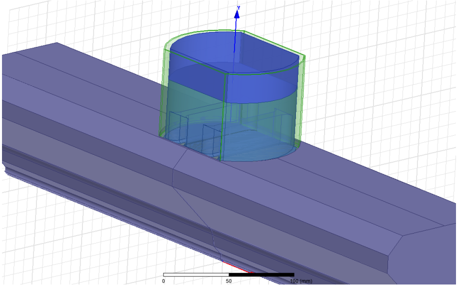

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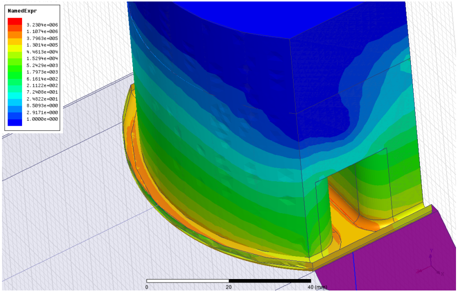

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Tuners

Calculation tools: Comsol and the 4-wire-transmission line model

- 15 (×4 quadrants) tuners equally spaced by 328 mm
- each 80 mm diameter tuner inserted in a 82 mm diameter boring
- tuner sensitivity and power deposition vs. penetration depth
- 4-wire-transmission line model:
    - RF stabilization
    - extreme position of tuners to correct potential mechanical errors

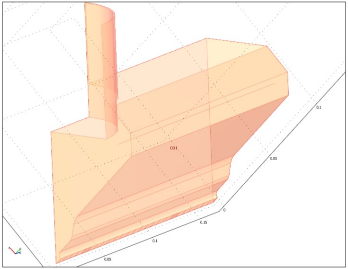

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Figure: Magnetic field on tuner #15 for 358.74 MHz.

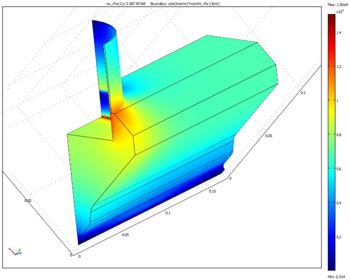

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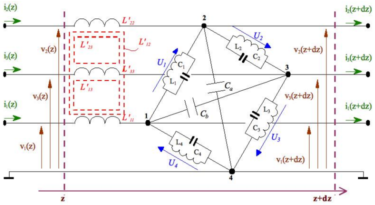
Figure: The 4-wire-transmission line.



Outline

What is the best emittance to inject in the RFQ?

⟶ We have studied the *transmission and the emittance evolution* for different input beam transverse emittances.

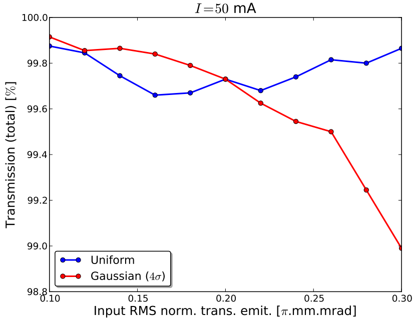


Figure: Transmission VS. input trans. emittance.

Transmission

- very sensitive to the input distribution
- remains very high over the all range

Emittances

Avoiding resonance exchanges and keeping the adiabaticity of the acceleration and bunching process leads to choose at the entrance of the RFQ: $\epsilon_{\mathrm{n,RMS}} = 0.20$ π.mm.mrad

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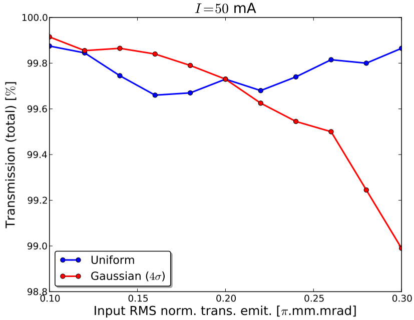

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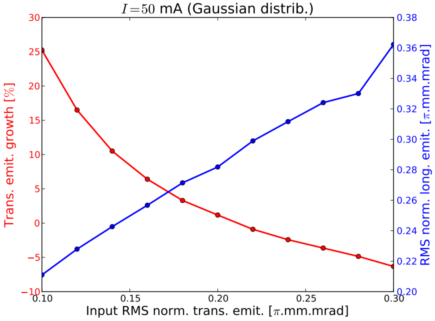

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RFQ as a chopper?

See "RFQ input to MEBT", presented at the ESS-Bilbao meeting on MEBT and Spoke Resonators, UPV/EHU, May 4-5 2011

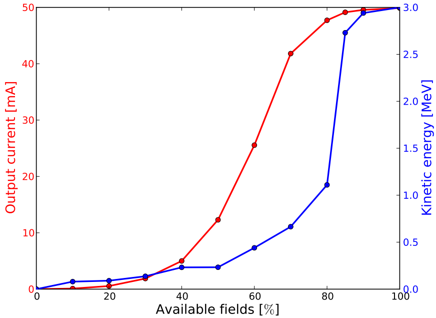

Figure: Current and energy vs. field availability.

Consequences:

- for the RFQ: damage due to the localization of the losses?
- for the MEBT: should not be a concern before the fields have reached 80 % availability

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Conclusions

1. Beam dynamics study is finalized
   → *ESS milestone* on the pole tips geometry to be delivered this summer
2. RF cavity design well advanced and in good progress
3. Thermo-mechanical calculations to be launched in September 2011
   → *ESS milestone* to be delivered early 2012

ESS RFQ design progress is strengthened by a good collaboration within the CEA-Saclay team: vicinity and commitment of people in different fields

ESS RFQ Saclay design meetings held on a regular basis

Acknowledgment

Many thanks to the CEA-Saclay team for its fruitful help in the preparation of this talk and for providing me with numerous images and graphs:
O. Delferrière, M. Desmons, R. Duperrier, A. C. France, O. Piquet and B. Pottin