ESS LINAC DESIGN

AND

COST OPTIMIZATION

AS A FUNCTION OF

BEAM DYNAMICS

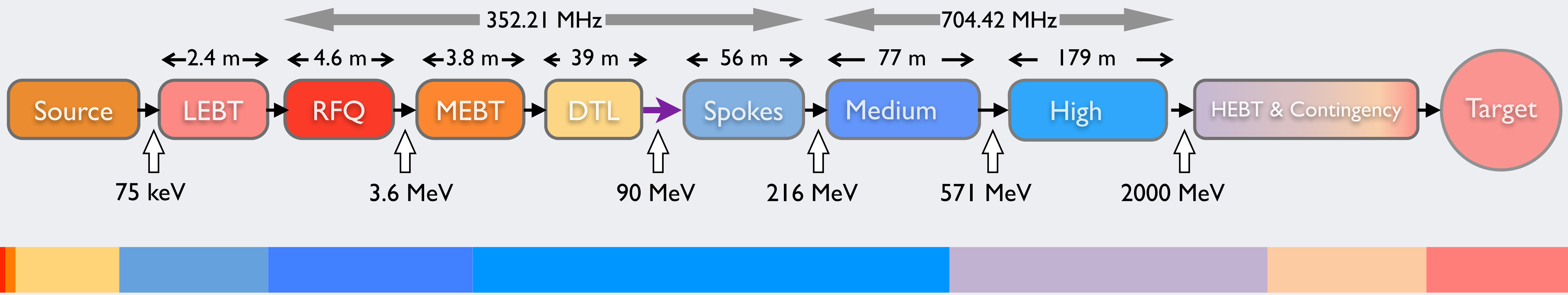
Mamad Eshraqi

HB 2014 , East Lansing, November 11

THE ESS

- **Power: 5 MW**
- **Energy: 2.0 GeV**
- **Current: 62.5 mA**
- **Repetition rate: 14 Hz**
- **Pulse length: 2.86 ms**
- **Duty cycle: 4%**
- **High reliability (>95%)**
- **Ions: p**

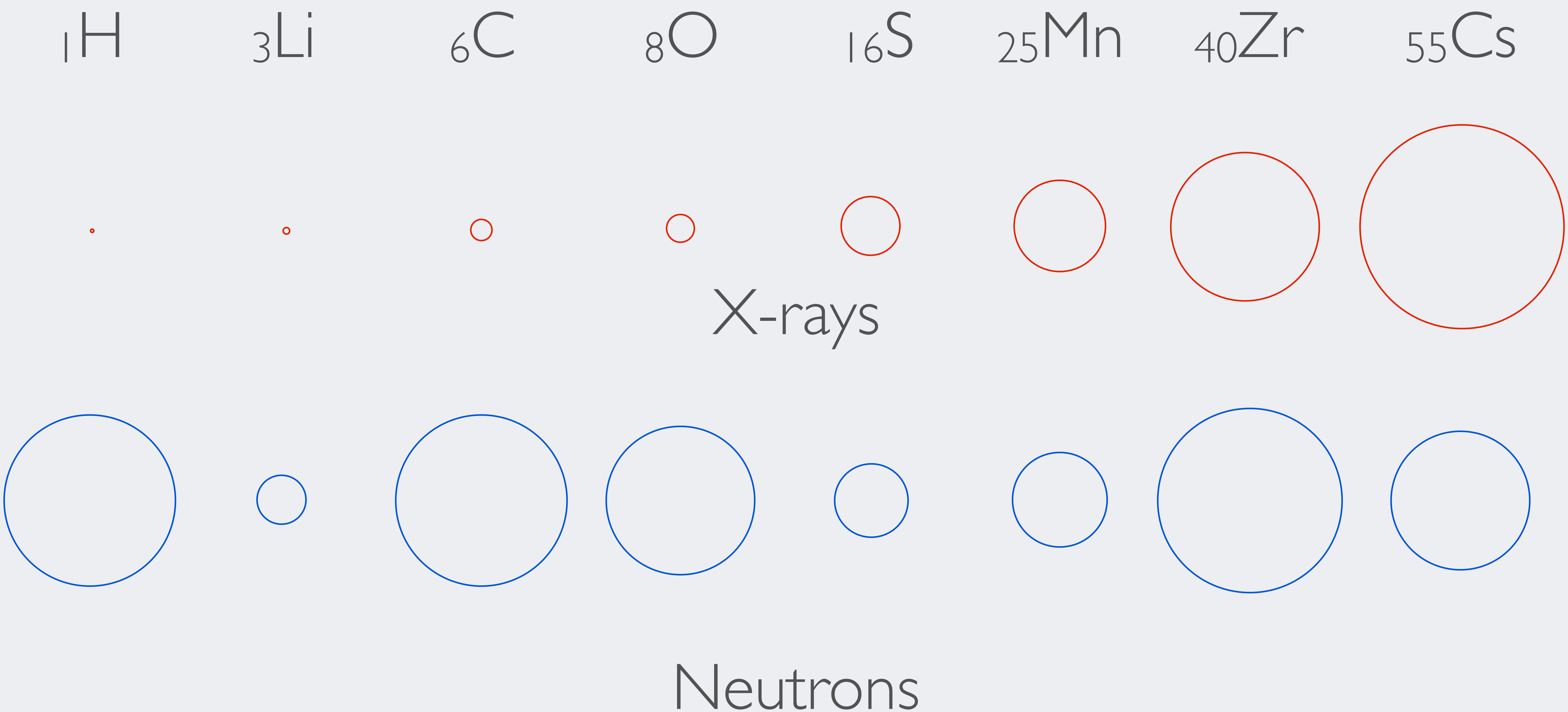
THE ESS LINAC



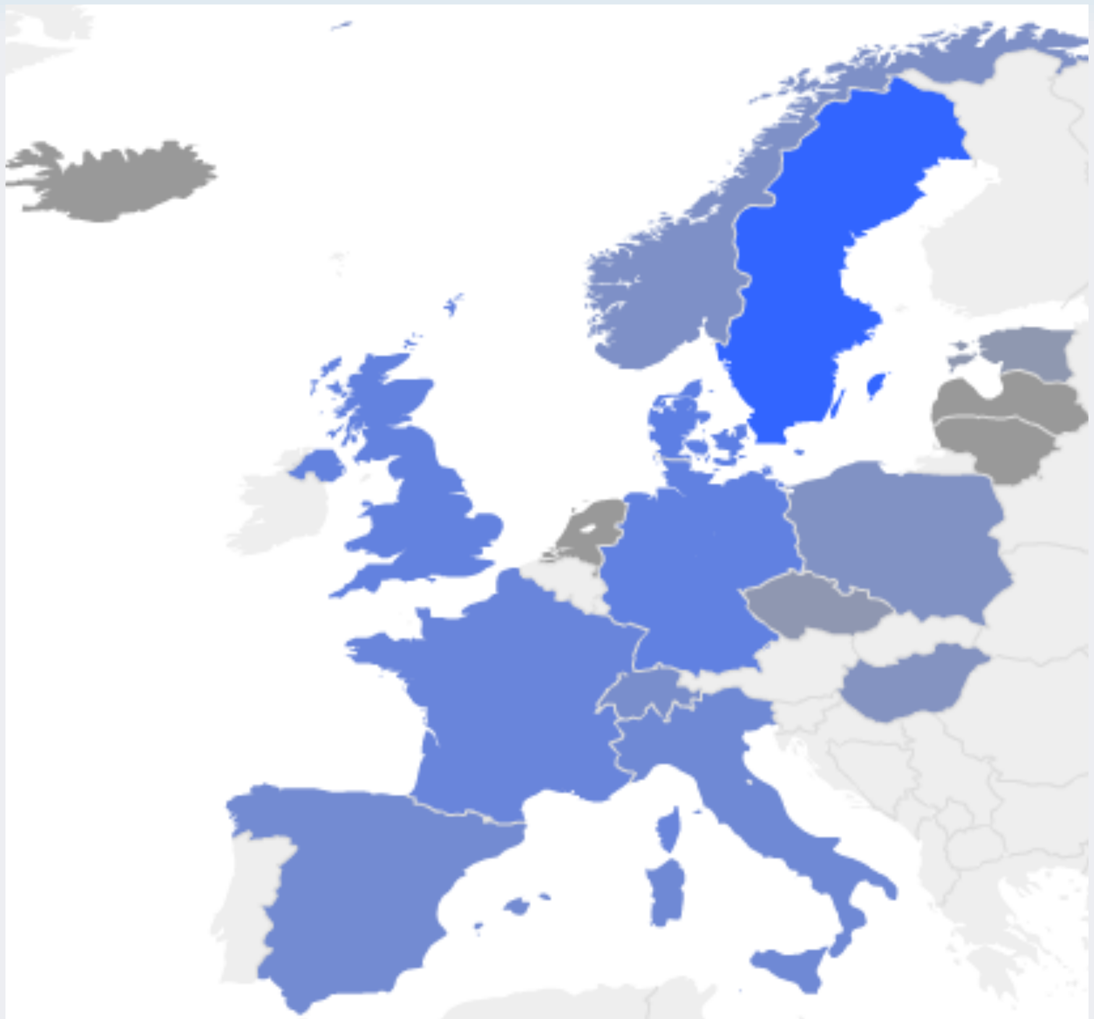
	Length (m)	W_in (MeV)	F (MHz)	β Geometric	No. Sections	T (K)
LEBT	2.38	0.075	--	--	1	~300
RFQ	4.6	0.075	352.21	--	1	~300
MEBT	3.81	3.62	352.21	--	1	~300
DTL	38.9	3.62	352.21	--	5	~300
LEDP + Spoke	55.9	89.8	352.21	0.50	13	~2
Medium Beta	76.7	216.3	704.42	0.67	9	~2
High Beta	178.9	571.5	704.42	0.86	21	~2
Contingency	119.3	2000	704.42	(0.86)	14	~300 / ~2

WHY NEUTRONS

Cross section of different atoms with photons and neutrons



INTERNATIONAL COLLABORATION



17 Partners today

Investment: 1.843 G€ (indexed)
Operation: 140 M€
Decommissioning: 346 M€

~50% ~30% ~15% ~5%

Complete and operate the best and ***most powerful neutron source*** *in the world by the end of* ***the decade****.*

European Spallation Source

DEFINING THE GOAL

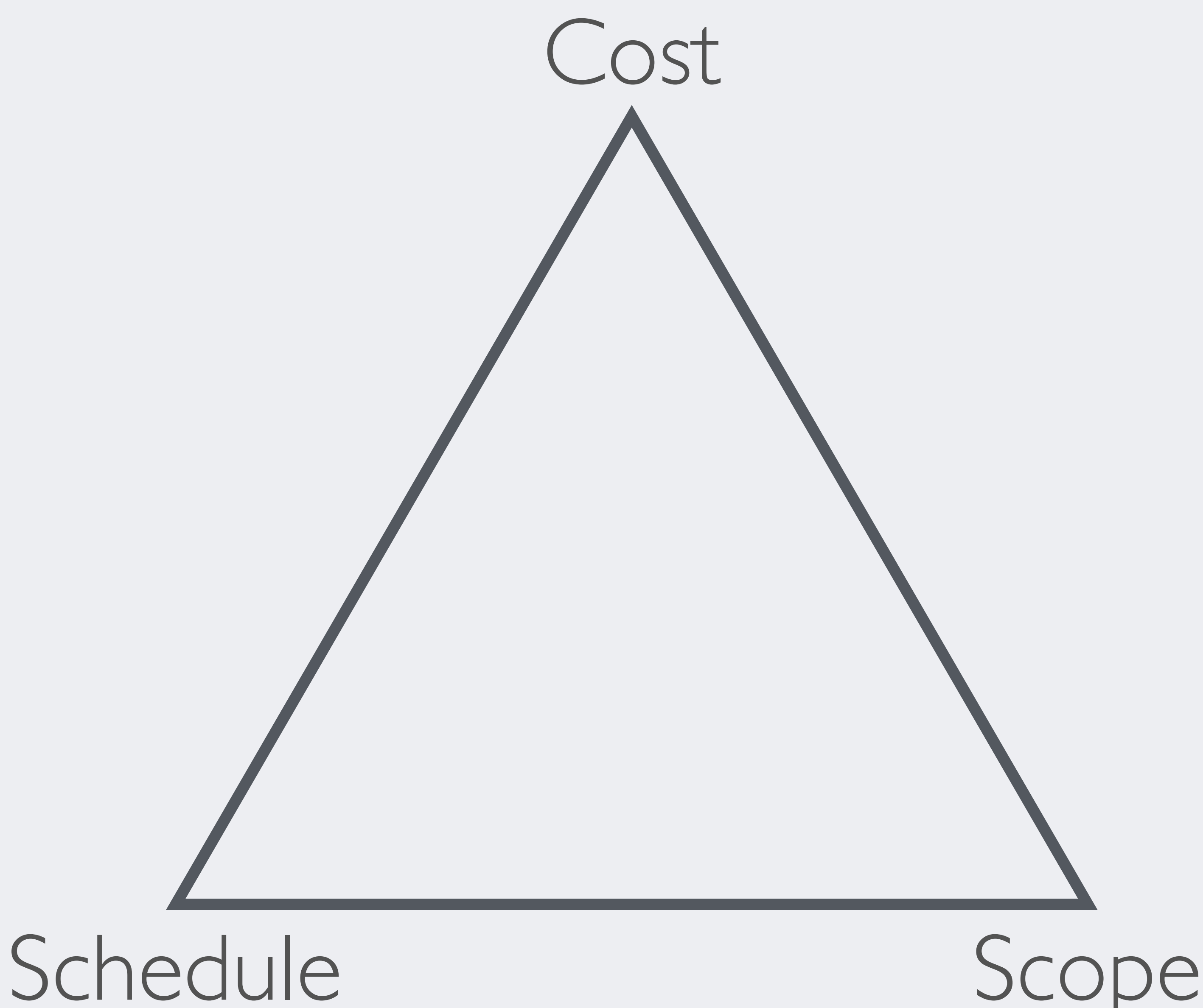
I believe that this nation should commit itself to achieving the goal, before ***this decade*** *is out, of* ***landing a man on the moon*** *and returning him safely to the earth.*

President Kennedy

Address to Congress on Urgent National Needs, 1961 May 25

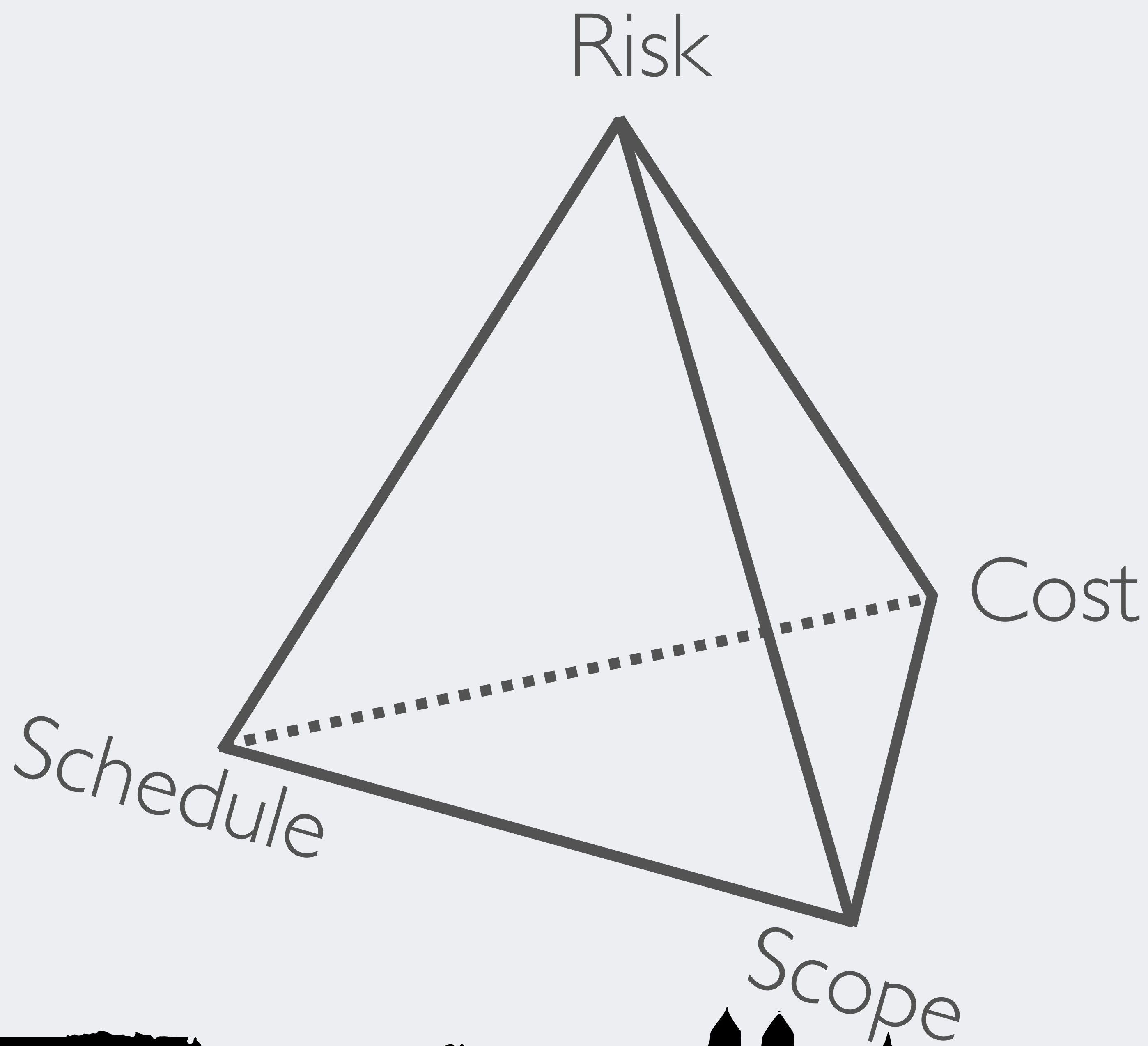
CONSTRAINTS

Each project should respect these three boundary conditions, where adjusting one affects the other two.



CONSTRAINTS

The only way to adjust the project cost/schedule/scope without affecting the other two is through adding risk to the project.



BEAM POWER

- Assuming a defined beam power:

$$P_b = I_b \cdot W_{linac}$$

$$I_b = I_{max} \cdot f_{pulse} \cdot L_{pulse} = I_{max} \cdot d.c.$$

$$W_{linac} = q \sum_i E_{acc_i} \; T_i \; L_i \; \cos(\phi_i)$$

ESS Accelerator's chief engineer Dave McGinnis

BEAM POWER

$$L_i = M_{cell_i} \cdot \frac{\beta_{g_i}\lambda_i}{n_i}$$

$$E_{acc_i} = E_{pk}\left(\frac{E_{acc}(\beta_g)}{E_{pk}}\right) = E_{peak} \cdot f_{acc}(\beta_g)$$

$$P_b = q \cdot I_{max} \cdot d.c. \cdot k \cdot E_{peak} \cdot \sum_i f_{acc}(\beta_g)\ T_i\ M_{cell_i} \cdot \frac{\beta_{g_i}\lambda_i}{n_i}\ \cos(\phi_i)$$

PARAMETERS TO PLAY WITH

$$P_b = q \cdot I_{max} \cdot d.c. \cdot k \cdot E_{peak} \cdot \sum_i f_{acc}(\beta_g)\ T_i\ M_{cell_i} \cdot \frac{\beta_{g_i}\lambda_i}{n_i}\ \cos(\phi_i)$$

E_{pk} : Peak electric surface field

I_{max} : Maximum current

$d.c.$: Duty cycle

β_g : Geometric beta

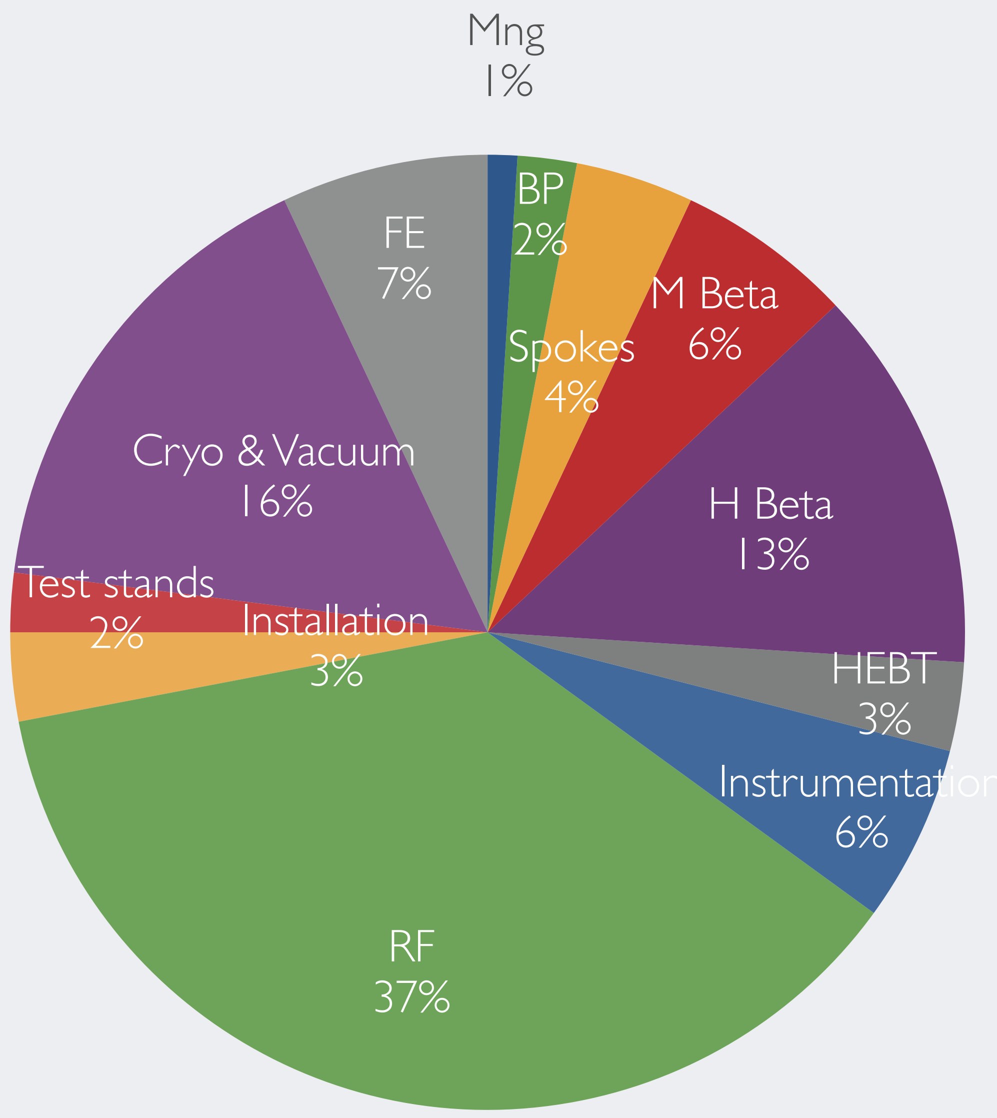
T : Transit time factor (by optimizing the geometric beta and transition energies)

ϕ_s : Synchronous phase

k : Scaling factor of the cavity fields wrt their max field.

COST CONTRIBUTORS

- Elliptical cryomodules occupy 19% of the cost
  - There are 45 elliptical cryomodules
  - The cryogenic plant absorbs 14% of the total cost.
- RF systems comprise 37% of the cost
  - The RF costs are distributed over five major systems
  - The elliptical section comprises 82% of the RF system cost
- For the elliptical section
  - 62% of the total cost of the linac
  - the klystrons and modulators comprise 80% of the RF system cost
  - 95% of the acceleration energy



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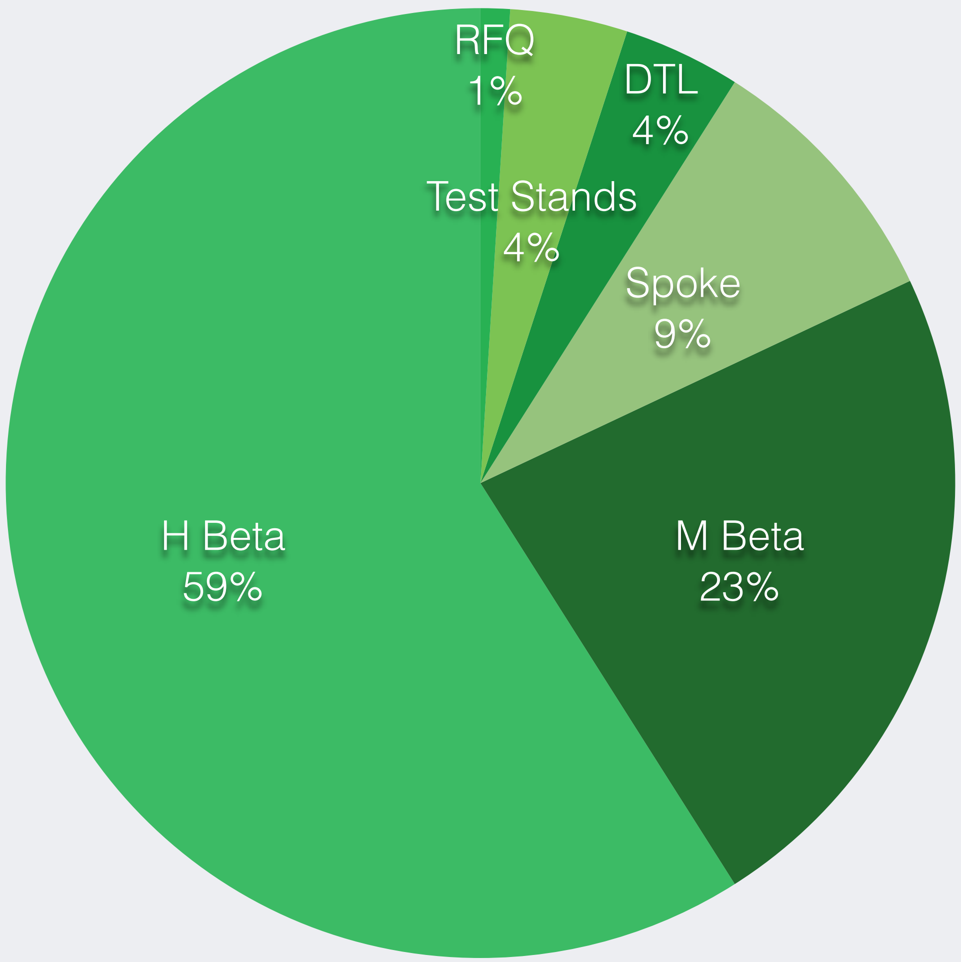
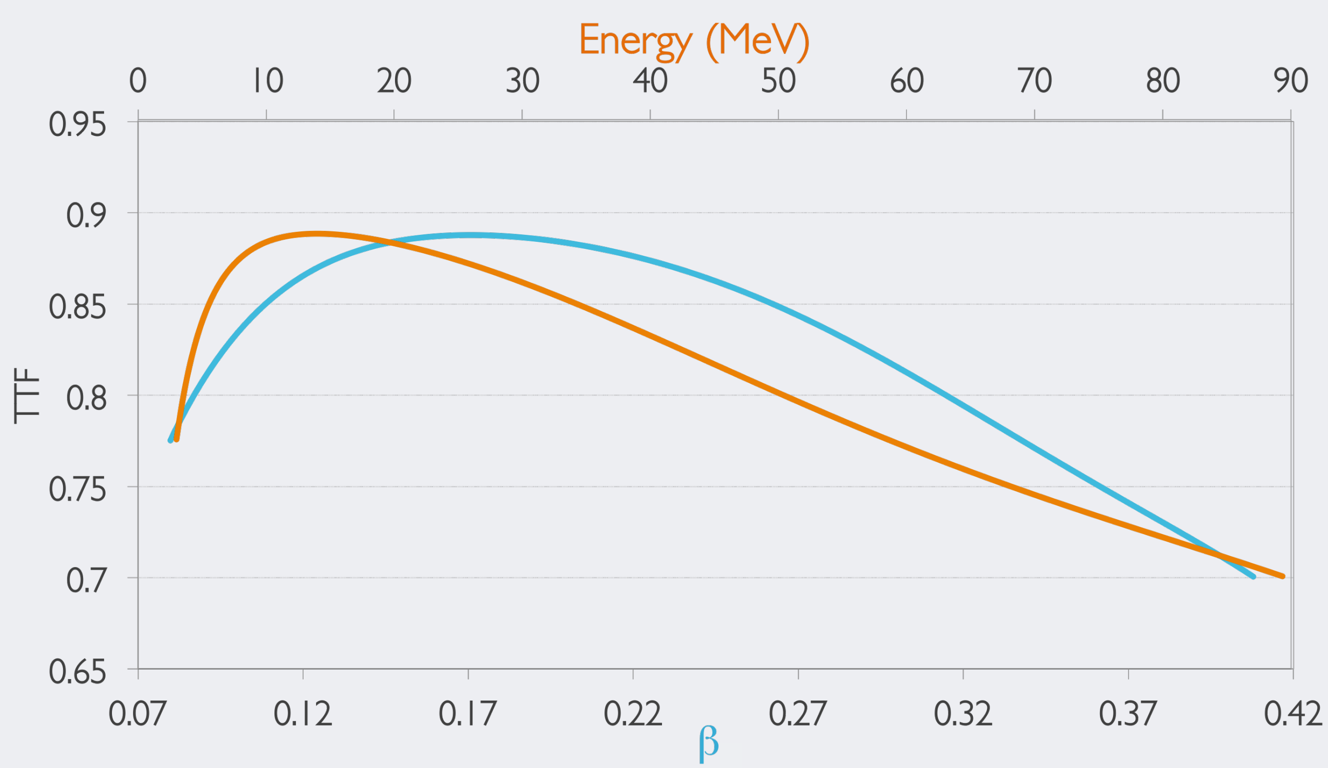


Dave McGinnis, "New Design Approaches for High Intensity Superconducting Linacs – The New ESS Linac Design", IPAC 2014

RFQ DTL TRANSITION

- The ESS RFQ gets a higher separation between dipole and quadrupole mode if its length is increased to 4.5 m*
- The TTF increases in DTL with energy, cells get longer (easier to build, longer PMQs with loser peak field), gaps get longer (lower spark rate), …
- These two lead an RFQ with 3.62 MeV of output energy

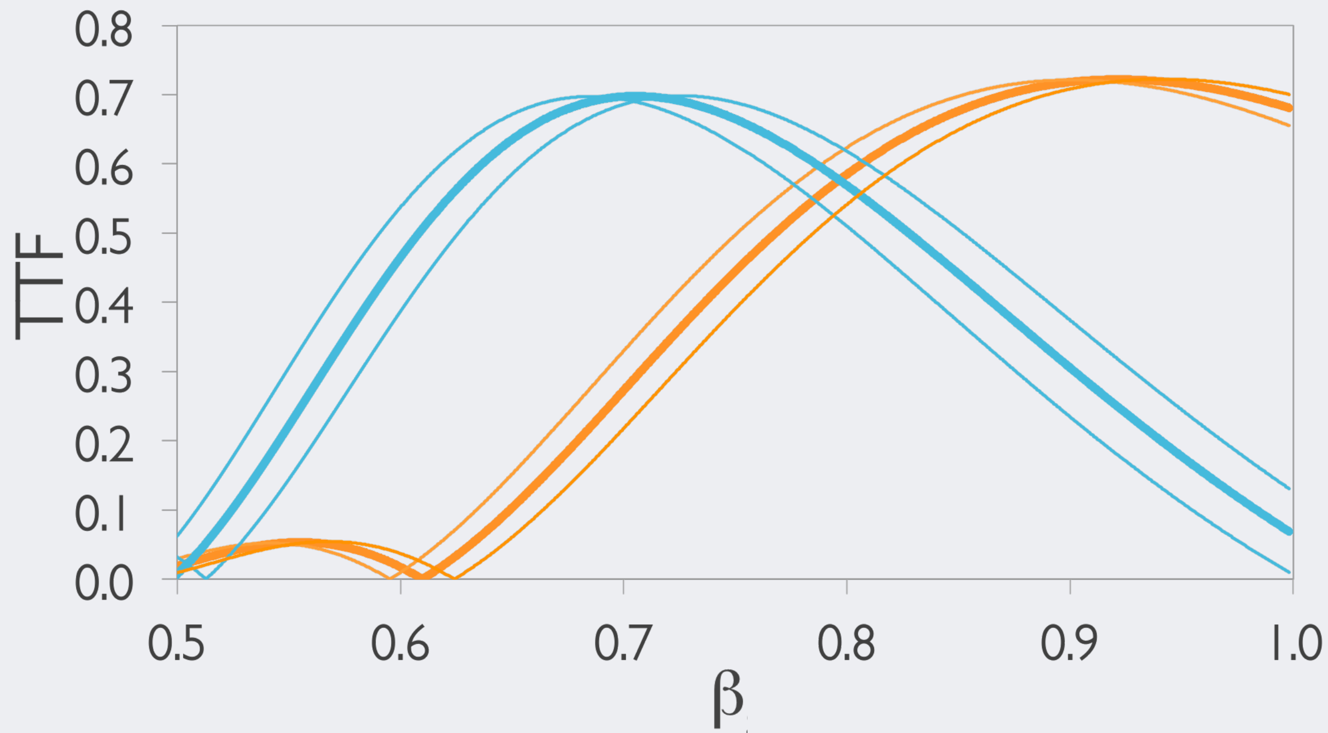


Transit time factor vs particle β and energy in DTL

* A. France, "Advanced RF Design and Tuning Methods of RFQ for High Intensity Proton Linacs", IPAC14

TTF AND TRANSITIONS

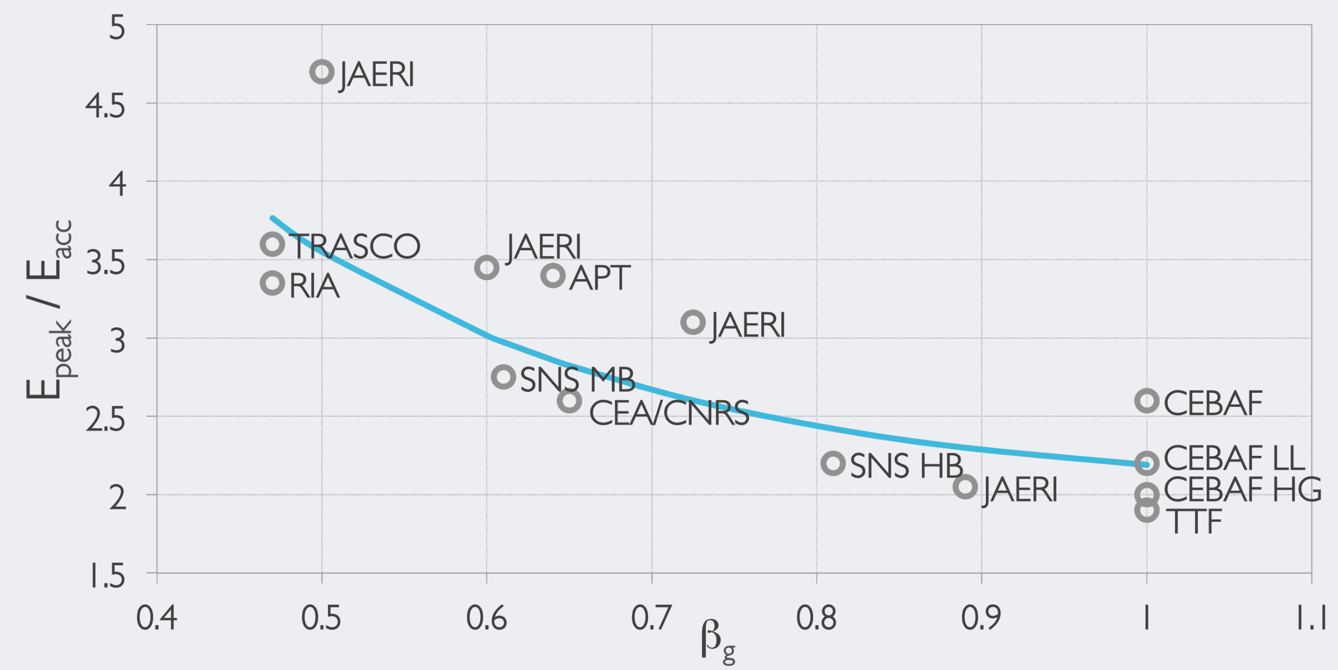
- In the SC structures, one intends to reduce the number of sections for reduced transitions (Beam physics POV), and engineering (Cost POV).
- This forces the designer to find a solution where the integral of TTF is the highest over the range
- A high average T is achieved by choosing the transition energies and geometric betas of cavities



TTF and transition between medium and high β section

ACCELERATING FIELD

- The accelerating gradient of the cavities are simulated based on a given cavity shape
- The cavity shape (geometric beta) should be defined by beam physics where the cavity field is needed to design a linac/accelerator
- One way out of this closed loop is to rely on already simulated cavities

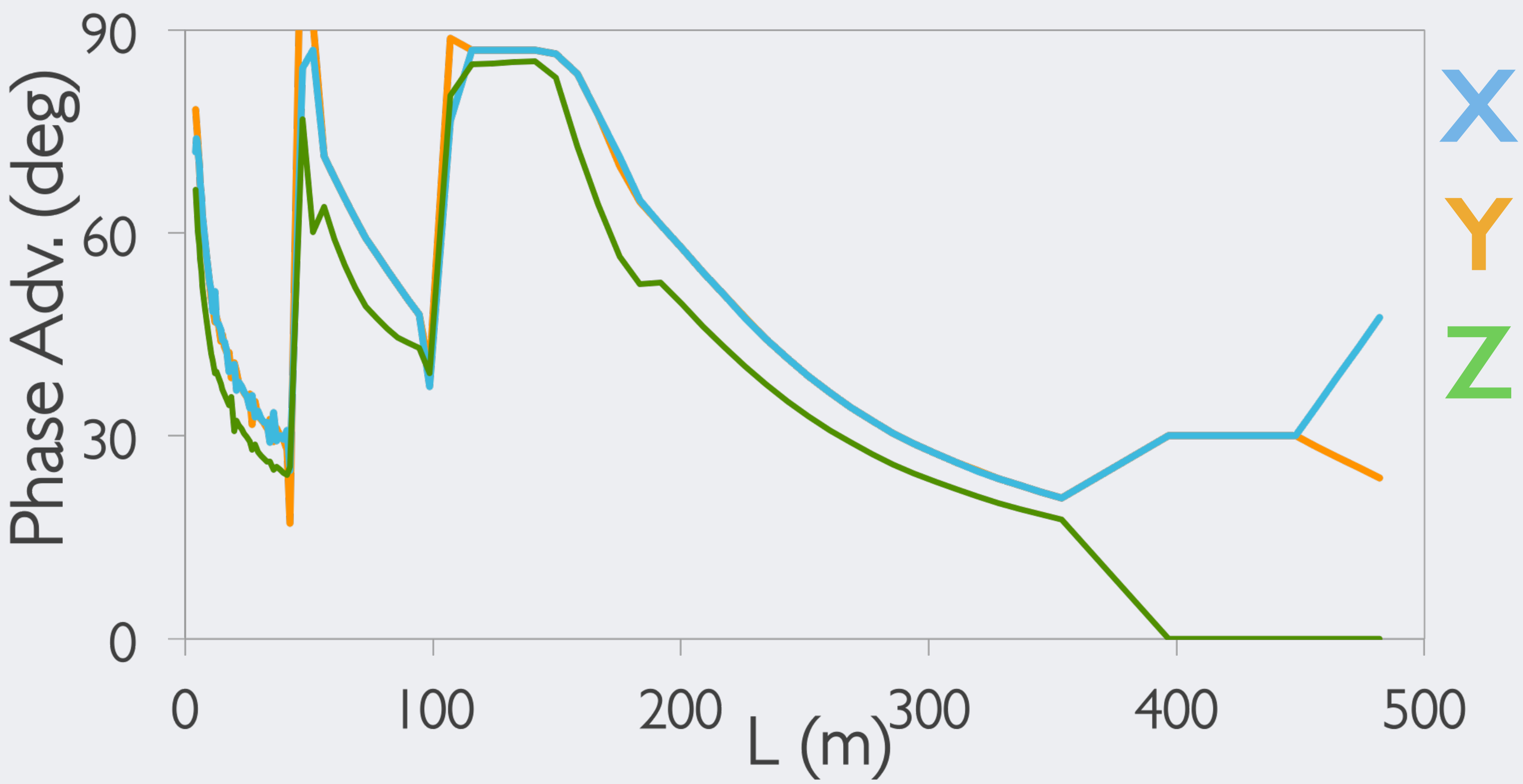


Surface electric field to accelerating field ratio as a function of β in superconducting elliptical cavities

Courtesy of Paolo Pierini

RULES OF THUMB

- Phase advance per period < 90 degrees



- Smooth average phase advance
- Avoiding strong tune depression

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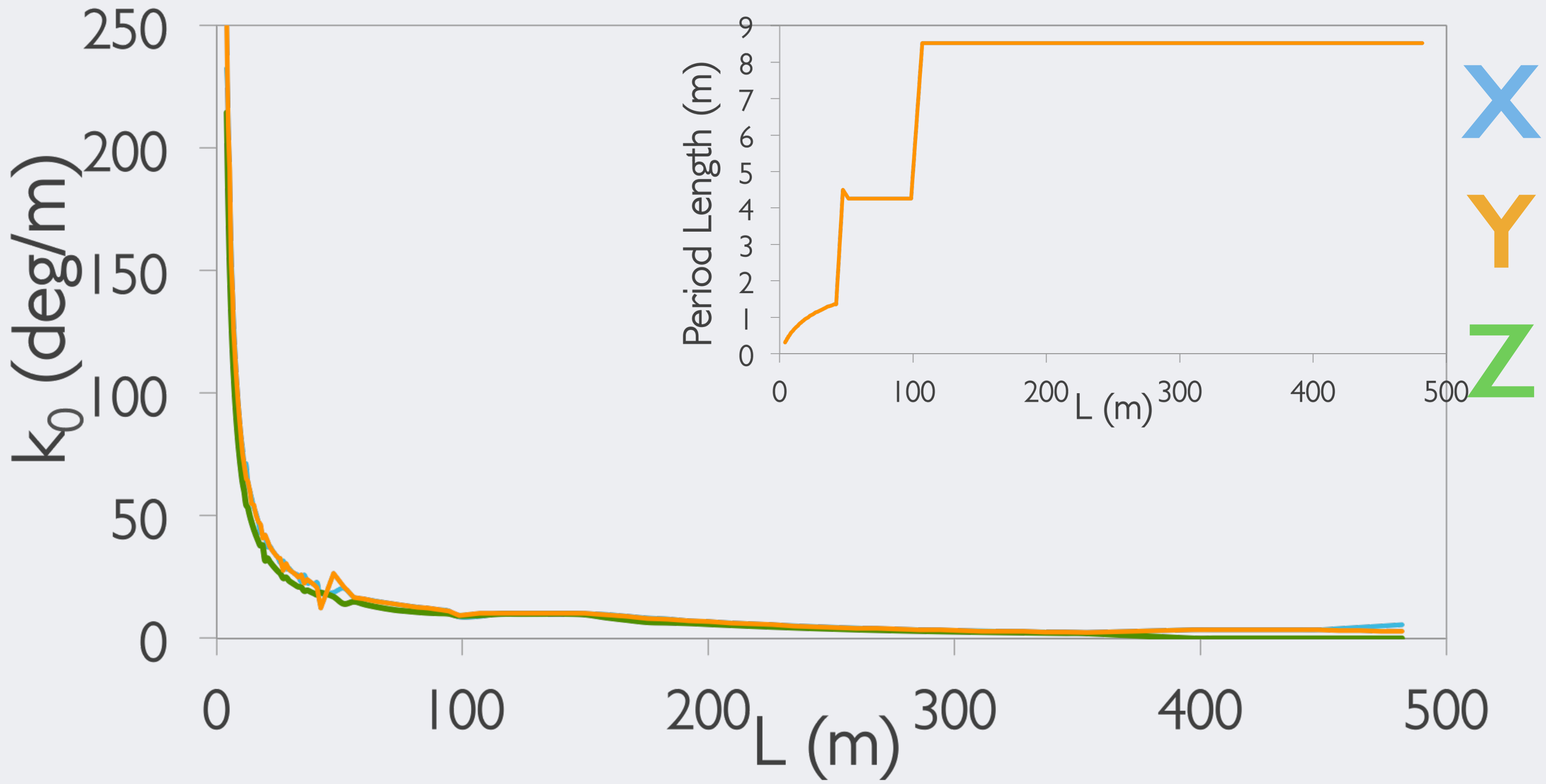

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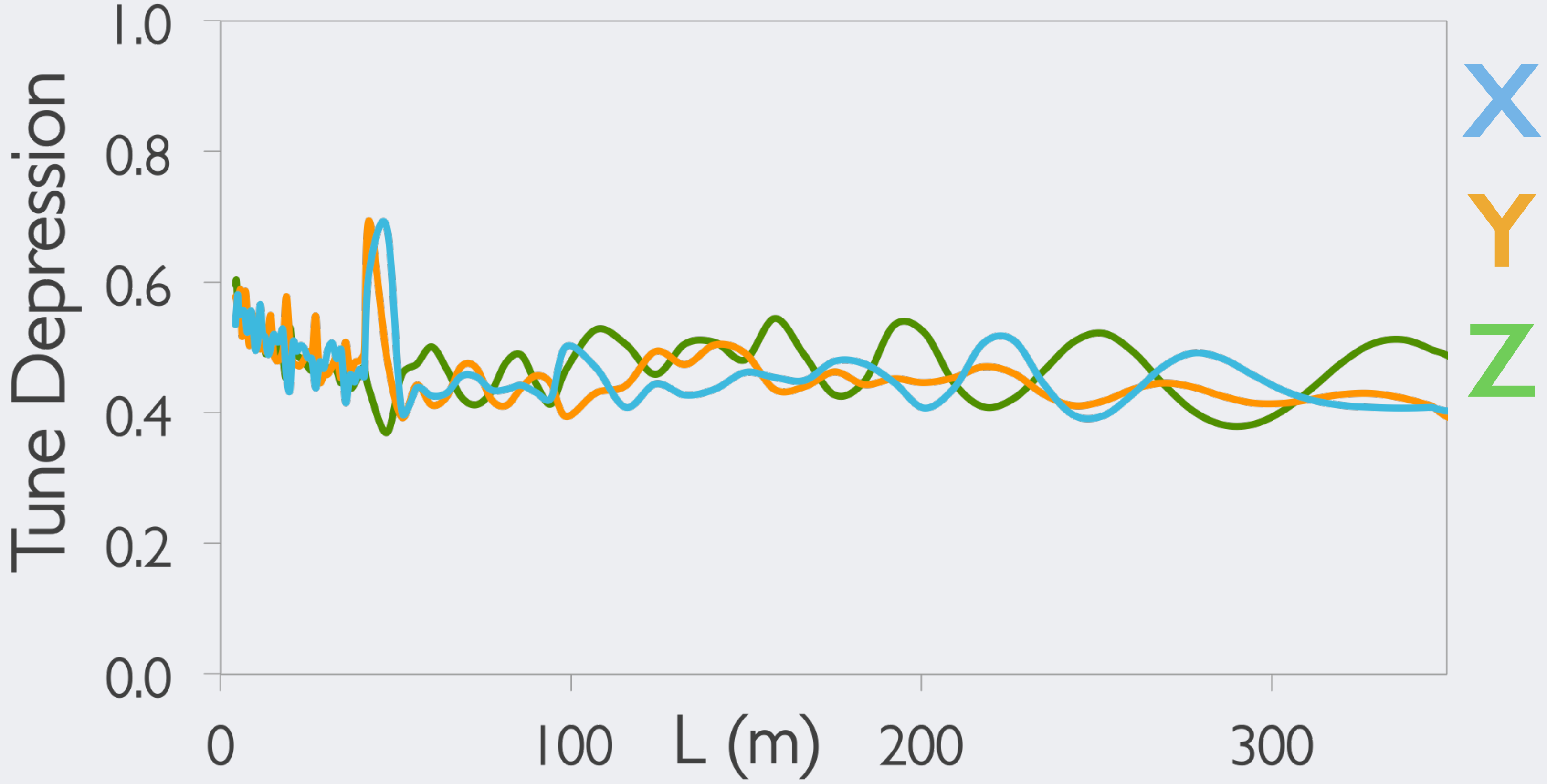
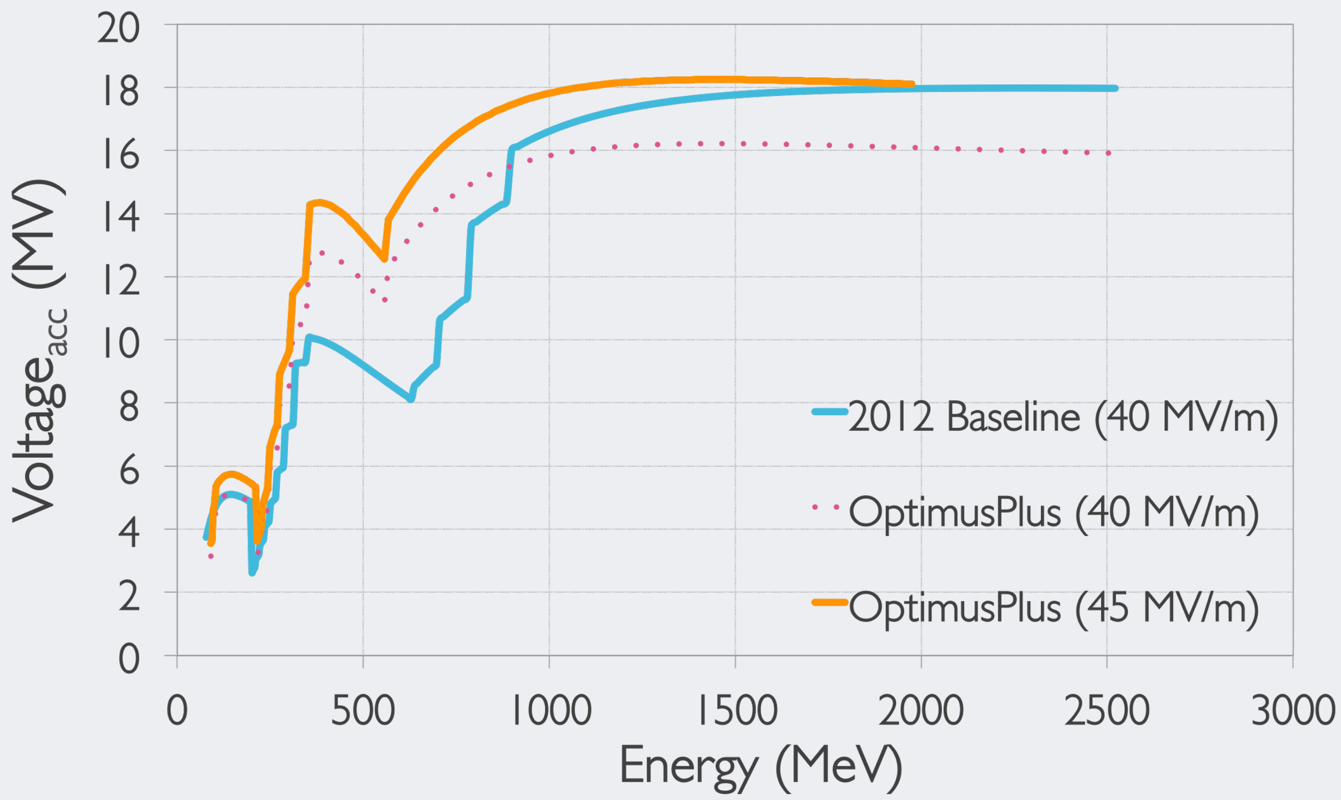


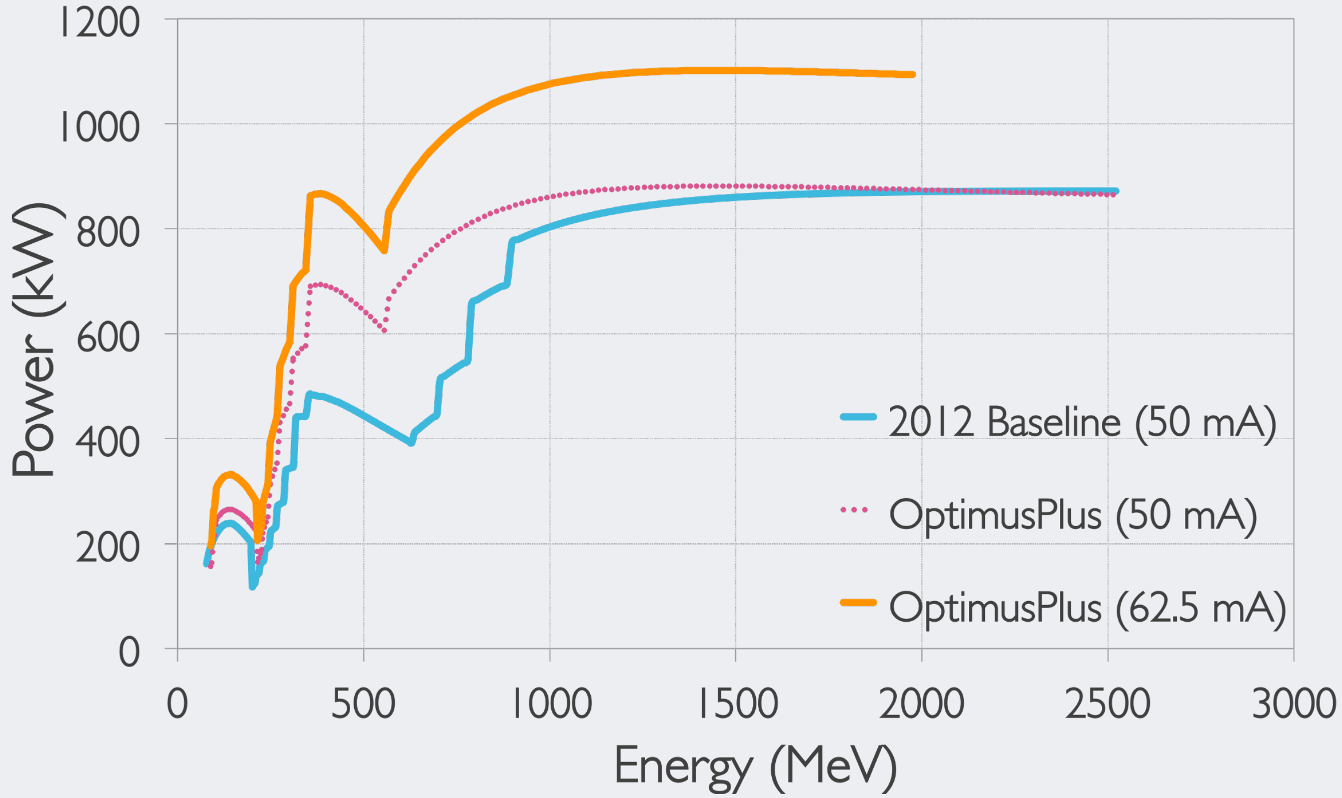
USING THE CAVITIES AT THEIR BEST

- To have a smooth phase advance / limited phase advance, one needs to set a limit on the cavity voltages around transition (Blue and Dotted lines)
- This causes the cavities to work "inefficiently", therefore requiring additional cavities to compensate for this loss of energy gain
- One can though design a structure where the losses are minimized (Orange line)

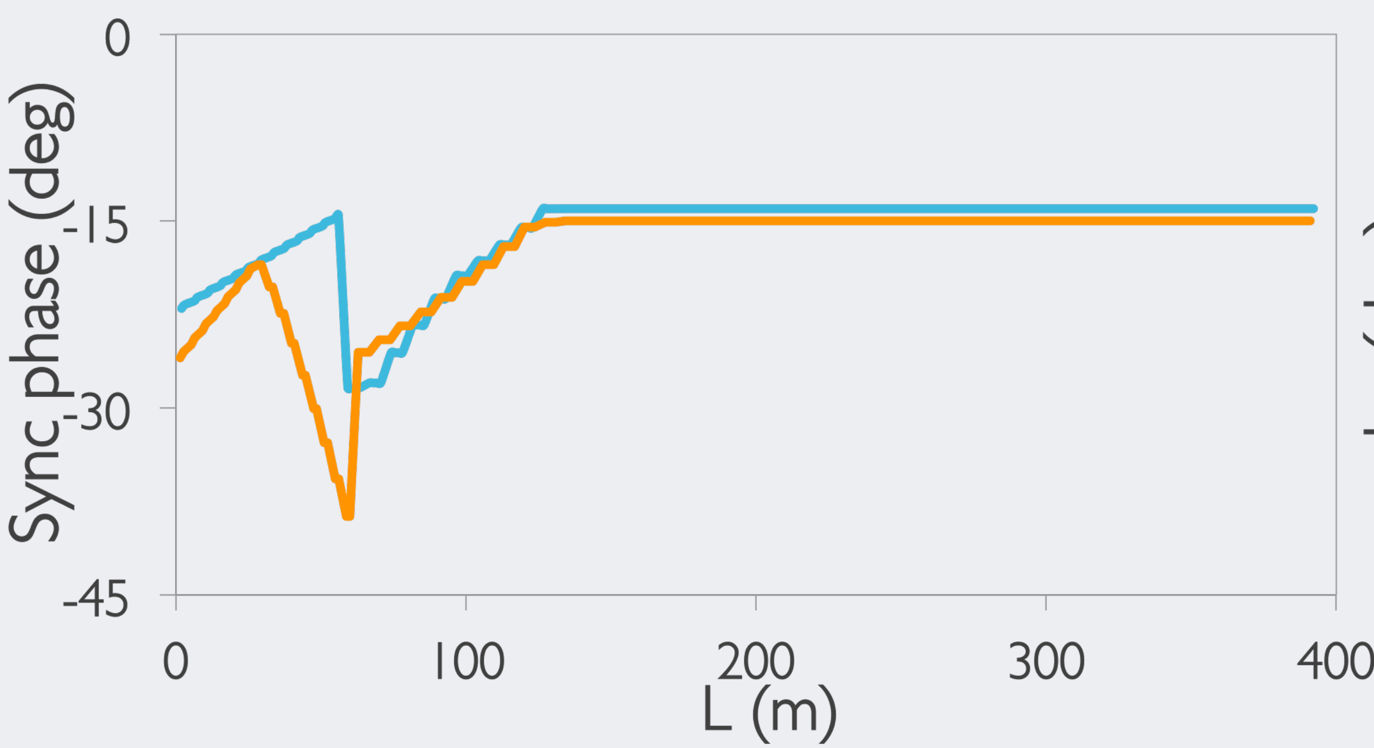


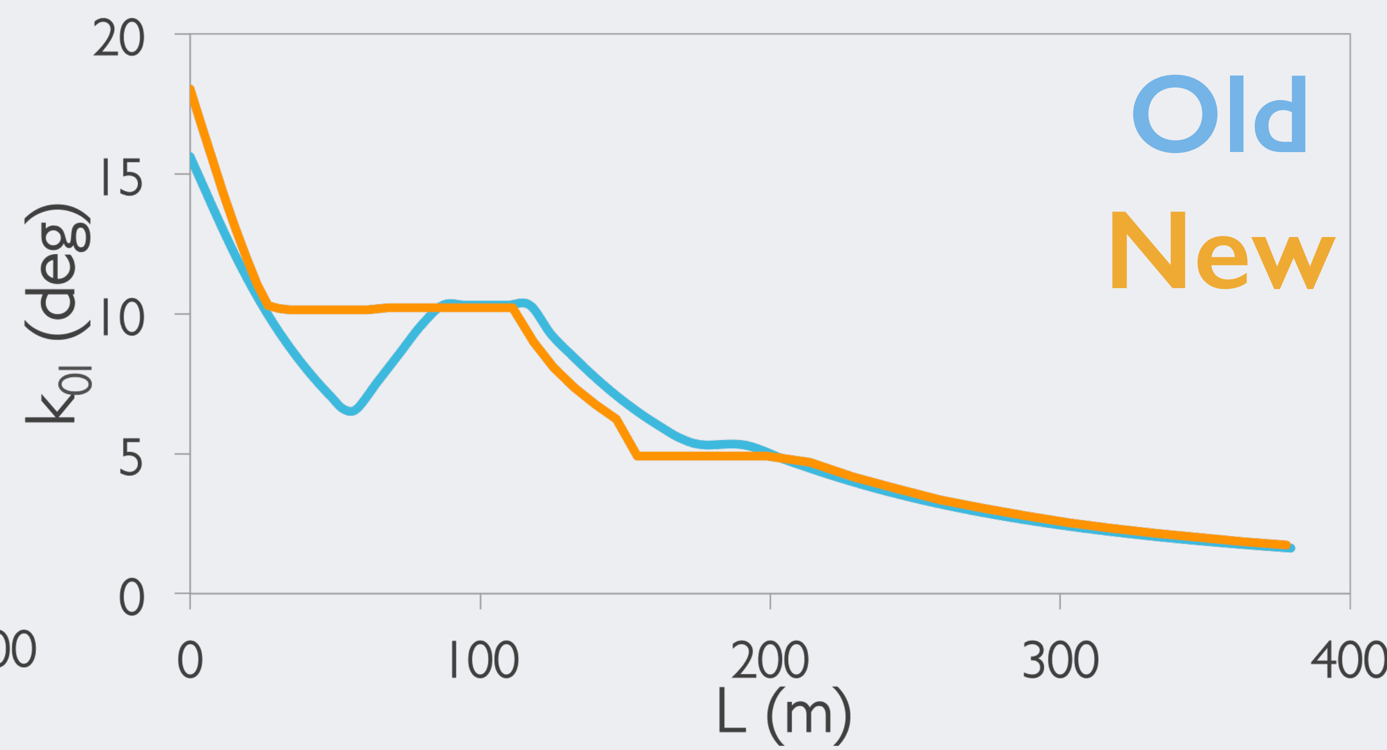
POWER PROFILE

- Though the intention of this optimization (and talk), was not reduction of the operational cost, the byproduct is a reduced power consumption.
- Klystron efficiency increases when it is operated at full power, having a higher number of cavities at higher power saves power/money!



SYNC. PHASE & PHASE ADV.





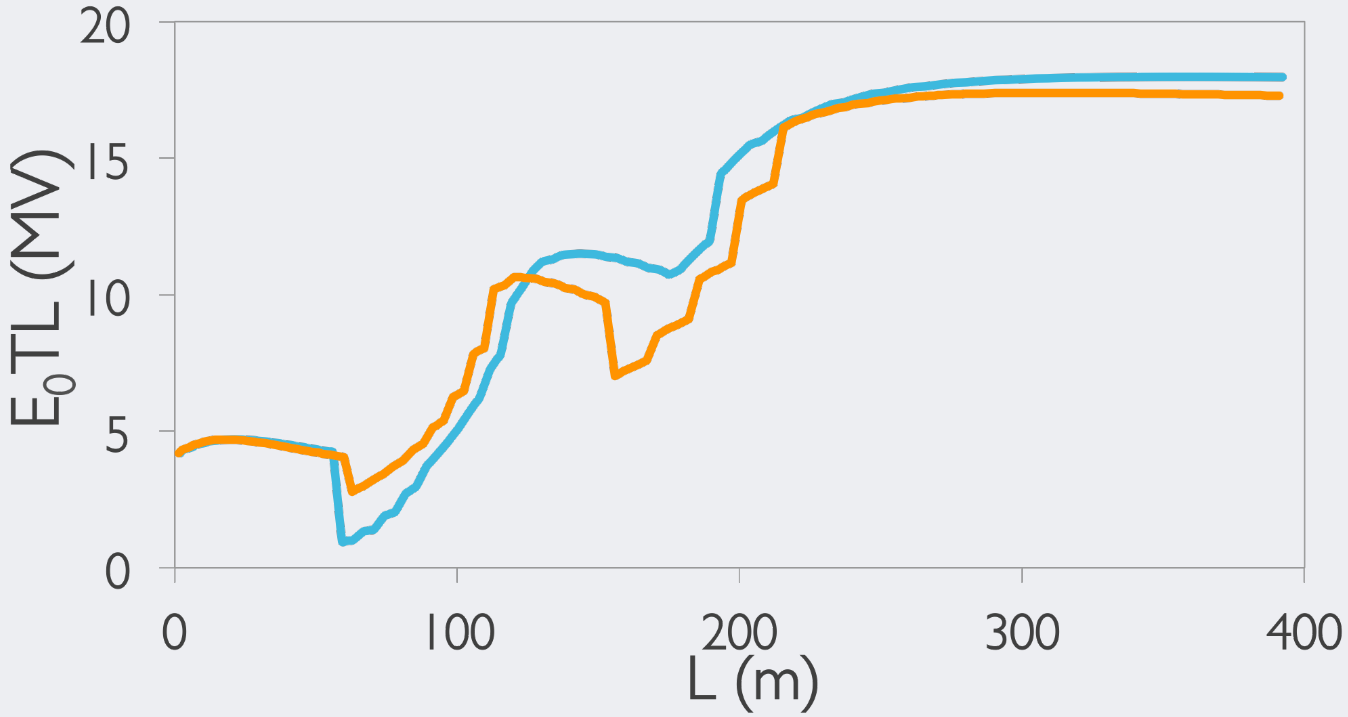
$$\phi_{704.42} = 2 \times \phi_{352.21}$$

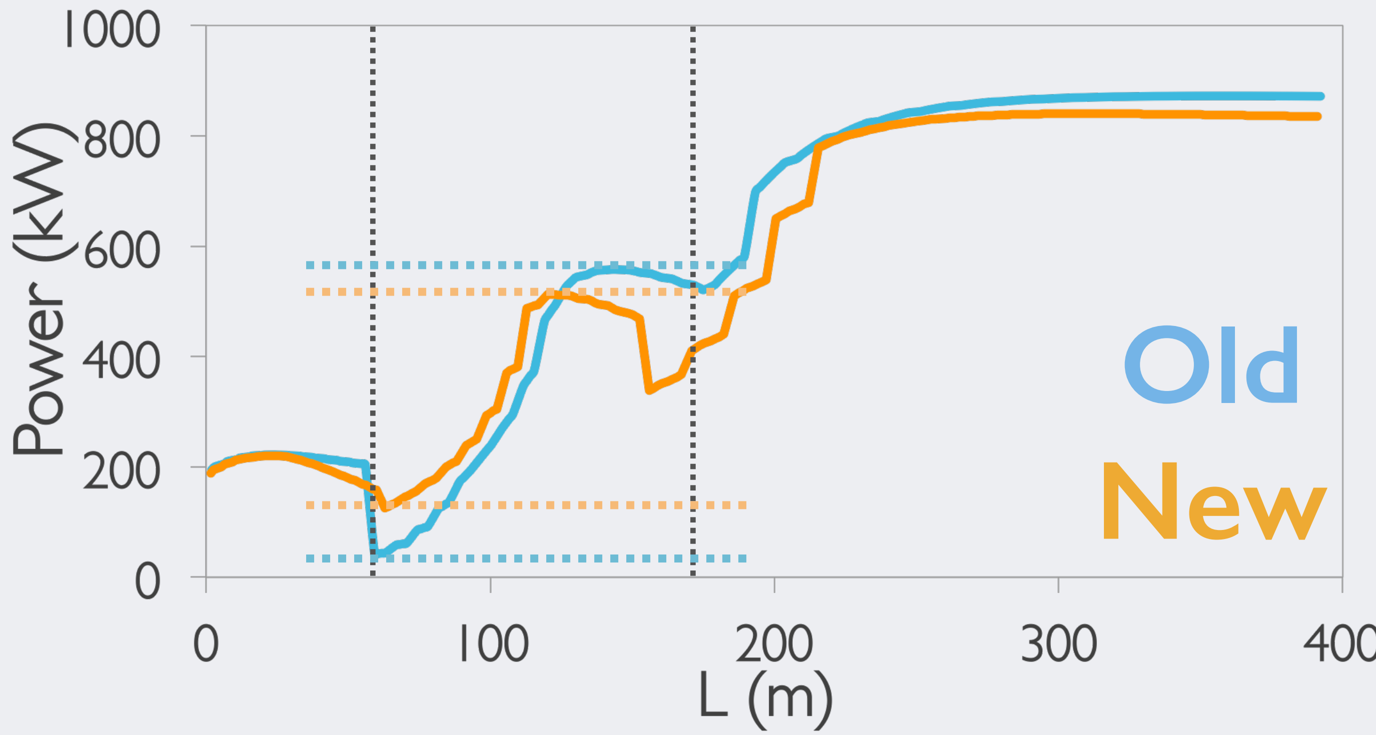
$$\lambda_{704.42} = 0.5 \times \lambda_{352.21}$$

$$k_{0l}^2 = \frac{2\pi q E_{acc} T \sin(-\phi_s)}{mc^2 \beta_s^3 \gamma_s^3 \lambda}$$

R. Duperrier, N. Pichoff, and D. Uriot, "Frequency jump in an ion linac", PR ST-AB **10**, 084201 (2007)

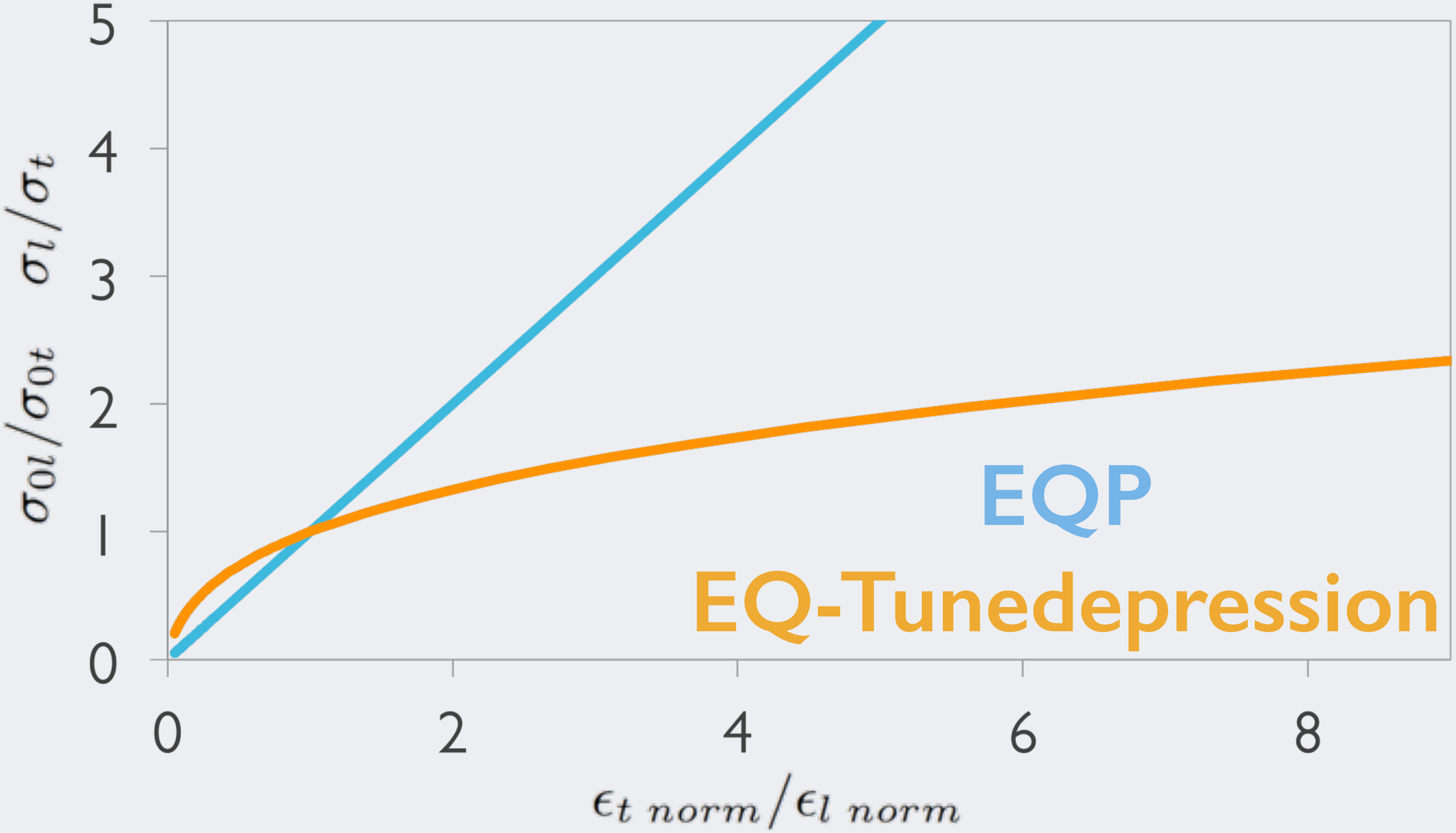
VOLTAGE & POWER





Power ratio: **~4** vs. **~13**

OPTIMIZED BEAM PHYSICS

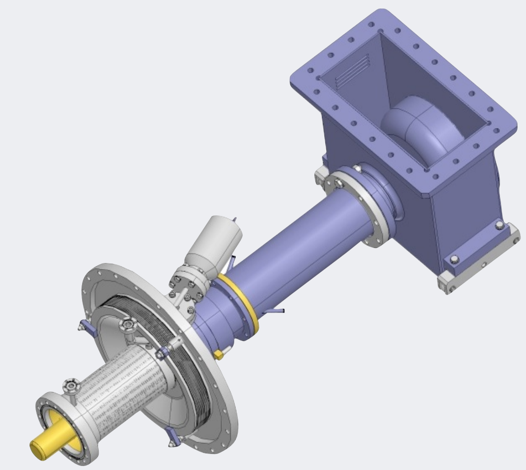


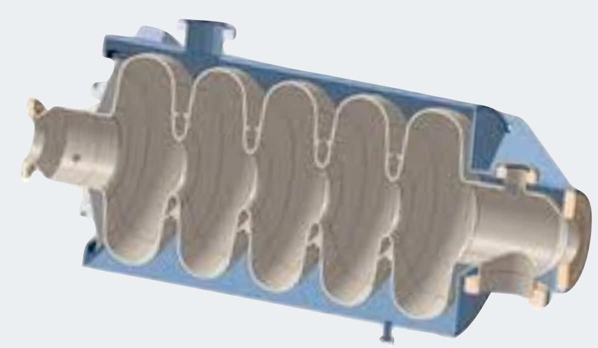
Equipartition vs. Equi-tune depression

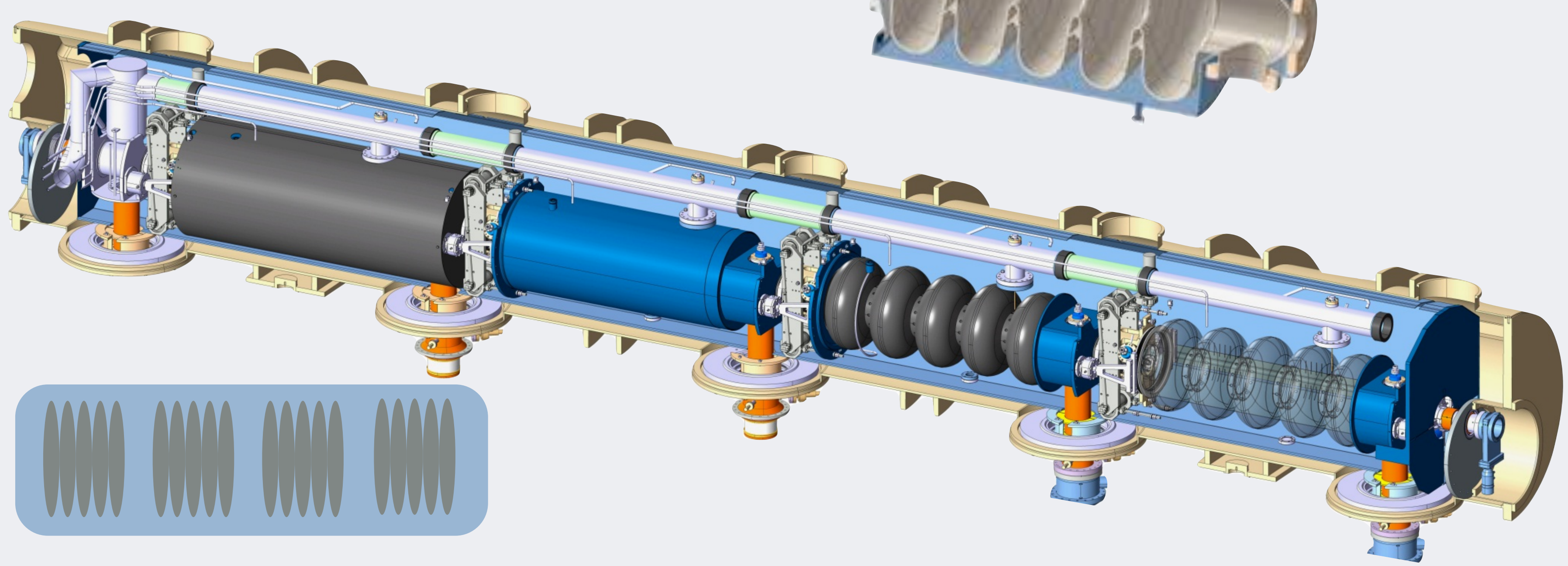
M. Eshraqi, J-M, Lagniel, "On the Choice of Linac Parameters for Minimal Beam Losses", IPAC 2013

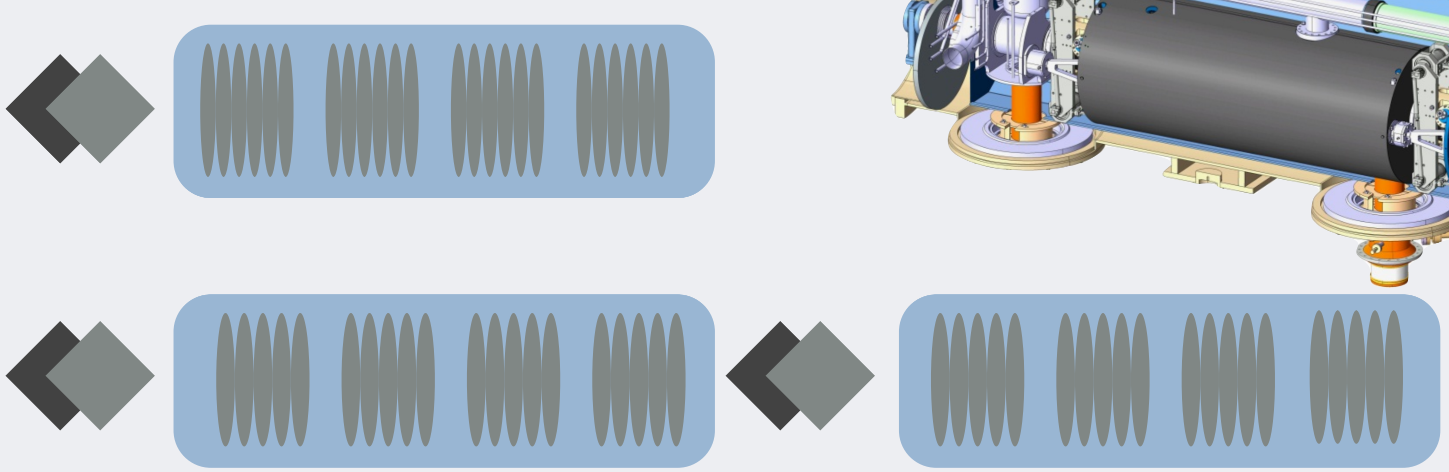
REDUCTION OF ENGINEERING

- The ESS case.
  - The number of cells in the medium beta section was increased to 6, to have the same length as the high beta cavities.
    - The same cryomodule design could be used
    - Two families of elliptical cavities accelerate the beam from 220 to 2000 MeV.

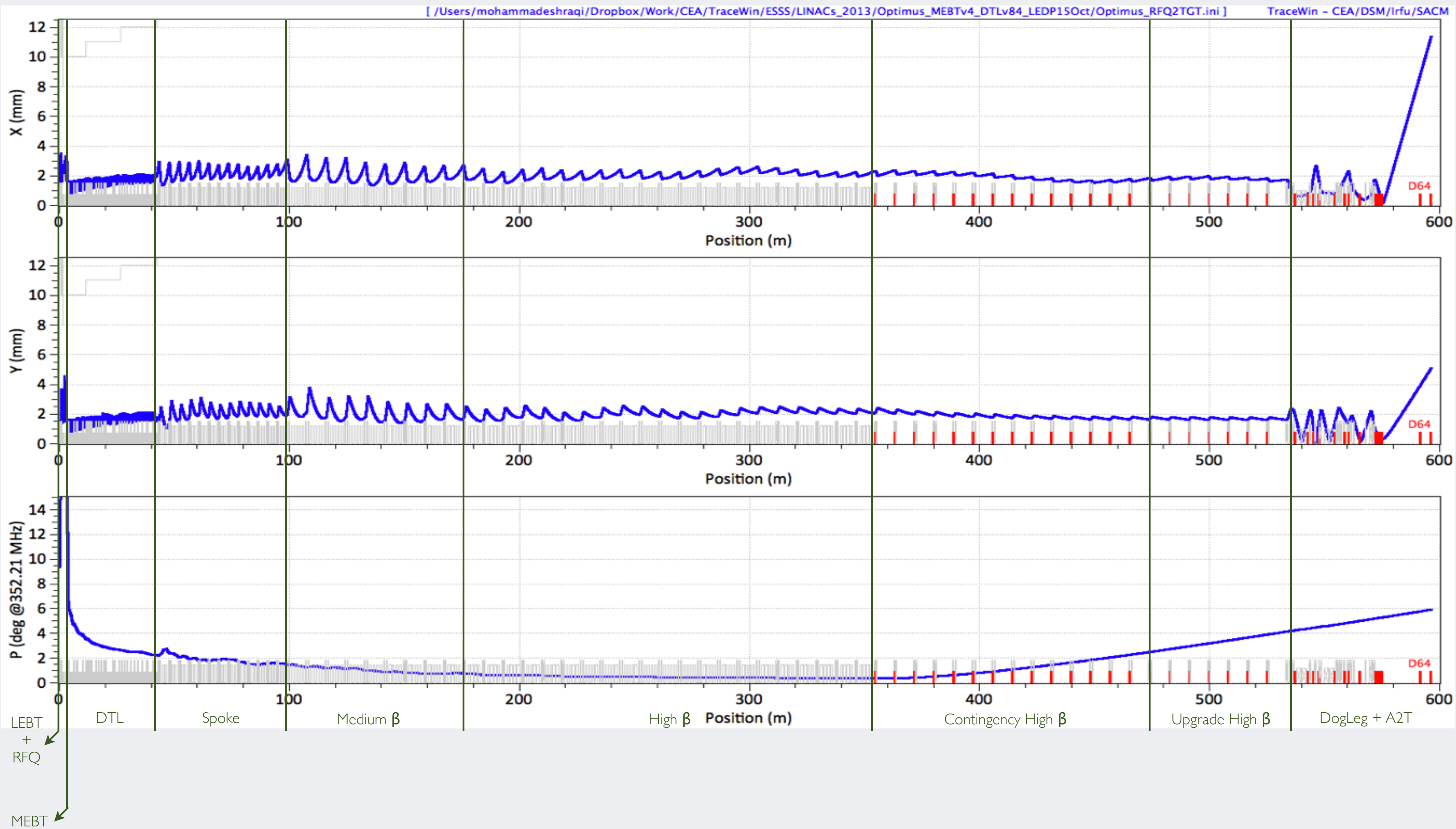








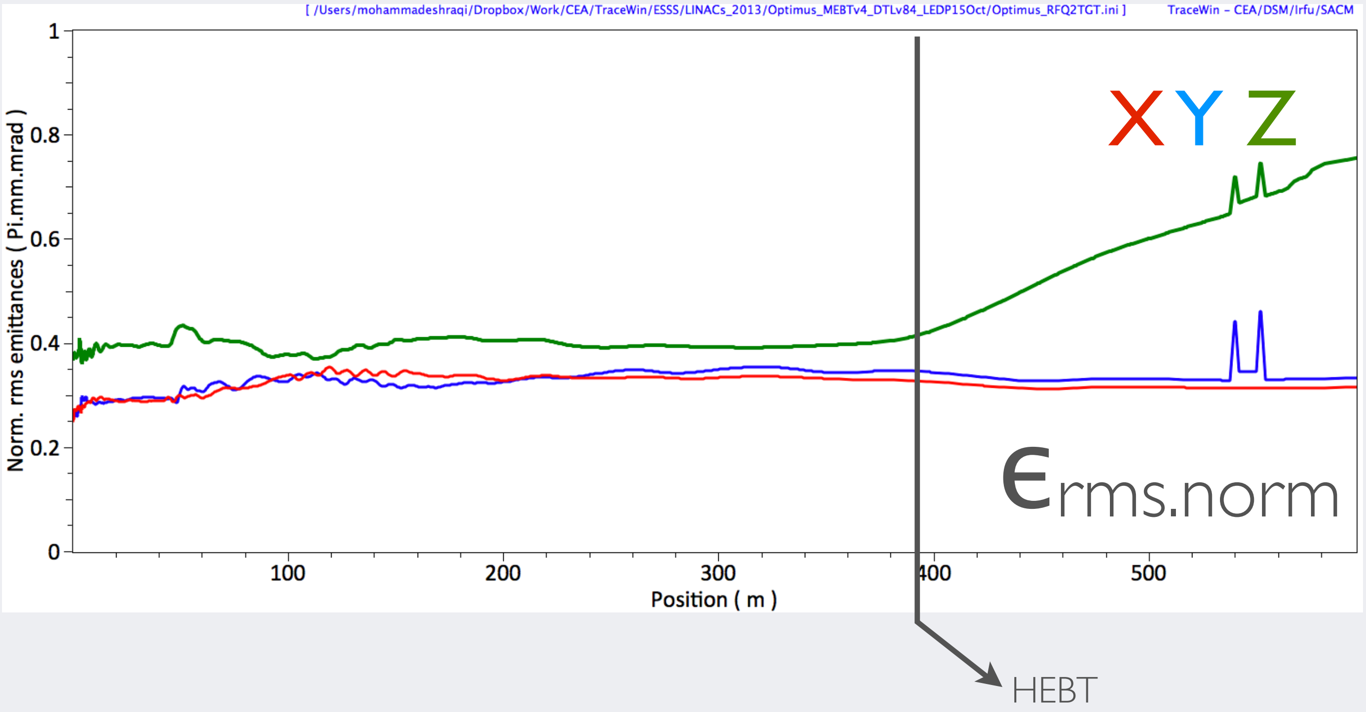
ENVELOPES



[/Users/mohammadeshraqi/Dropbox/Work/CEA/TraceWin/ESSS/LINACs_2013/Optimus_MEBTv4_DTLv84_LEDP15Oct/Optimus_RFQ2TGT.ini]
TraceWin - CEA/DSM/Irfu/SACM
X (mm)
Y (mm)
P (deg @352.21 MHz)
Position (m)
D64
LEBT + RFQ
MEBT
DTL
Spoke
Medium β
High β
Contingency High β
Upgrade High β
DogLeg + A2T

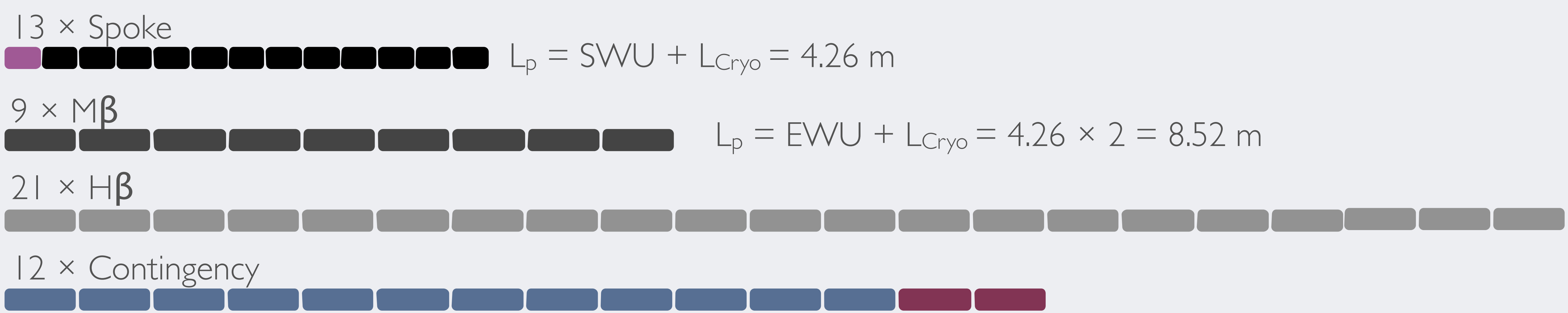
EMITTANCE

- A beam with gaussian distribution, 4D, cut at 4 sigma is generated at the RFQ input, tracked through RFQ and saved at the END to be used in simulations.
- This beam is tracked from MEBT to target.
- RMS norm. emittance degradation and exchange are very limited in the linac.



MITIGATING THAT RISK!

- The major risk of the new lattice is 25% increase in current and 11.25% increase in accelerating gradient.
  - In case of lower current (coupler/space-charge/loss limitations) the linac will still work, but at a lower power
- Free space at the end of the linac provides space for additional cryomodules to recover the lost energy/power
- Uniform Lattice would permit cryomodule replacement at the transitions



SUMMARY

- Initially, after a series of linac designs and optimization, the linac is costed
- The main cost contributors are identified and by adjusting and re-optimizing the linac parameters and design the cost is reduced
- Minimizing the engineering reduces the cost and helps the schedule
    - R&D can also reduce cost; IOTs, Surface treatment of cavities
- The new design shall include the ability to mitigate the risks
- Beam dynamics known rules could be revisited to find better solutions

Thank you for your attention