Segmentation considerations for the ESS linac

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Outline

Introduction

Original question from Mats Lindroos:

" Could you define the dimensions of the linac tunnel? "

Investigation of different topics

- Beam dynamics: consolidation of the ESS linac architecture
- Parameters and location of the linac components: cavities, magnets (inside or outside the cryostat), power couplers . . .
- Reliability issues
- Tentative evaluation of the cryogenic power

$\longrightarrow$ Study the segmentation

Content

1.
   - Definition of the segmentation
   - Presentation of the two linac architectures for the comparison study
2.
   - Focus on spoke cavities
   - Consideration of 2 K operation
3. Estimation of the cryogenic consumption for the two extreme options

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What is segmentation?

Segmentation: CRYO-SEGMENTATION and VACUUM SEGMENTATION

How the cryogenic power is distributed and shared along the (SC) linac?

(Hightly) segmented linac

- Short and independant cryo-modules
  Large number of cold-to-warm transitions
- Concern: Reliability
  - *Rapid exchange of one module*
  - *Warm quadrupoles: easy alignment*
- Application: ADS (transmutation of nuclear wastes and energy production)

Not (much) segmented linac

- Long cryo-modules connected to form cryo-strings
  Reduction of the cold-to-warm transitions
- Concern: Filling factor (length) and static losses
  Maintenance scheduled during shutdown
- Application: Linear colliders

$\longrightarrow$ Segmenting linacs has a huge impact on cryostating (cryo-module design)

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Two examples

Figure: The SC linac at the SNS

Figure: The SC linac of FLASH

ESS linac parameters

In the presented study, the ESS linac nominal parameters have been considered:

- $I = 50$ mA
- 50 MeV to 2.5 GeV
- 4 % beam duty cycle

Comment: See M. Eshraqi et al., "Conceptual Design of the ESS LINAC", proceedings of IPAC'10, for an updated ESS reference linac

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The ESS segmented linac

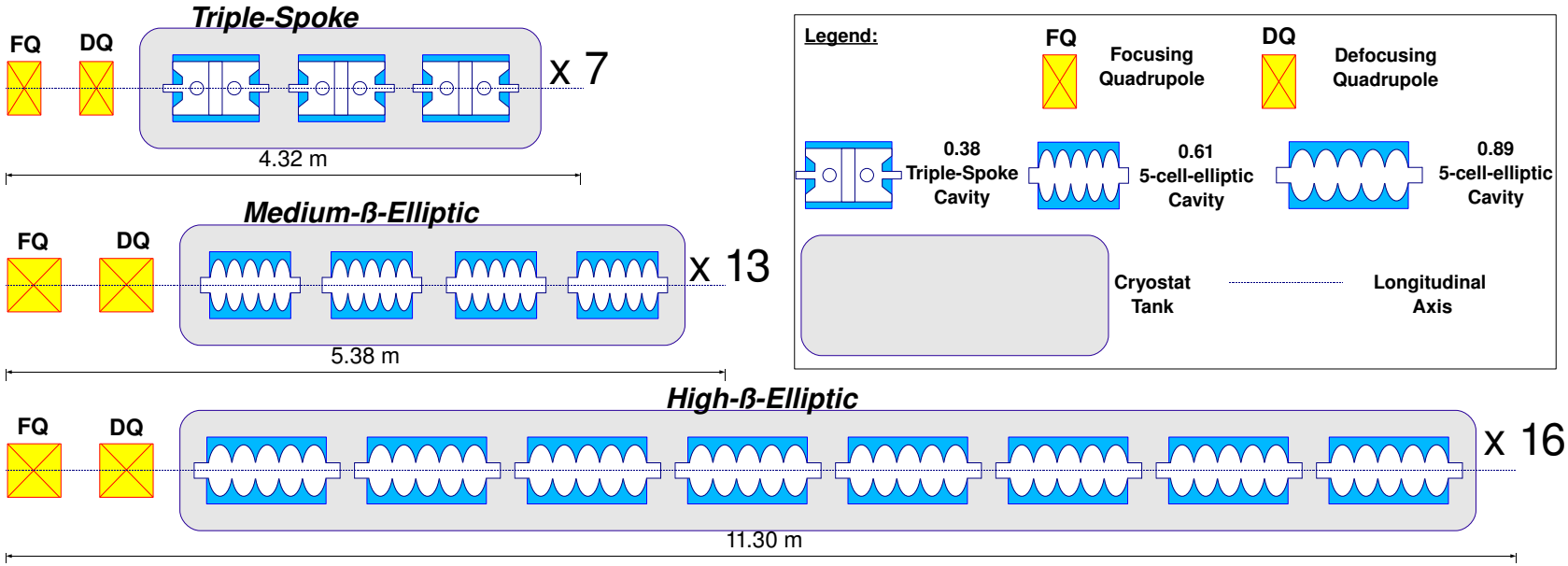

Figure: Periods of the segmented linac

The ESS not segmented linac

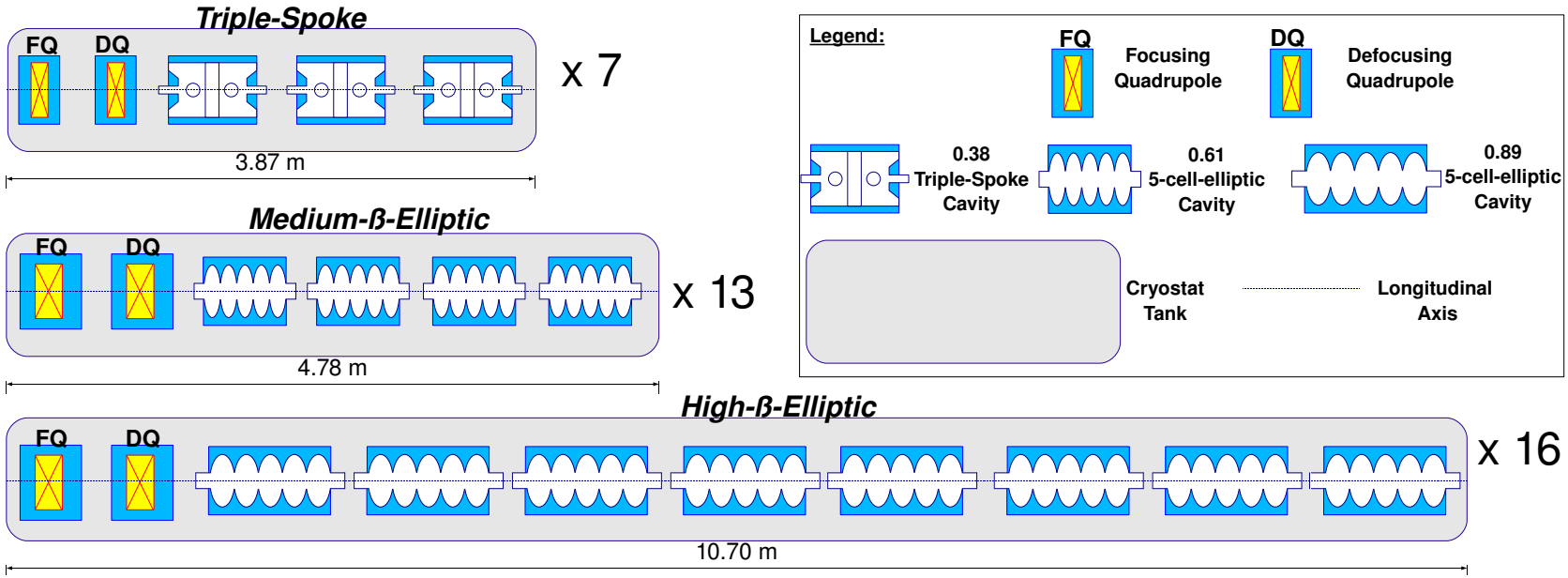

Figure: Periods of the not segmented linac

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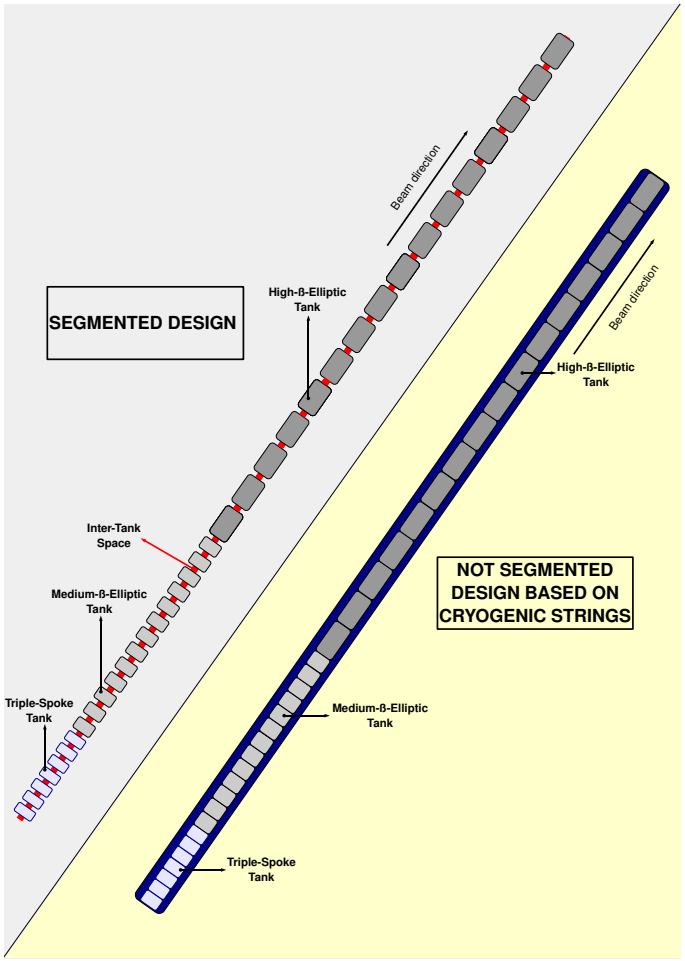


Figure: Schematic comparison of the two architectures

Linac length (SC)

- Not segmented: 260 m
- Segmented: 281 m

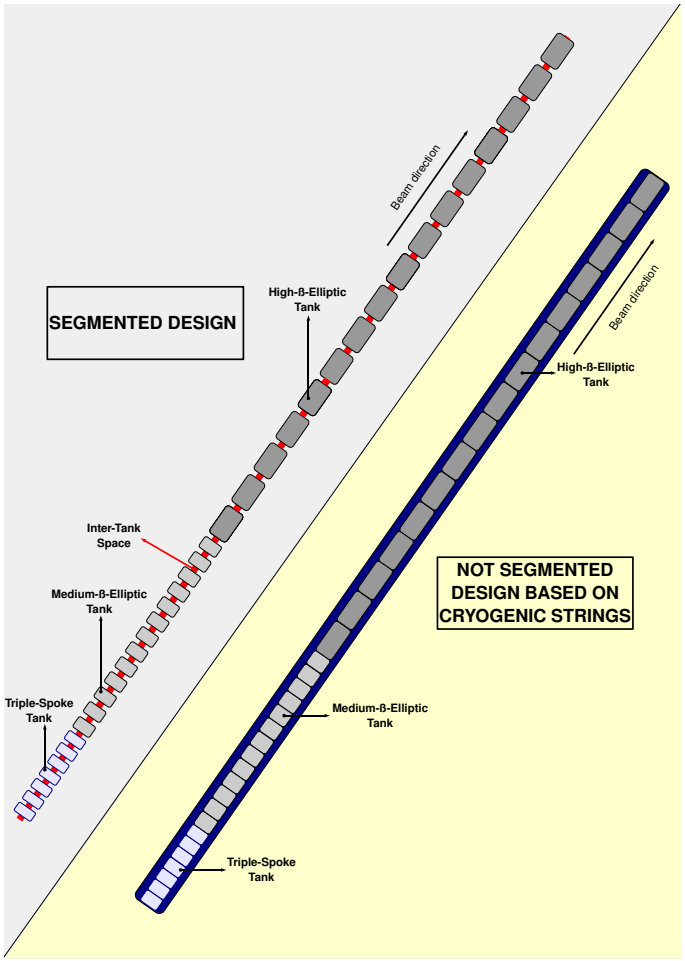
$\longrightarrow$ only 8 % longer

Real estate gradient

The not segmented design does not offer significant advantages

Can we estimate the heat loads in the cryogenic lines?

First observations



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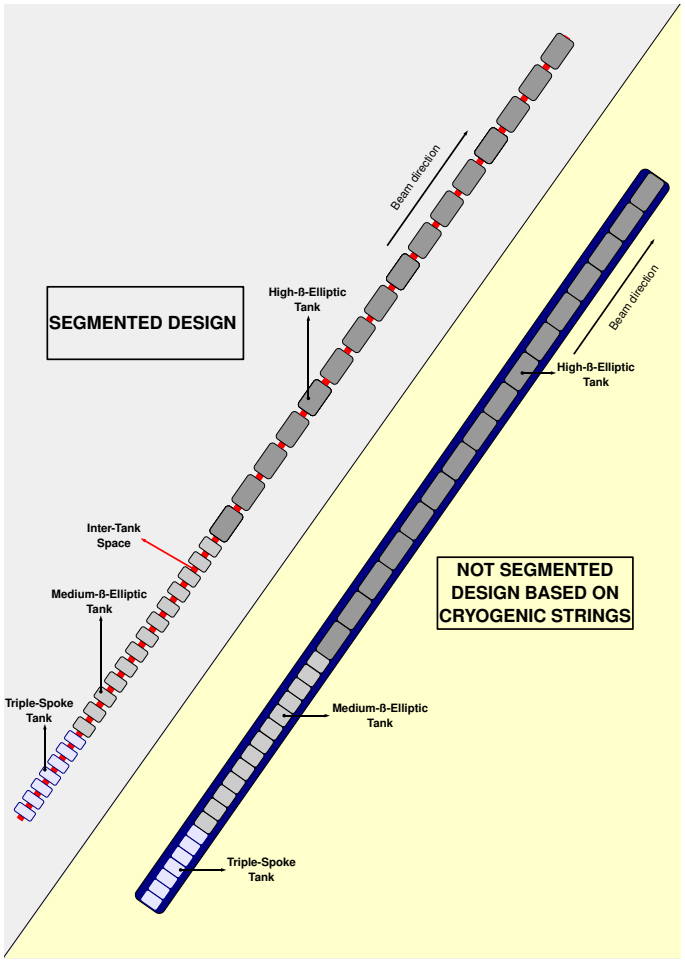

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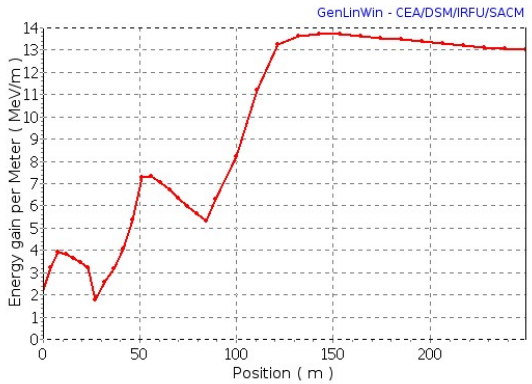
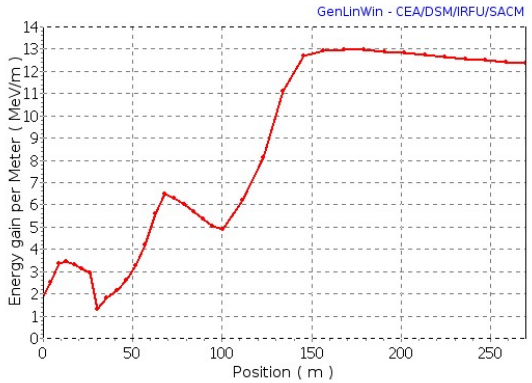


Figure: Energy gain (not segmented linac)



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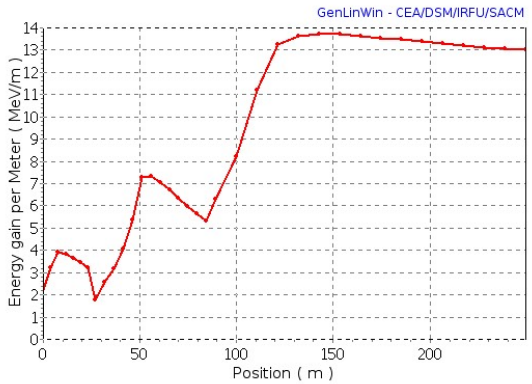

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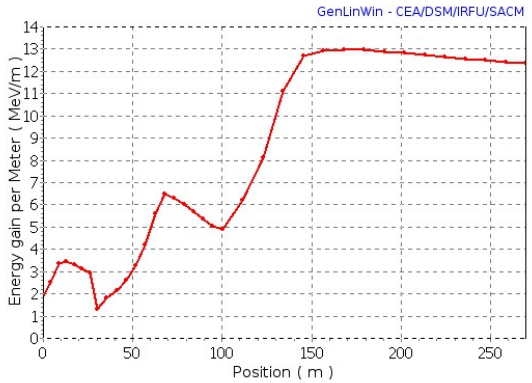

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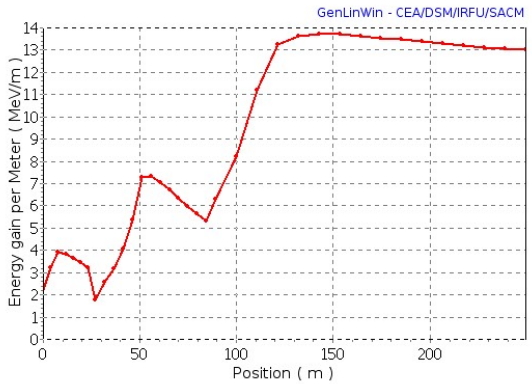

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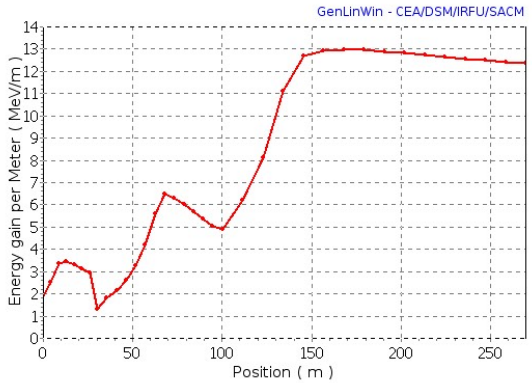

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How to calculate the static and dynamic (RF) losses?

The static heat loads

Scaled from:

- CERN-SPL study for the not segmented desisn
- SNS experience for the segmented linac

The dynamic heat loads

Power dissipation in the cavity walls:

$$P_{diss} = \eta \frac{(E_{acc} L_{acc})^2}{\left(\frac{r}{Q}\right) Q_0}$$

Evaluate the dynamic heat load requires to know the cavity parameters:

- Well known for elliptical cavities
- Few statistics for spoke resonators

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Quality factor and shunt impedance

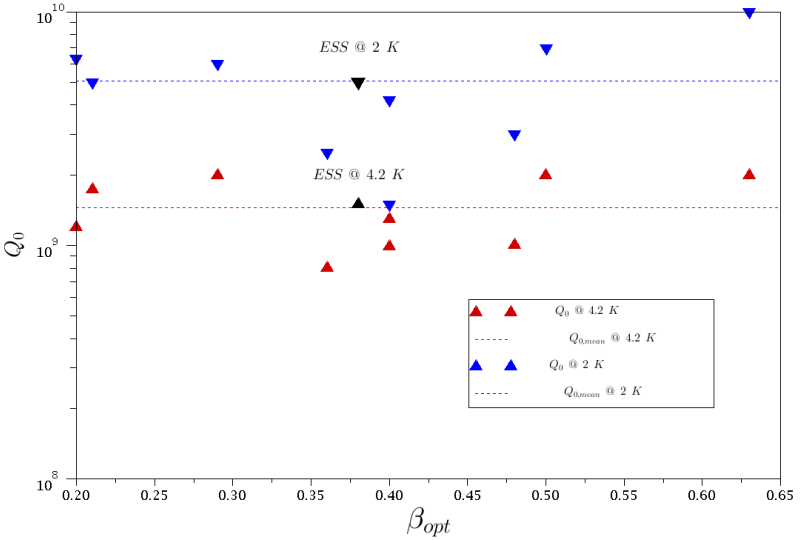

Figure: Quality factor

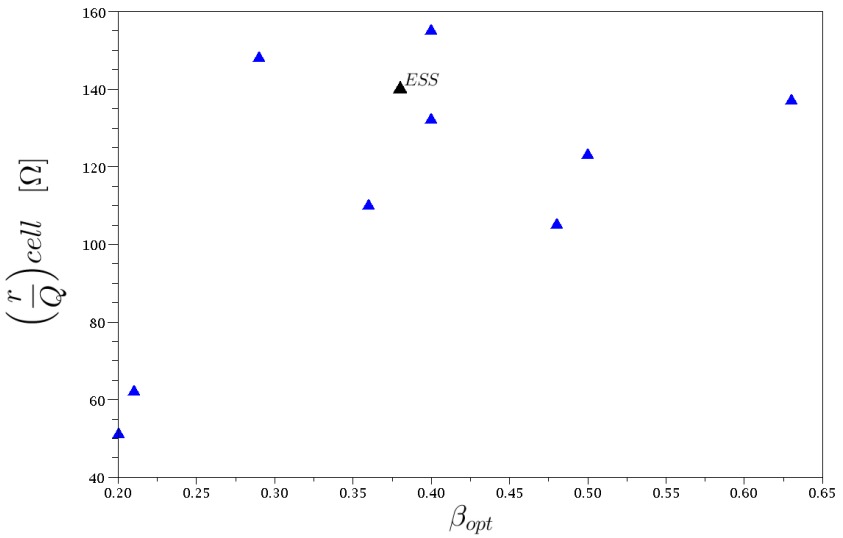

Figure: Shunt impedance over quality factor

Peak fields

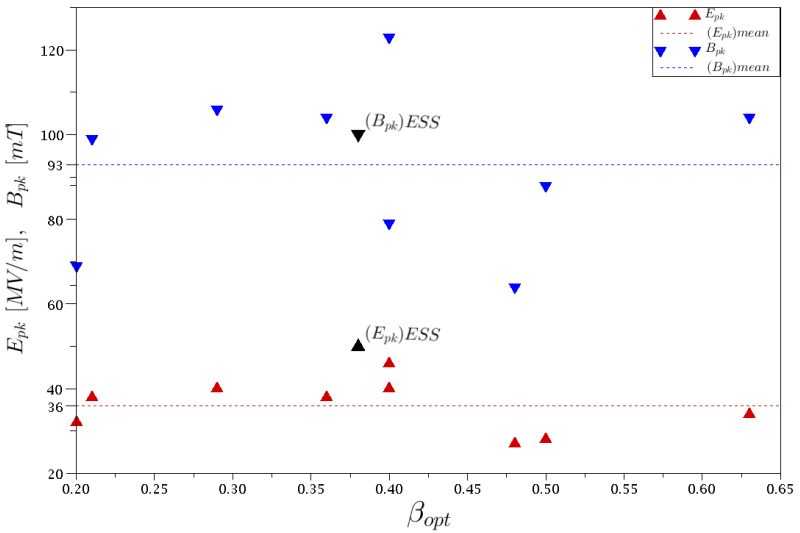

Figure: Maximal surface fields

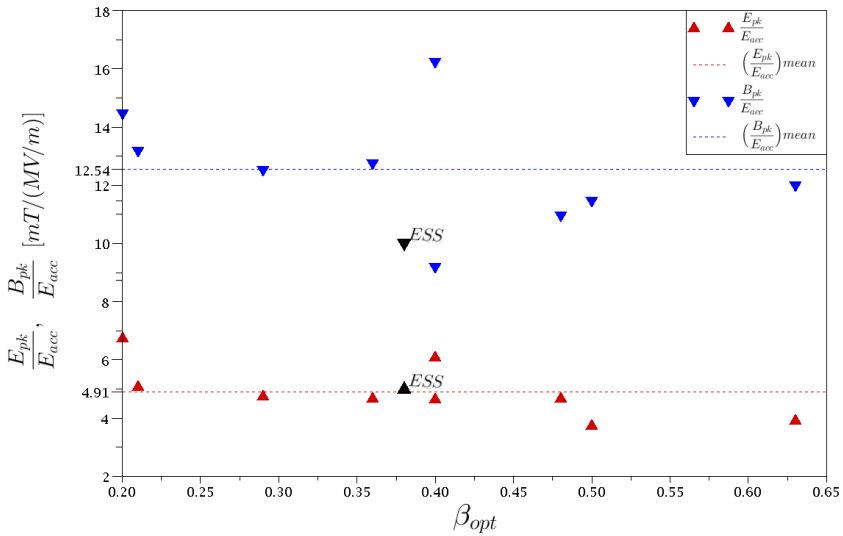

Figure: Maximal surface fields over accelerating field

Accelerating gradient definition: $E_{acc} = \dfrac{V_{acc}}{\frac{n_{gap}}{2}\beta_{opt}\lambda_{RF}}$ (valid for π-mode)

Proposed ESS spoke cavity parameters

Frequency	352.21 *MHz*
Cell number	4
Wall-to-wall length	647 *mm*
Optimal beta	0.38
Maximum surface peak electric field	50 MV/m
Maximum surface peak magnetic field	100 mT
Cavity quality factor at 4.2 K	$1.5 \cdot 10^9$
at 2 K	$5 \cdot 10^9$
r/Q	560 Ω
Nominal accelerating gradient	8 MV/m

Table: ESS triple-spoke cavity parameters

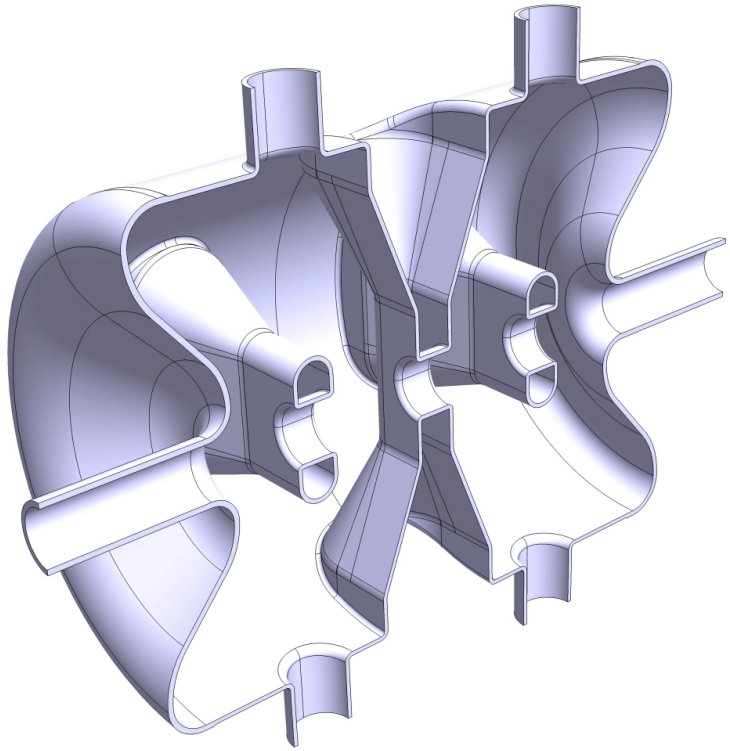

Figure: Triple spoke cavity (IPN-Orsay)

Spoke 2 K operation

- $R_s \propto f^2$: for $f = 352.24$ MHz $T_{He} = 4.2$ K is sufficient
- $\epsilon_{4.2\ K}/\epsilon_{2\ K} = 3.5$

Why shall we consider a possible 2 K operation?

- $\longrightarrow$ Reduced RF losses at 2 K could offset the financial aspect increase in refrigeration cost
- $\longrightarrow$ Better accelerating performances, better mechanical behavior

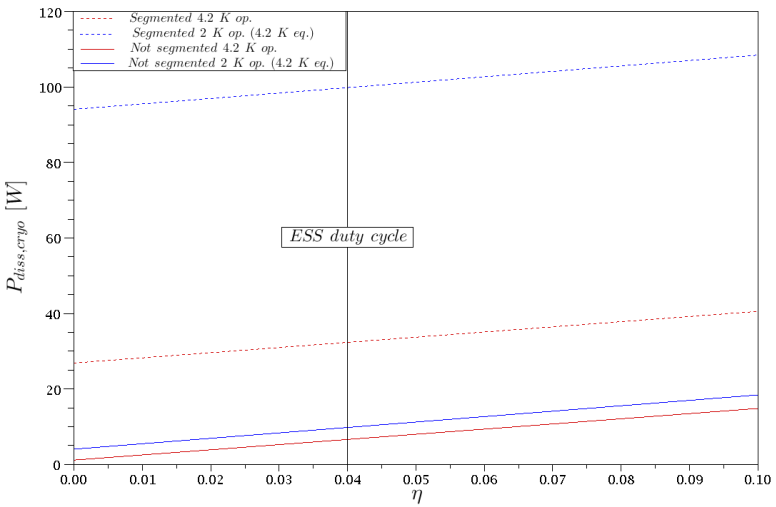

Figure: Estimated heat loads

Observations

1. Segmented design:
   - Dominated by static losses
   - Losses explode for $\eta > 0.04$
2. Not segmented design:
   - Losses in the same order
   - Losses increase linearly

Operating spoke at 2 K is not meaningful

What is the cryogenic consumption for the whole linac?

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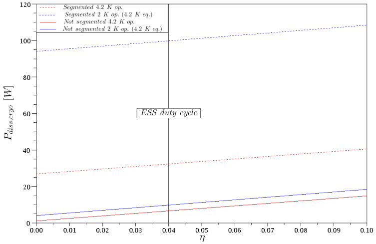

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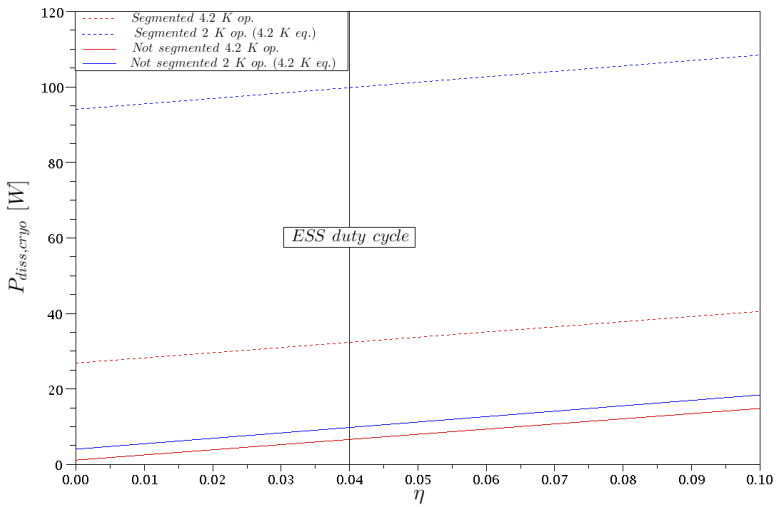

Figure: Estimated heat loads

Observations

1. Segmented design:
   - Dominated by RF losses
   - Losses could be reduced by 2 K operation
2. Not segmented design:
   - Losses in the same order
   - Could be meaningful

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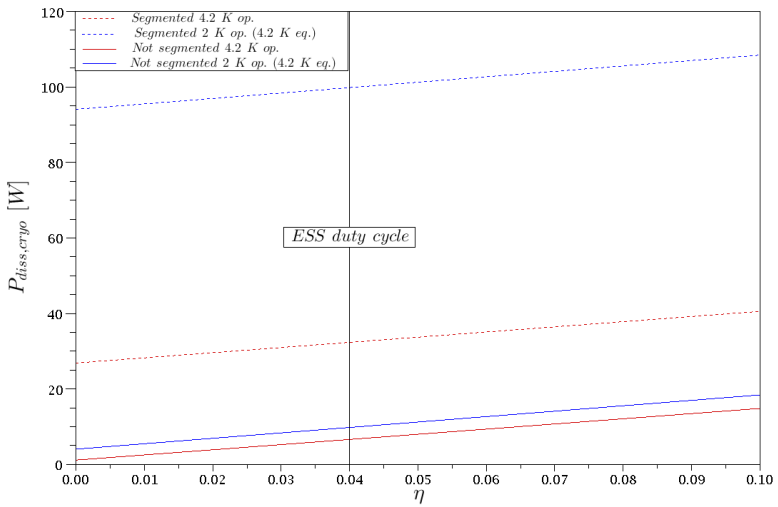

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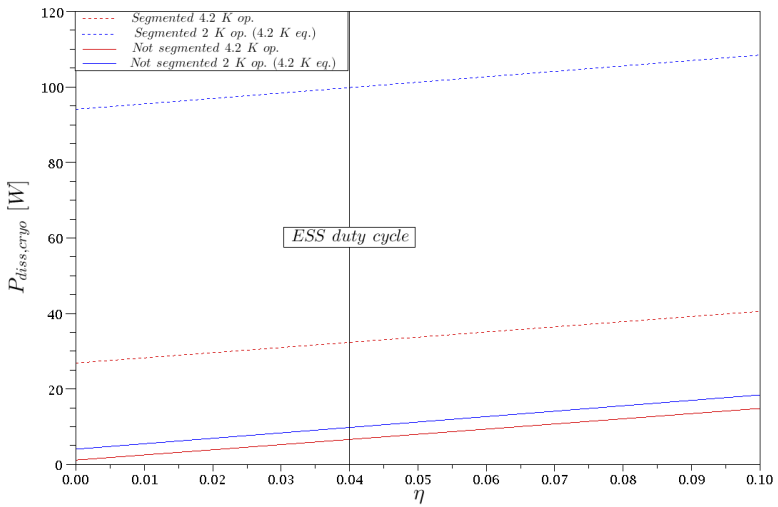

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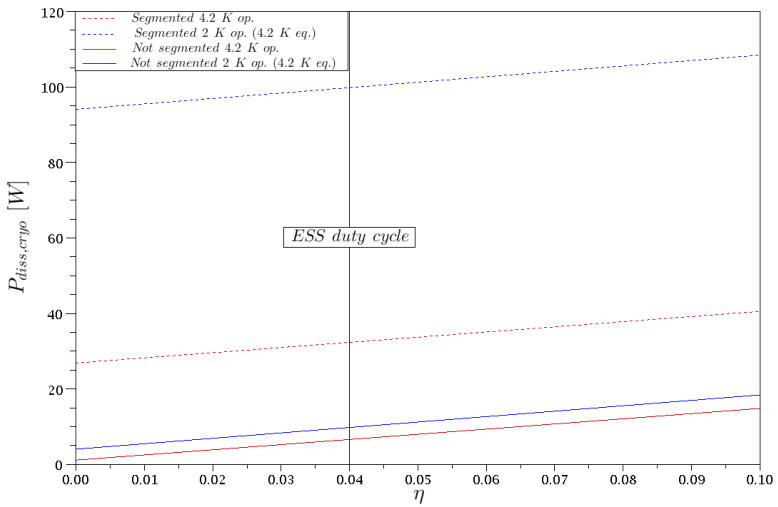

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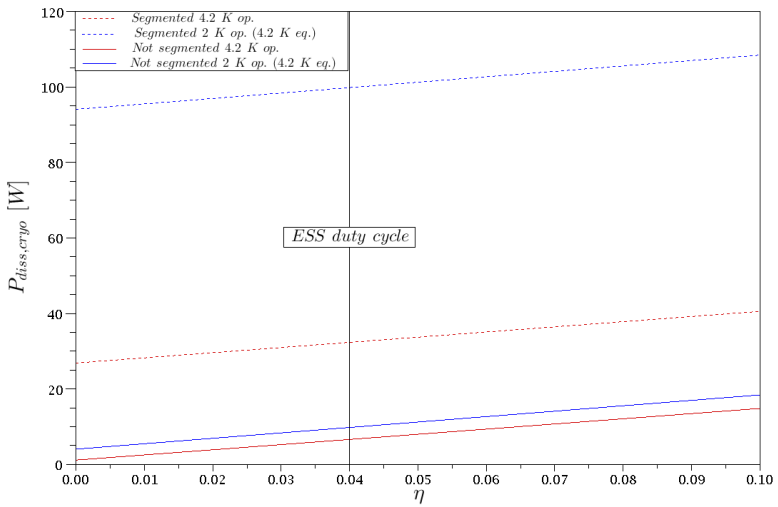

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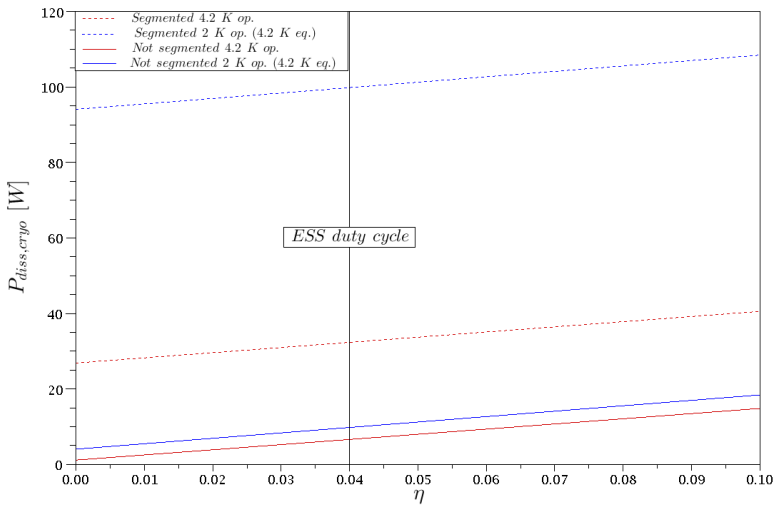

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Outline

All the results are here!

		Triple-spoke	Medium-β-elliptic	High-β-elliptic
Dynamic RF load per module $[W]$		(4.2 K op.) 5.47 (2 K op.) 1.64	8.43	37.30
Static load per module $[W]$	Segmented	24.79	25.71	34.69
	Not segmented	1.20	1.48	3.32
Static heat load contribution $[\%]$	Segmented	(4.2 K op.) 82 (2 K op.) 94	75	48
	Not segmented	(4.2 K op.) 18 (2 K op.) 42	15	8
Heat load per module in the $5-8$ K level shielding $[W]$ (only for the not segmented design)		6.33	7.82	17.50
Contribution of the shielding to the total heat load $[\%]$ (only for the not segmented design)		(4.2 K op.) 49 (2 K op.) 39	18	11
Total heat load per module $[W]$ eq. at 4.2 K	Segmented	(4.2 K op.) 30.26 (2 K op.) 92.51	119.49	251.97
	Not segmented	(4.2 K op.) 13.00 (2 K op.) 16.27	42.51	159.67
Total heat load per section $[kW]$ eq. at 4.2 K	Segmented	(4.2 K op.) 0.212 (2 K op.) 0.648	1.553	4.032
	Not segmented	(4.2 K op.) 0.091 (2 K op.) 0.114	0.553	2.555
Total contribution per section $[\%]$	Segmented	(4.2 K op.) 3.7 (2 K op.) 10.4	26.8 24.9	69.6 64.7
	Not segmented	(4.2 K op.) 2.8 (2 K op.) 3.5	17.3 17.2	79.9 79.3
Total heat load per linac $[kW]$ eq. at 4.2 K	Segmented	(4.2 K op.) (2 K op.)	5.797 6.233	
	Not segmented	(4.2 K op.) (2 K op.)	3.199 3.222	
Total heat load per linac $[kW]$ eq. at 4.2 K incl. 1 W/m beam loss	Segmented	(4.2 K op.) (2 K op.)	6.533 7.022	
	Not segmented	(4.2 K op.) (2 K op.)	4.043 4.133	

The study:

1. Investigates four different scenarios
2. Details the losses for each section

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Comparison of the estimations

The segmented linac

- Largely dominated by static losses
  - Triple-spoke: 94 % (2 K) and 82 % (4 K)
  - Medium-β-elliptic: 75 %
  - High-β-elliptic: 48 %
- Operating spoke at 2 K: spoke contribution raises from 3.7 % to 10.4 %
- Total cryogenic power: 6.2 kW

The cryo-string-based linac

- RF losses play an important role
  - Triple-spoke: 58 % (2 K) and 82 % (4 K)
  - Medium-β-elliptic: 85 %
  - High-β-elliptic: 92 %
- Operating spoke at 2 K adds a negligible contribution to the total loads
- $\sim$ 260 m of SC modules: $\sim$ 1 kW (eq. at 4 K) of cryogenic consumption induced by beam losses (1 W/m)
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The hightly segmented linac requires 1.6 – 1.7 times more cryogenic power than the cryo-string-based linac

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Conclusion

Summary

1. Presentation of two linac architectures:
   $\longrightarrow$ Real estate and lengths: no significant difference
2. Focus on spoke resonators
   - Proposed spoke parameters
   - Consideration of 2 K operation: more cryogenic power required
3. Tentative comparison study of the cryogenic consumption
   $\longrightarrow$ $1.6 - 1.7$ times more cryogenic power for the segmented linac

Perspectives

- Benefits from the cryogenic technology state-of-the-art to reduce the static heat loads of the segmented linac
- Hybrid option may be considered
- Segmentation is part of an iterative process: beam dynamics, cryogenics, RF and mechanical design, costing ...
- ESS: $>$ 22 instruments and a community of 5 000 users!

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2. Focus on spoke resonators
   - Proposed spoke parameters
   - Consideration of 2 K operation: more cryogenic power required
3. Tentative comparison study of the cryogenic consumption
   $\longrightarrow$ $1.6 - 1.7$ times more cryogenic power for the segmented linac

Perspectives

- Benefits from the cryogenic technology state-of-the-art to reduce the static heat loads of the segmented linac
- Hybrid option may be considered
- Segmentation is part of an iterative process: beam dynamics, cryogenics, RF and mechanical design, costing . . .
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