Beam dynamics of a heavy-loaded X-band electron linac for neutron production

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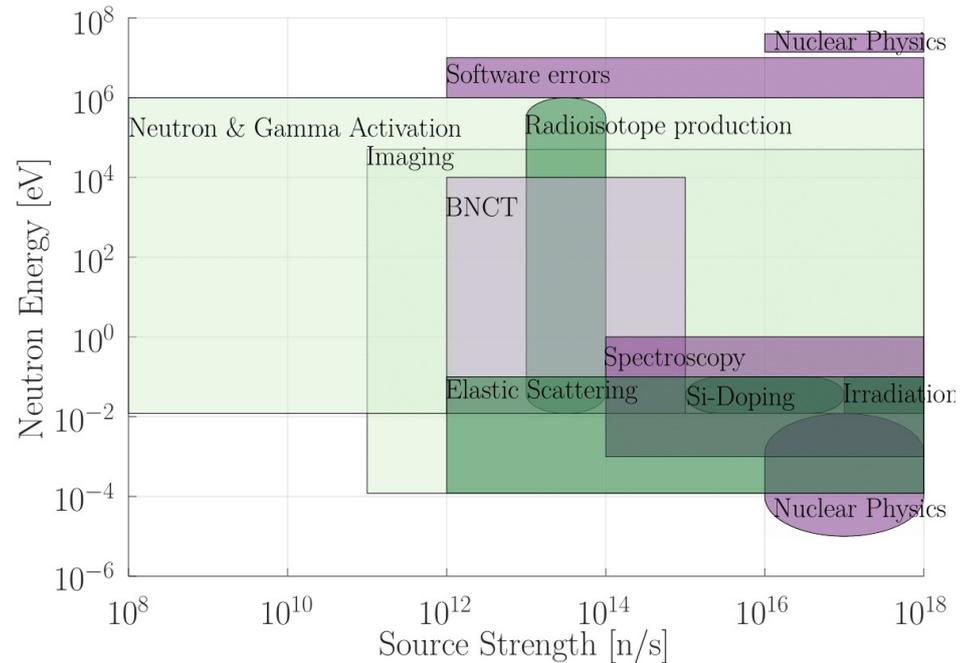
[2] CERN, Meyrin, 1217, Switzerland

Outline

- I. Motivation

  - Efficiency

  - Heat deposition

- II. On axis studies (Baseline)

  - Photoinjector

  - LINAC

- III. Tolerances

- Further work and conclusion
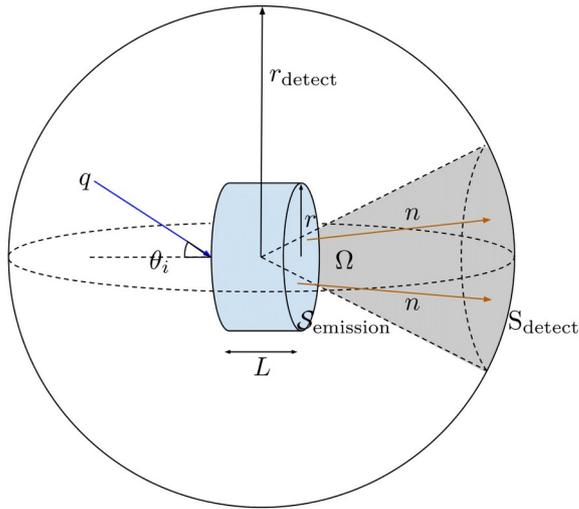
Necessity for neutron sources

- **Uprising demand**: Wide variety of research areas make use of neutrons

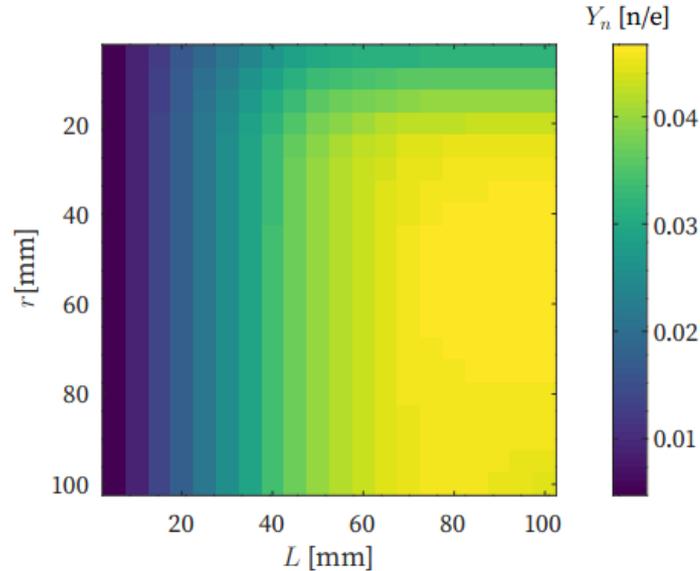 – Not only research: Industrial and medical applications! [1, 2]

Neutron production with electrons

- Single tungsten target where **γ,n** processes occur

- G4beamlines simulations **[3]**
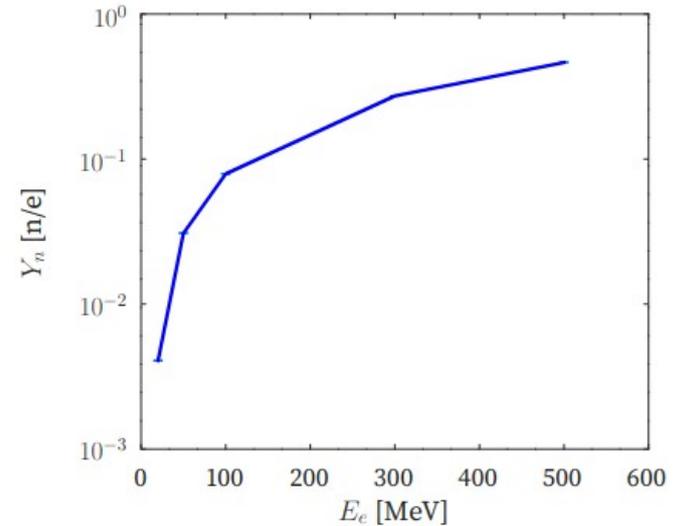
  - Optimal dimensions: r = 40mm; L = 80 mm

$$Y_n(E_e) \equiv \frac{N_n(E_e)}{N_e}$$

Neutron production setup

Dimensions scan for maximum yield for <Ee> = 500 MeV

Optimal yields for different energies

High intensity e-linac proposals

- Targeted figure of merit: **Source strength**

$$I_n \equiv I_{e,\mathrm{av}} Y_n$$

- Two normal-conducting high-intensity linacs are considered

  – **HPCI – linac**:   S-band Photoinjector   + X-band TW structures   **[5]**

  – **CTF3 drive-beam linac**: S-band Thermoionic gun   + S-band TW structures   **[6]**

Magnitude	Units	HPCI-linac	CTF3 drive beam linac
f	GHz	12.00	3.00
Q_{bunch}	nC	0.285	2.33
N_{bunches}		1000	2100
$f_{\mathrm{RF\text{-}cycle}}$	Hz	100	100
$I_{e,\mathrm{av}}$	μA	28.50	489.3

High-intensity compact linac specifications **[5, 6]**
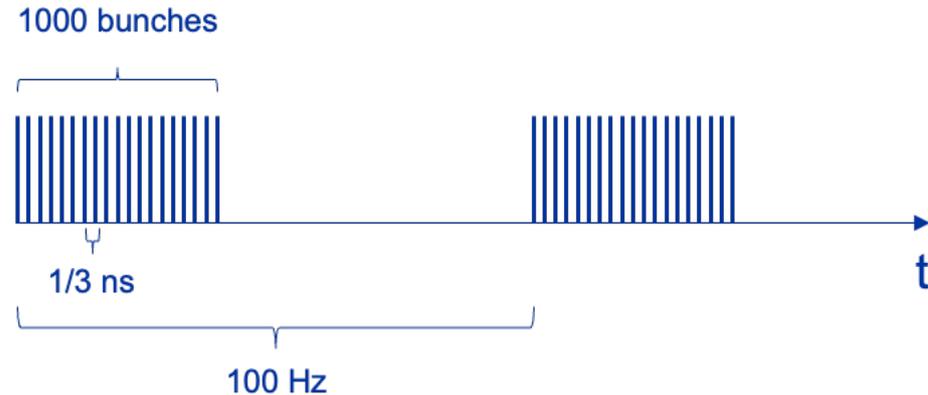
Train schematics for the HPCI linac
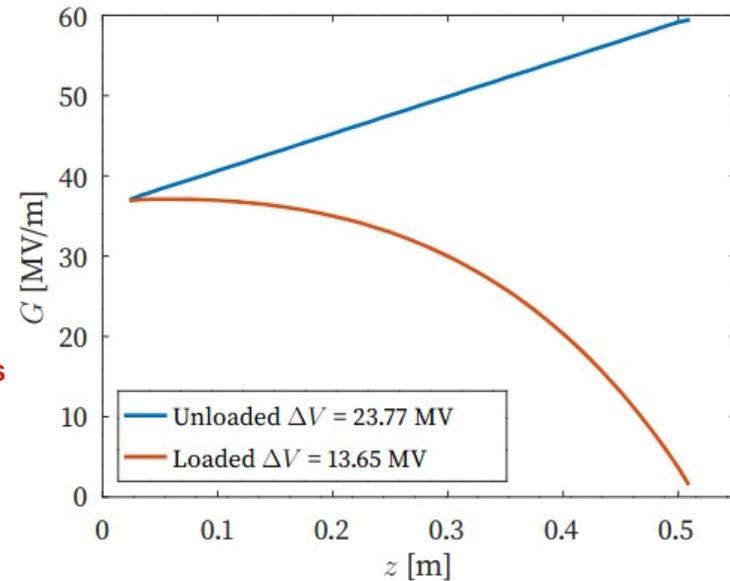
Full Beam Loading Operation

- **Beam Loading**: Gradient reduction due to beam-cavity interaction

- **Full Beam Loading**: High intensity so that **all energy is substracted** from the structure

f_b [GHz]	q_{bunch} [pC]	min. $N_{bunches}$
12.00	150.6	657
6.00	301.2	329
4.00	451.8	219
3.00	602.4	165
2.00	903.6	110
1.50	1204.8	83

I use 1000 bunches

Full BL configurations (refer to steady state)

**Challenges: Beam dynamics, heat deposition**

Accelerating gradient of an HPCI X-band linac in full BL operation

Full Beam Loading Operation

- **Beam Loading**: Gradient reduction due to beam-cavity interaction

- **Full Beam Loading**: High intensity so that **all energy is substracted** from the structure

- Despite BL being inherent, it **maximizes the RF-to-beam efficiency.**

$$\eta = \frac{\Delta P_{\text{beam}}(t)}{P_{\text{in}}(t)} = \frac{I(t)}{P_{\text{in}}(t)} \int_0^L G(z,t) \mathrm{d}z = 0.927$$

$$\eta_{\text{av}} = \frac{\int_0^{T_{\text{pulse}}} \Delta P_{\text{beam}}(t) \, \mathrm{d}t}{\int_0^{T_{\text{pulse}}} P_{\text{in}}(t) \, \mathrm{d}t} = 0.896$$
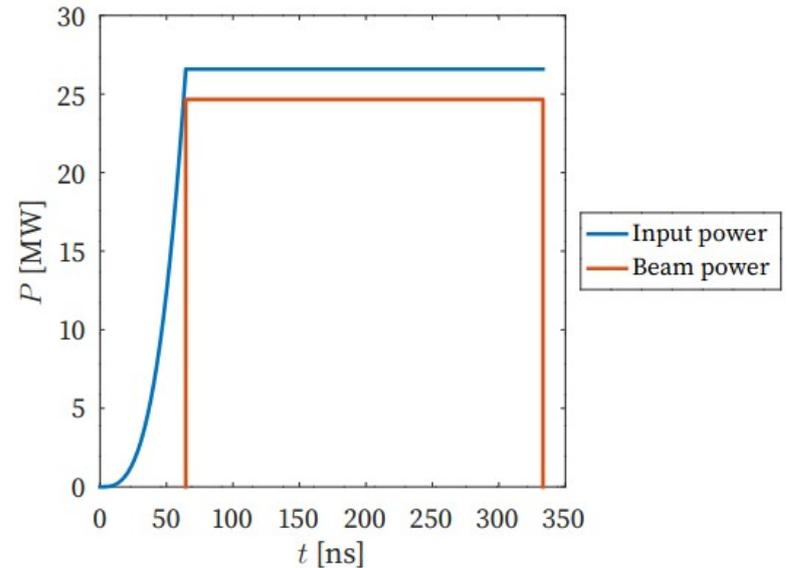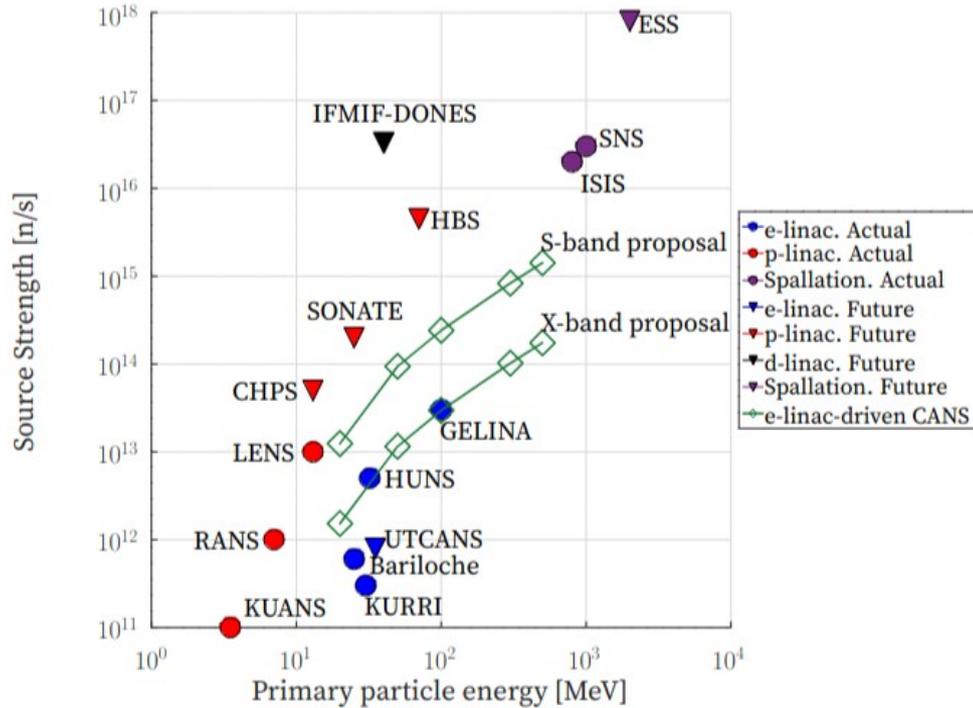

RF power and beam energy gain power
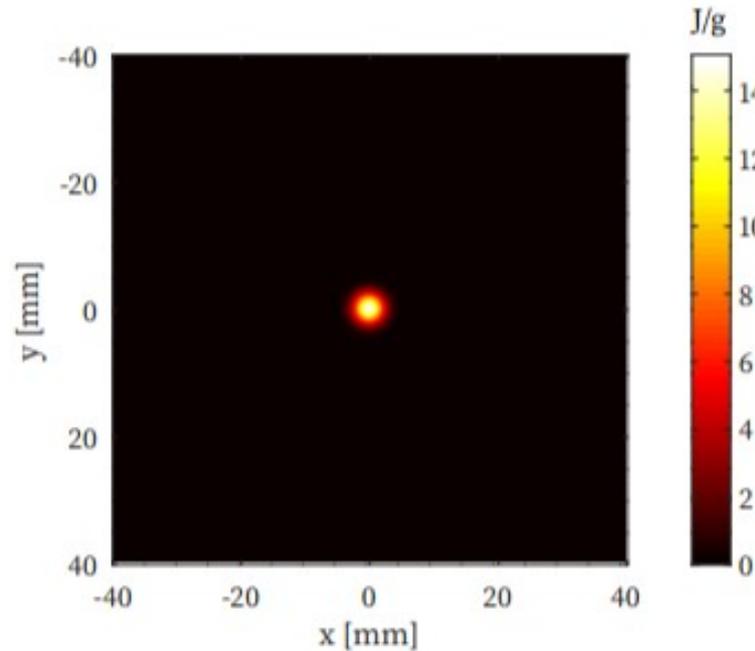
State-of-the-art comparison

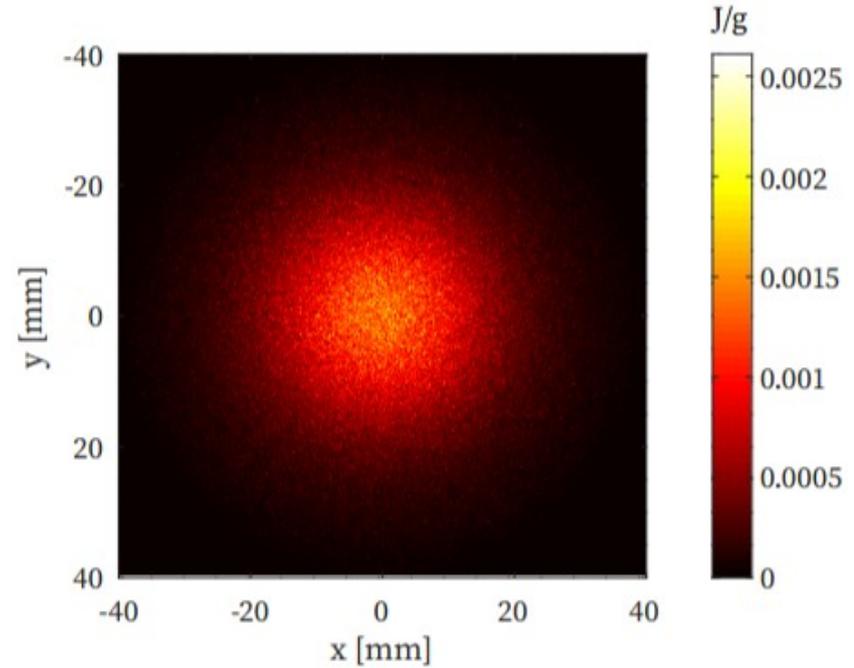$$P_{\text{beam}} = I \cdot E/e$$

[7]
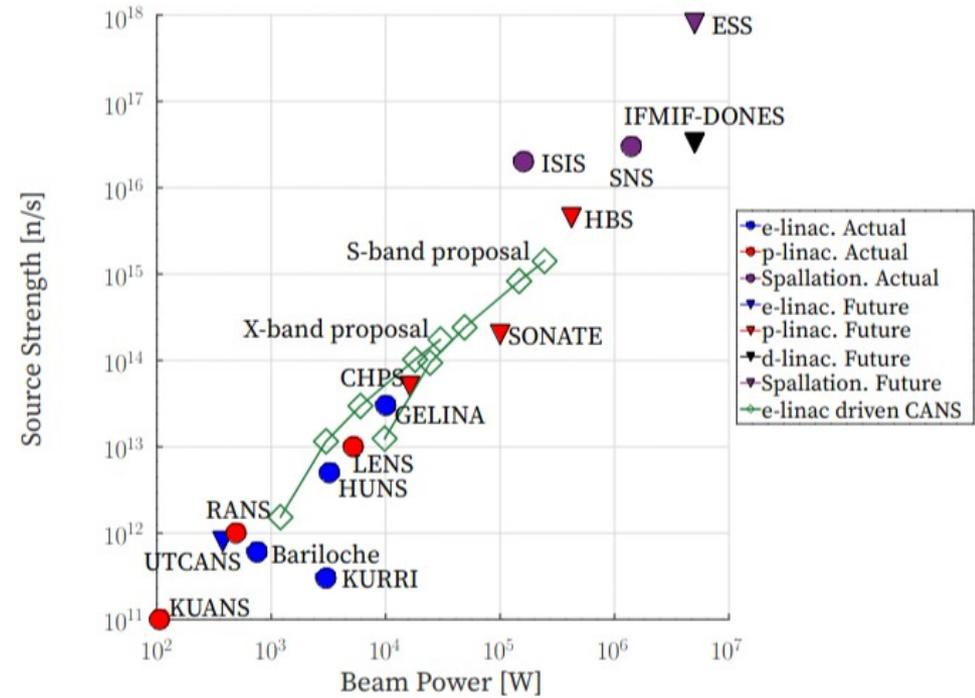
Heat Deposition

- Non-uniform energy deposition → Large temperature increase → Non-elastic mechanical stresses

- Depends on beam intensity and beam size ($\sigma_x = \sigma_y = 1.3$ mm)

Heat deposition profile at z= 0 mm.

Heat deposition profile at z = 80 mm.

Heat Deposition

- Non-uniform energy deposition → Large temperature increase → Non-elastic mechanical stresses

- Depends on beam intensity and beam size ($\sigma_x = \sigma_y = 1.3$ mm)

- Pure tungsten: Limit of 35 J/g

For CTF3, PEDD @ 500 MeV exceeds the 35 J/g limit by a factor 4.
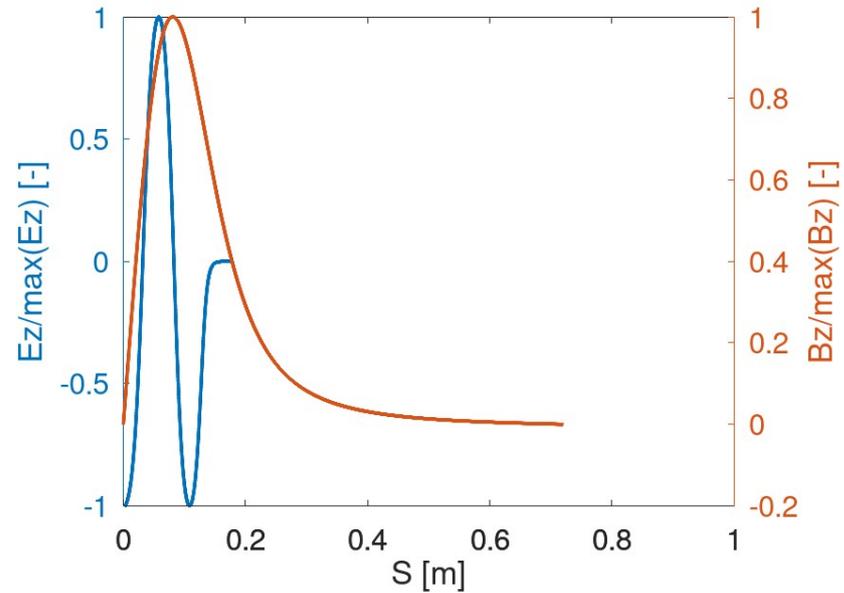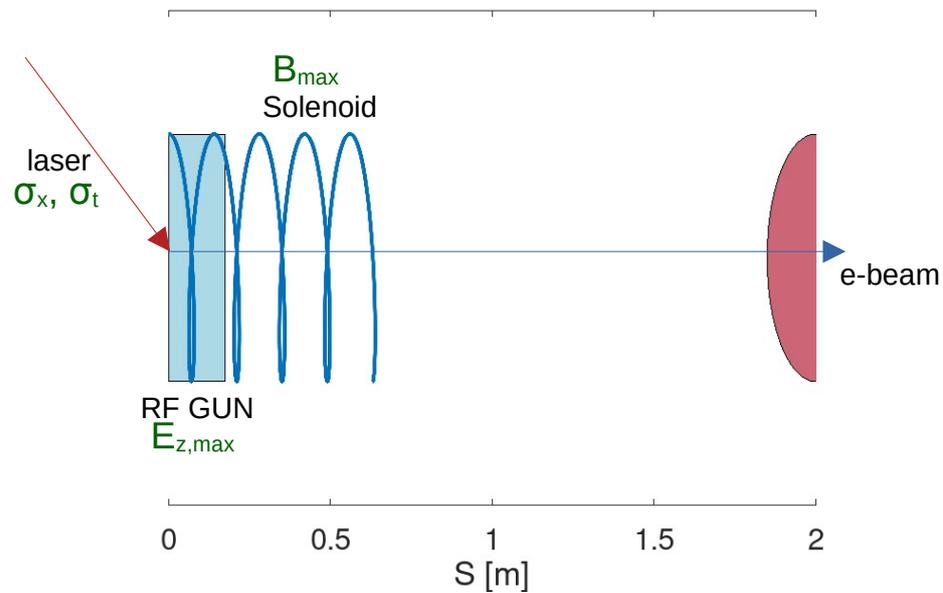Transverse beam size can be aumented a factor 2

→ Necessity to carry out **beam dynamics** simulations
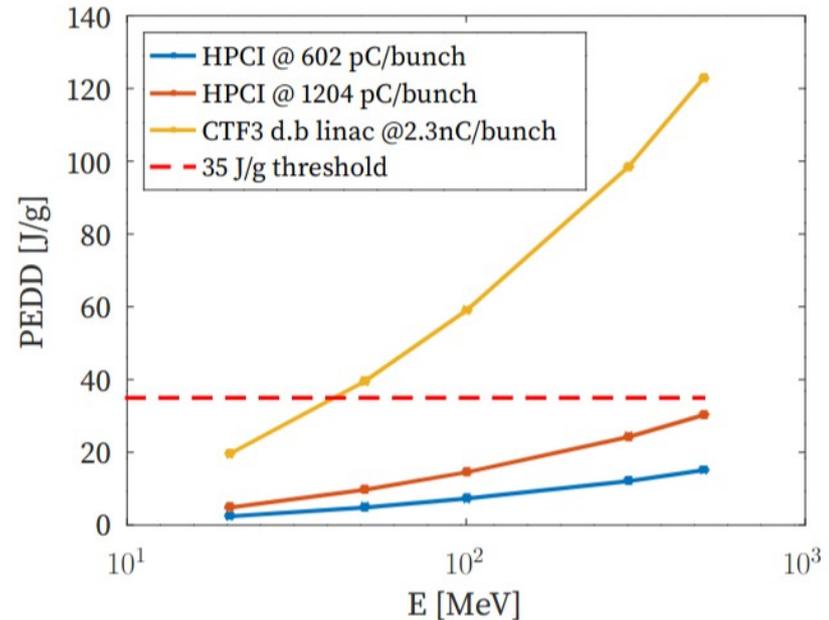
PEDD values for the different e-linac proposals with $\sigma_x = \sigma_y = 1.3$ mm
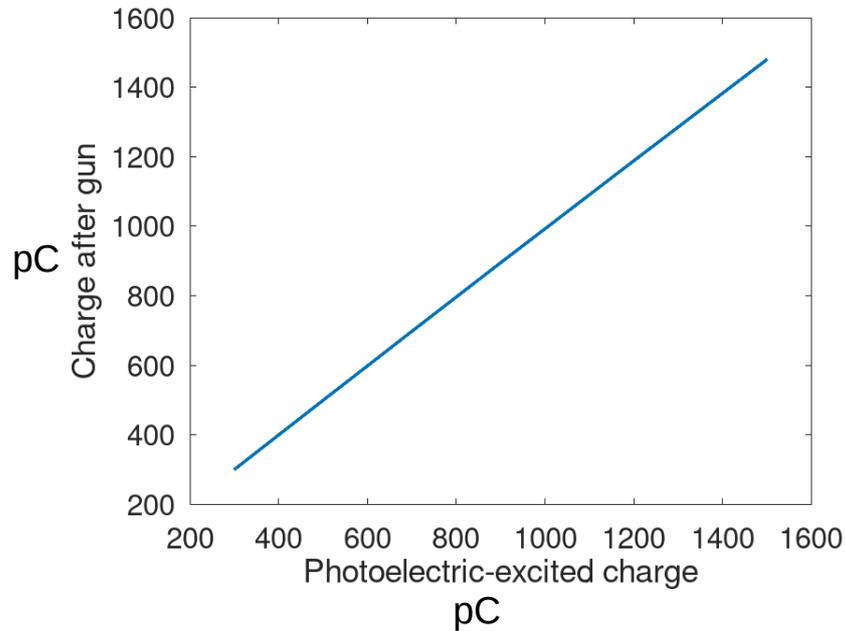
Photoinjector

- (CLEAR Layout) S-band gun + Solenoid + Drift (empty for instrumentation)

Degrees of freedom for optimization: σ_x, σ_t, E_{zmax}, B_{max}
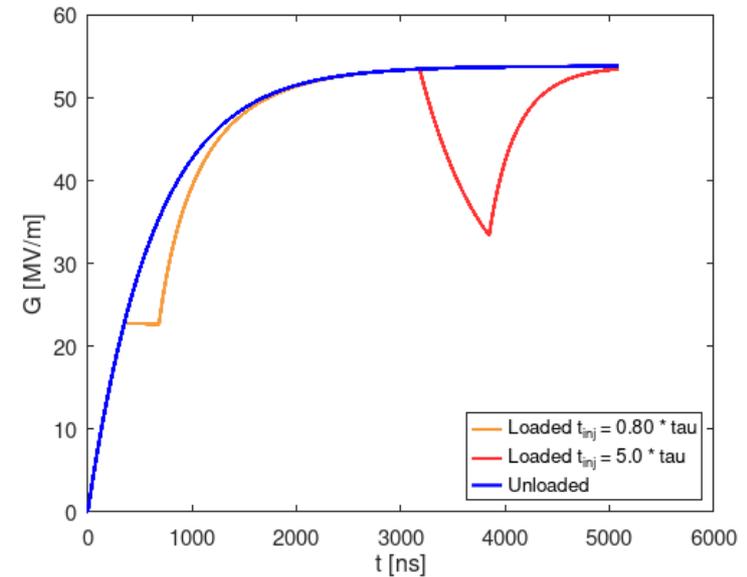
Photoinjector

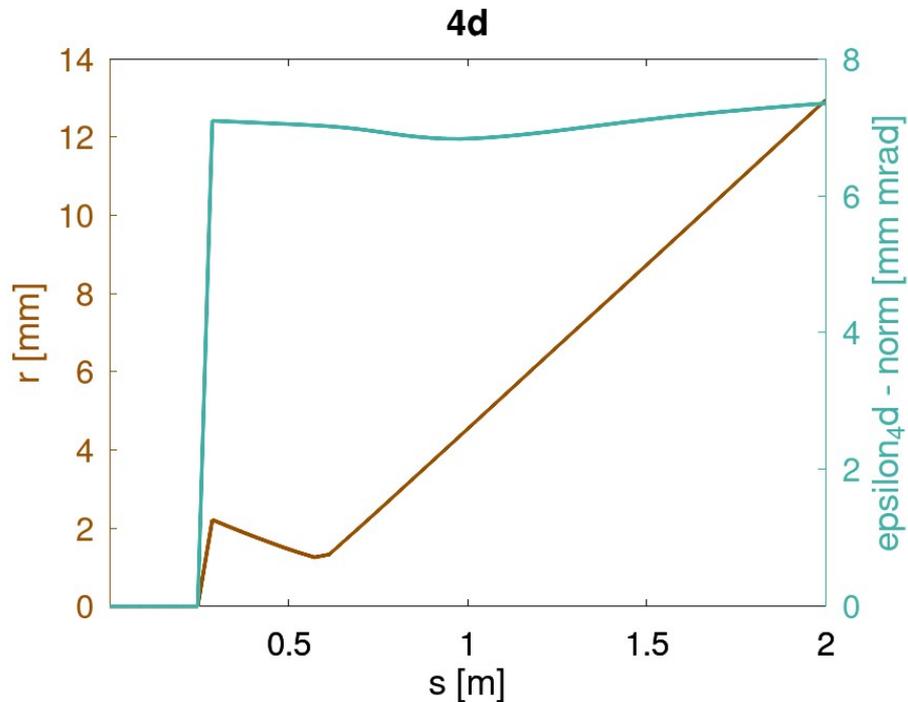- **Challenges**: Space charge (not really)

Beam Loading! $\rightarrow$ t = 0,82 т.

$E_{gain} \approx 3,8$ MeV

Photoinjector

$$\sigma^{4D} = \begin{bmatrix} <xx> & <xx'> & <xy> & <xy'> \\ <x'x> & <x'x'> & <x'y> & <x'y'> \\ <yx> & <yx'> & <yy> & <yy'> \\ <y'x> & <y'x'> & <y'y> & <y'y'> \end{bmatrix}$$
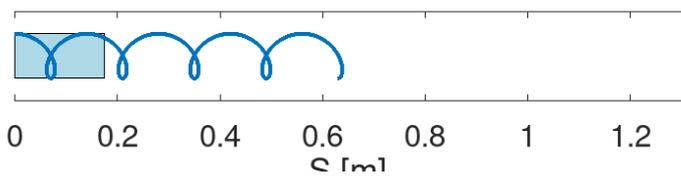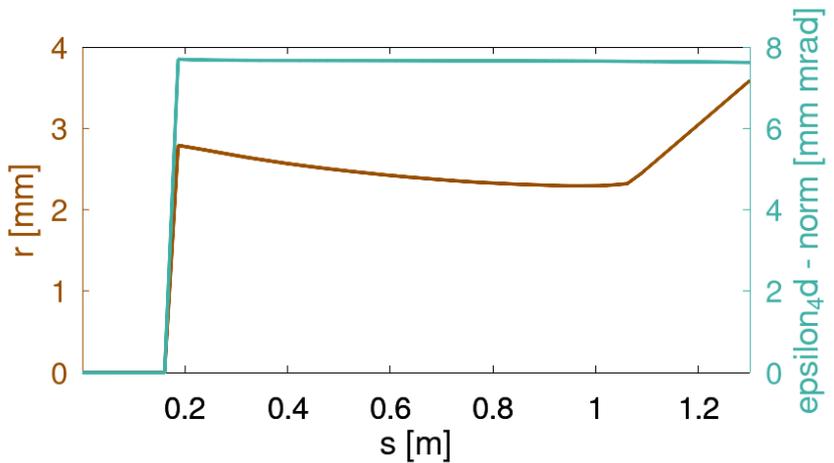
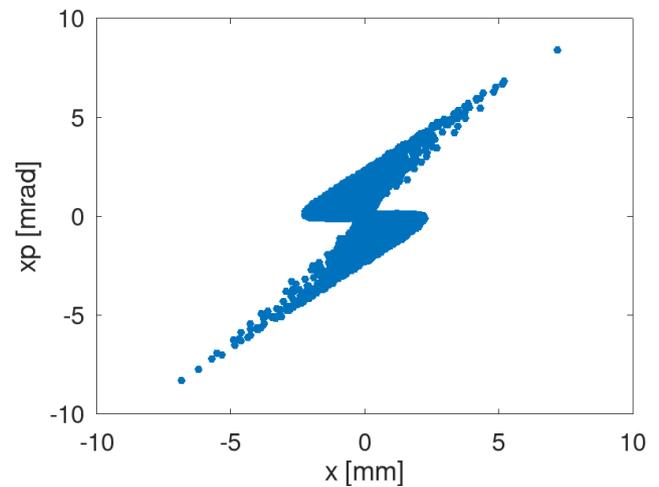$$\varepsilon_{4d} = \sqrt{\det(\sigma_{4d})}$$

The merit function accounts for:
- Charge maximization (I.e all 602pC survive)
- Min ε
- Min r
- Max E

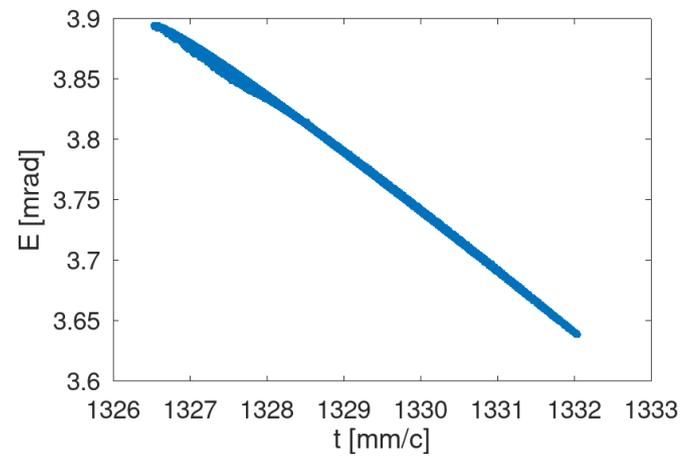AITANA
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Photoinjector

- Alternative for 1,3 m (smaller beam size)

mean pos = -0.00 mm, size = 1.08 mm

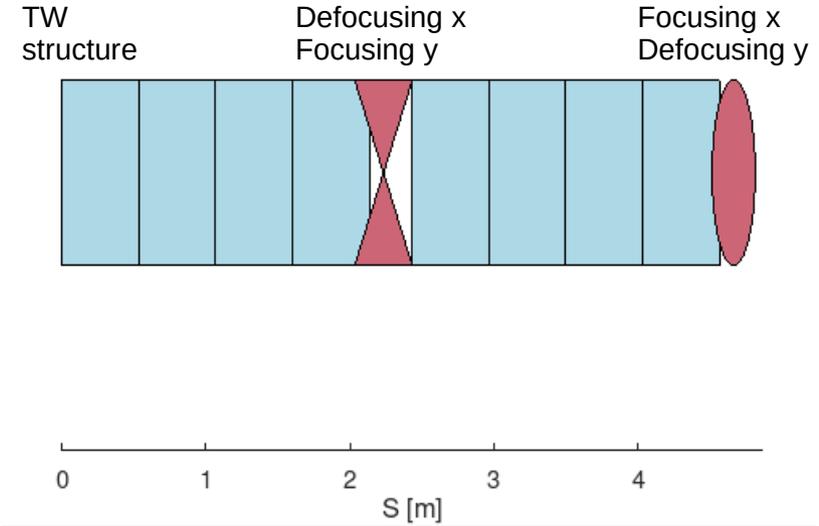mean E = 3.81 MeV, sigmaE = 0.05 MeV
sigma$_t$ = 1.15 mm/c

Magnitude	Unit	Value
σ_x	mm	0,805
σ_t	ps	1,41
ϕ_{RF}	deg	-78,3
$B_{z,\,max}$	T	0,168

LINAC

- After RF-gun: N FODO Lattices (up to 500 MeV)

    – X-band TW structures (12 GHz)

    – Apperture: 4,1-3,2 mm

    – Full BL → dV = 13,7 MV

    – φ, |k|

- On crest → Fatal performance
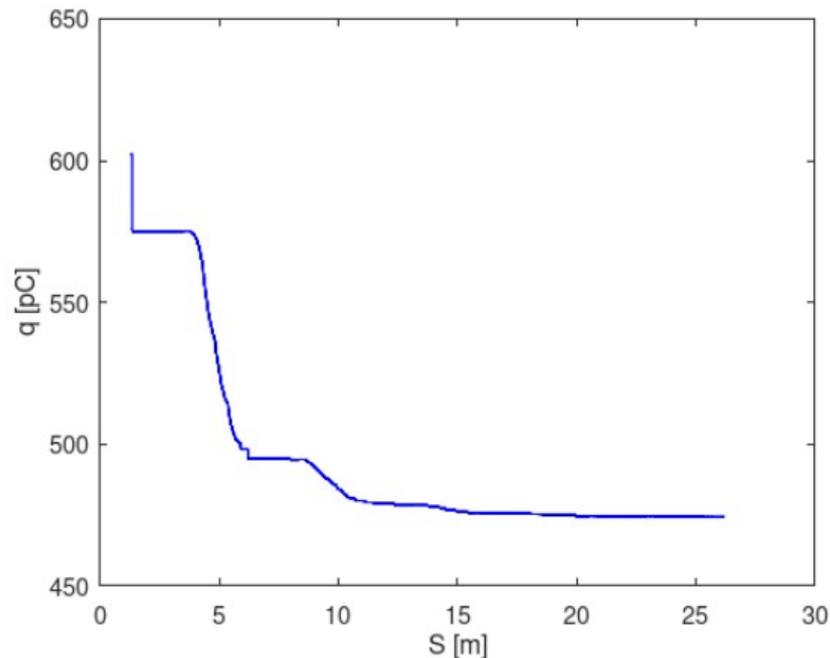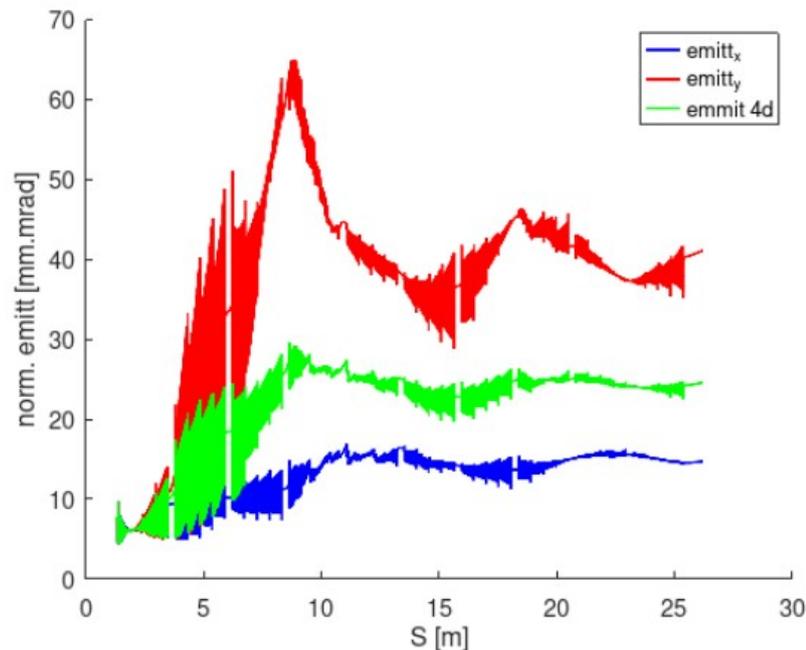
    – ON CREST → RF-correlated energy spread → Filamentation and phase-advance mismatch, induced by energy spread
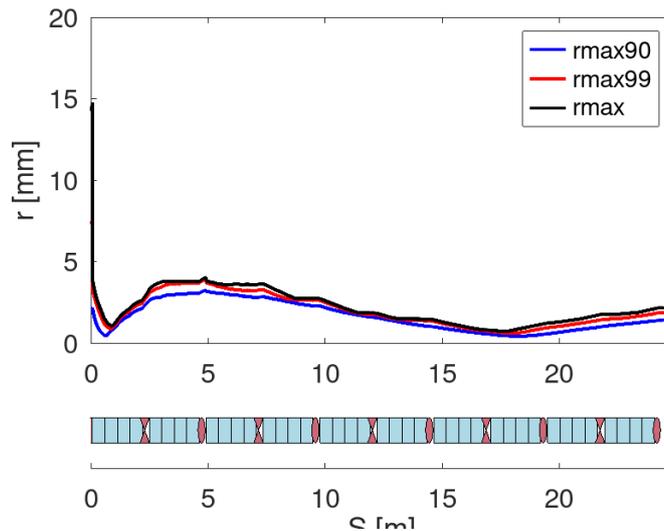
    – Wakefields BBU instability

LINAC

The merit function accounts for:
- Beam Power maximization
    - All 602pC survive + max E
- Min ε_{4d}

- On crest

LINAC

- Optimal:
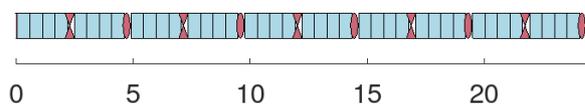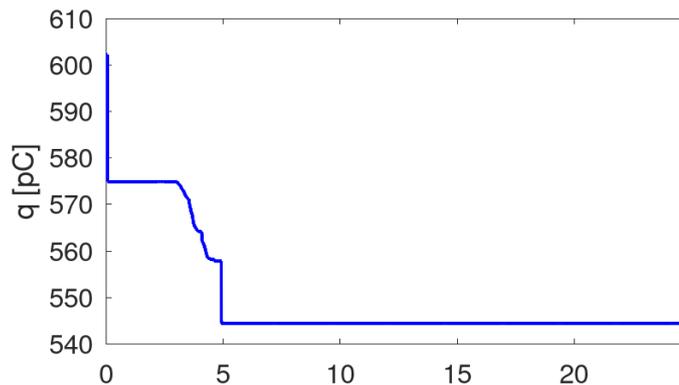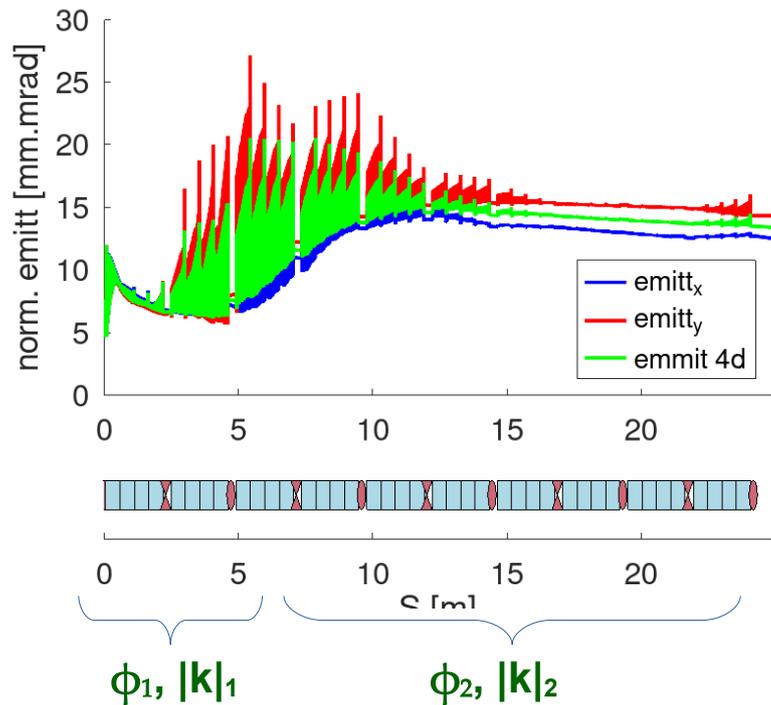
Magnitude	Unit	Value
k_1	$1/\mathrm{m}^2$	2.12
k_2	$1/\mathrm{m}^2$	2.35
ϕ_1	deg	-21.4
ϕ_2	deg	-3.34

Magnitude	Unit	Value
L	m	24.8
ε_{4d}	$\mathrm{mm}\cdot\mathrm{mrad}$	13.4
$P_{\mathrm{beam,\,av}}$	kW	24.7
$\langle E \rangle$	MeV	451.9
q_{bunch}	pC	-546.1

$\phi_1,\ |k|_1$ $\phi_2,\ |k|_2$

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LINAC

- EXTRA FOCUSING:
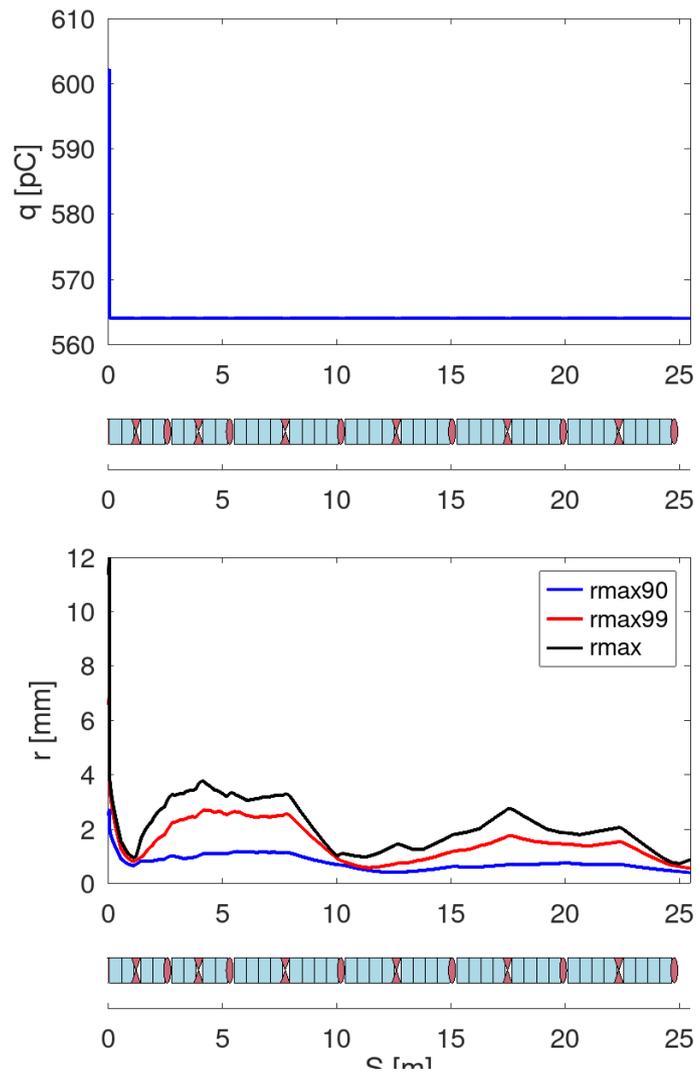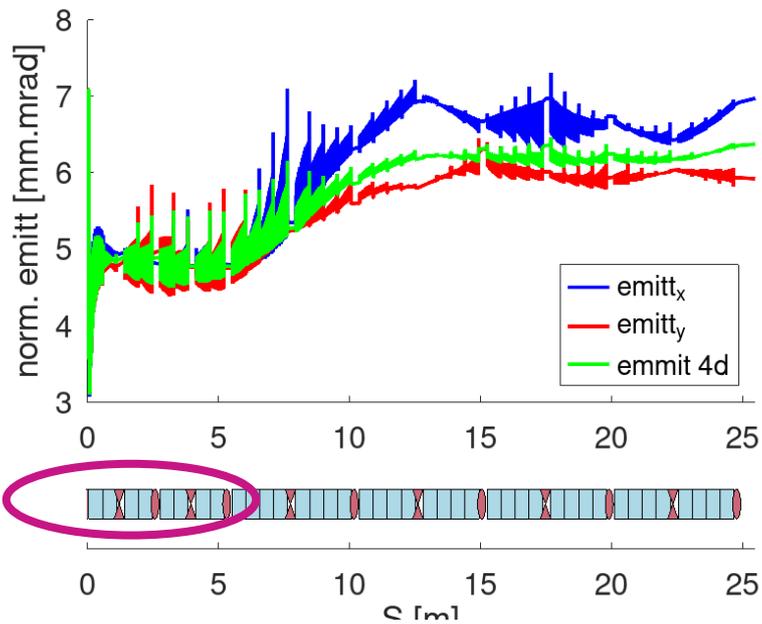
Magnitude	Unit	Value
k_1	$1/\mathrm{m}^2$	4.0
k_2	$1/\mathrm{m}^2$	3.86
ϕ_1	deg	-10.5
ϕ_2	deg	-3.3

Magnitude	Unit	Value
L	m	25.5
ε_{4d}	$\mathrm{mm}\cdot\mathrm{mrad}$	6.4
$P_{\mathrm{beam,\,av}}$	kW	25.6
$\langle E \rangle$	MeV	452.4
q_{bunch}	pC	-565.7

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LINAC

mean pos = -0.00 mm, size = 1.08 mm

- SMALLER BEAM:

Still some halo …
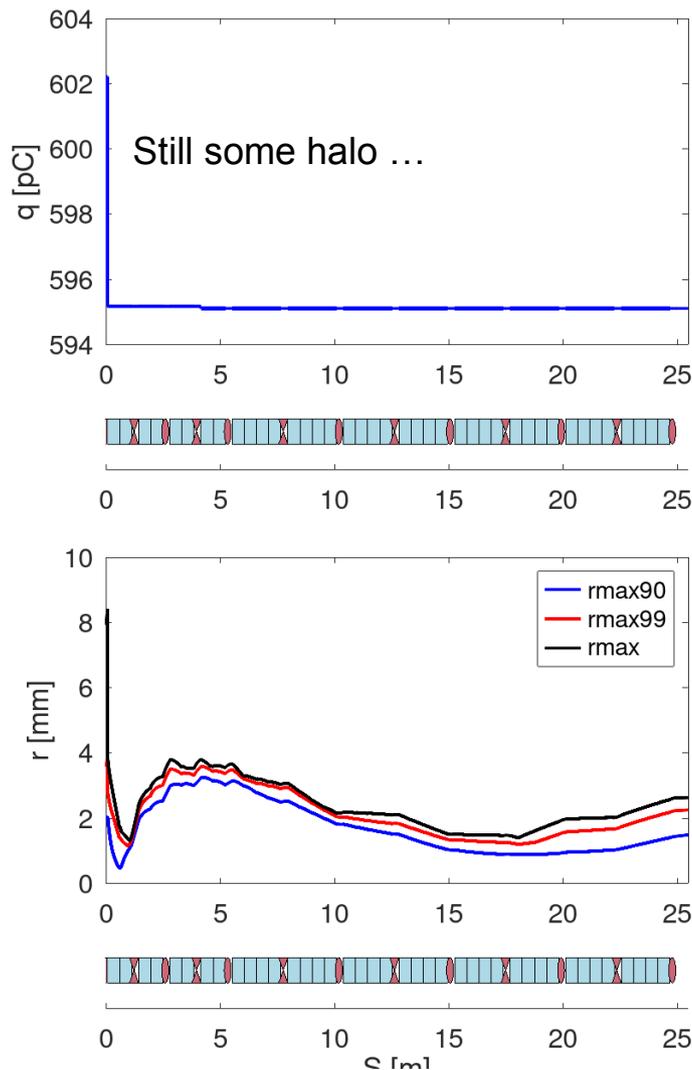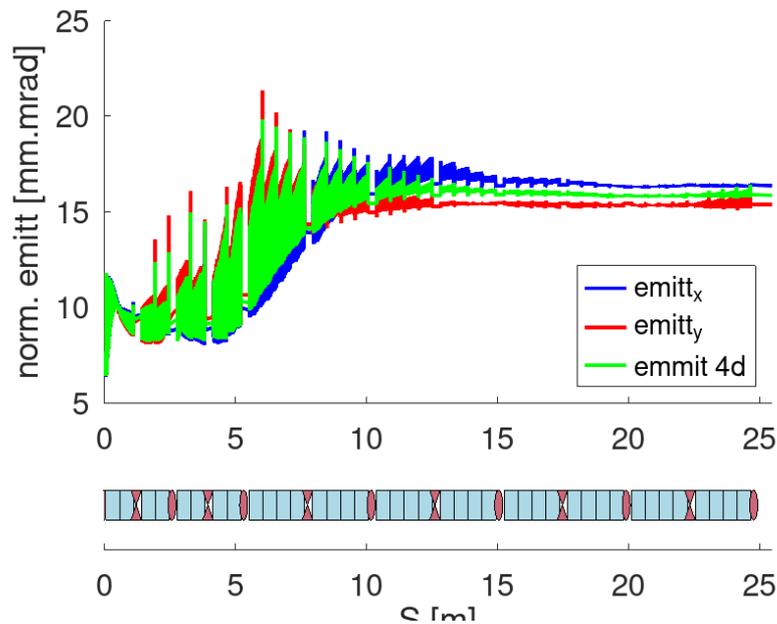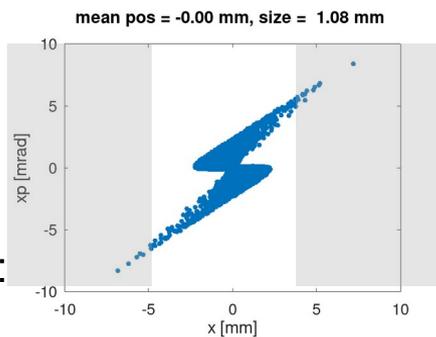
Magnitude	Unit	Value
k_1	$1/\mathrm{m}^2$	2.08
k_2	$1/\mathrm{m}^2$	1.2
ϕ_1	deg	-23.2
ϕ_2	deg	-1.5

Magnitude	Unit	Value
L	m	25.5
$\varepsilon_{\mathrm{4d}}$	$\mathrm{mm} \cdot \mathrm{mrad}$	15.8
$P_{\mathrm{beam,\ av}}$	kW	27.2
$\langle E \rangle$	MeV	456.4
q_{bunch}	pC	-595.9

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Tolerances

- A realistic machine suffers from jitter in $\langle x\rangle_0$, $\langle x'\rangle_0$, ϕ_{RF}, etc. The proposed design should admit 10% of variation without:

  - Beam losses through the accelerator

  - Loss of beam power < 5%

- Further optimization needed
  (Still some degrees of freedom to act upon)

Beams with offsets up to $10\%\sigma_x$
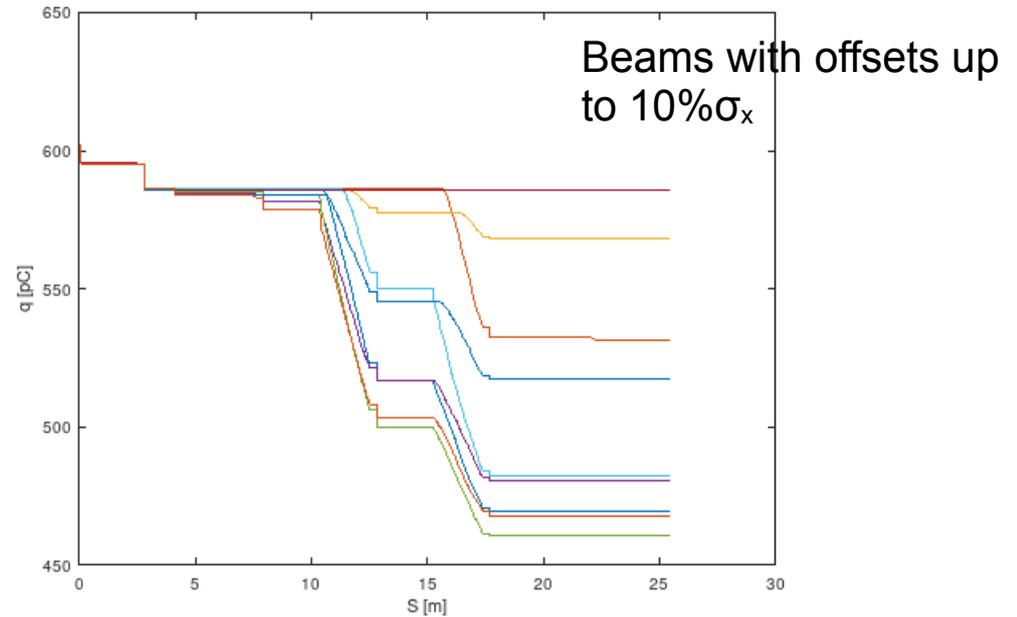
Conclusions

- Electron-linac-based neutron source arise as an affordable alternative for neutron production ~10^{15} n/s

  - Efficiency

  - Compactness

- Heavy-loaded beam transport through an X-band linac is challenging from the beam dynamics point of view due to high sensitivity to instabilities

  - Less efficiency when considering realistic beam transport is expected

  - Optimizations show potential to achieve ~25-30 kW beam power in ~25 m.

- Still, unique attempt of transport of high charge through an X-band linac

Further work

- Baseline – Further improvements

- Tolerances: Define figures of merit (amp. Factor) and further optimize to achieve 10% tolerance

- Repeat with less q_{bunch}: 550 pC, 500 pC.

- Simulate with G4beamlines to give a final set of parameters

- Write down in PhD thesis

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Thanks for your attention

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