HF-RFQ
and
S-Band BTW

Cavities for Medical Applications

KT Medical Applications Seminar
07.07.2017

Benjamin Koubek
BE-RF-LRF

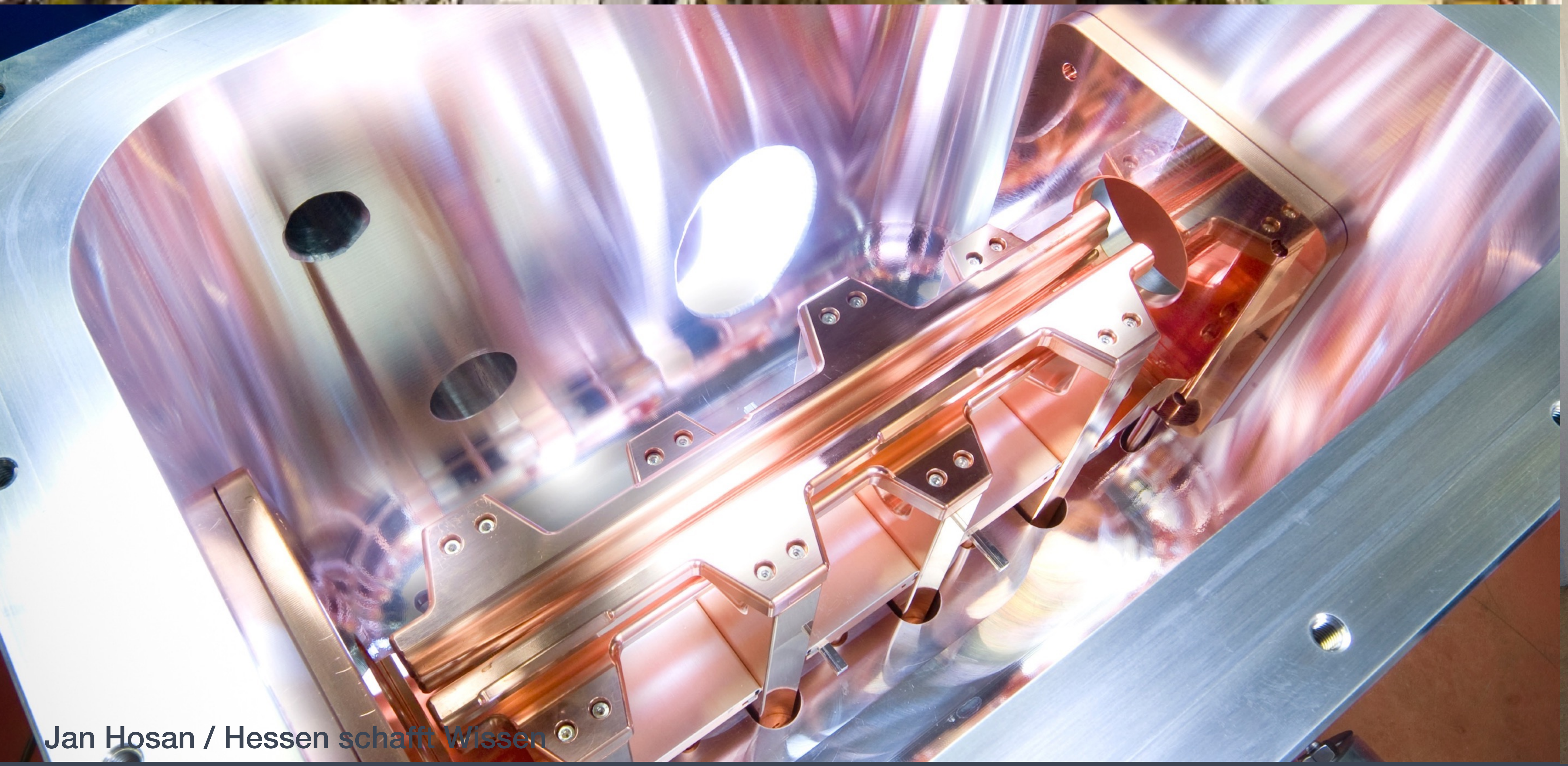
Overview


https://media-cdn.tripadvisor.com/media/photo-s/03/9b/2f/80/frankfurt.jpg


www.uni-frankfurt.de

Accelerator Physics

- RF simulations
- RF measurements
- Tuning


Jan Hosan / Hessen schafft Wissen

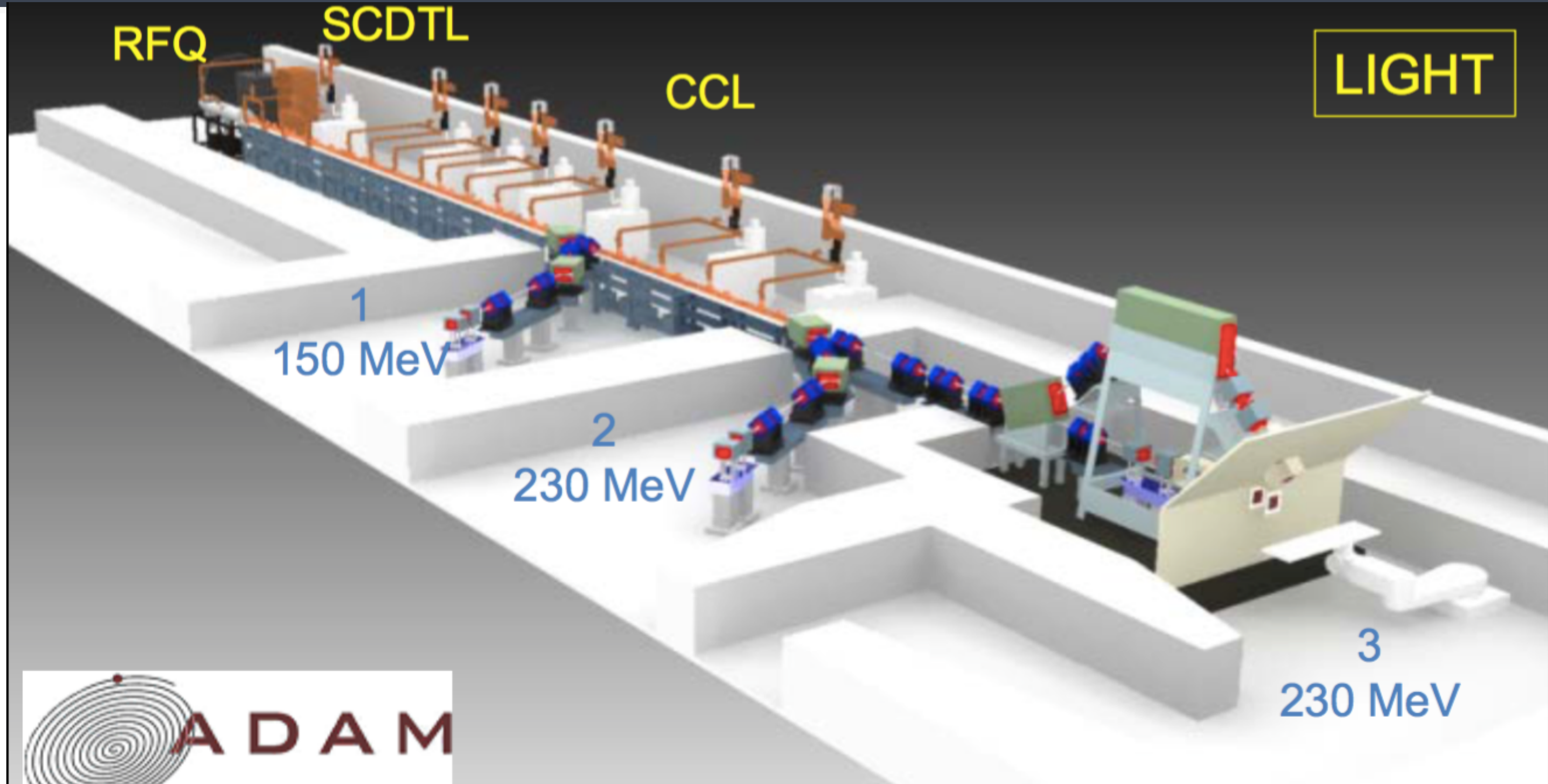
Overview

Why Protons for Cancer Therapy?

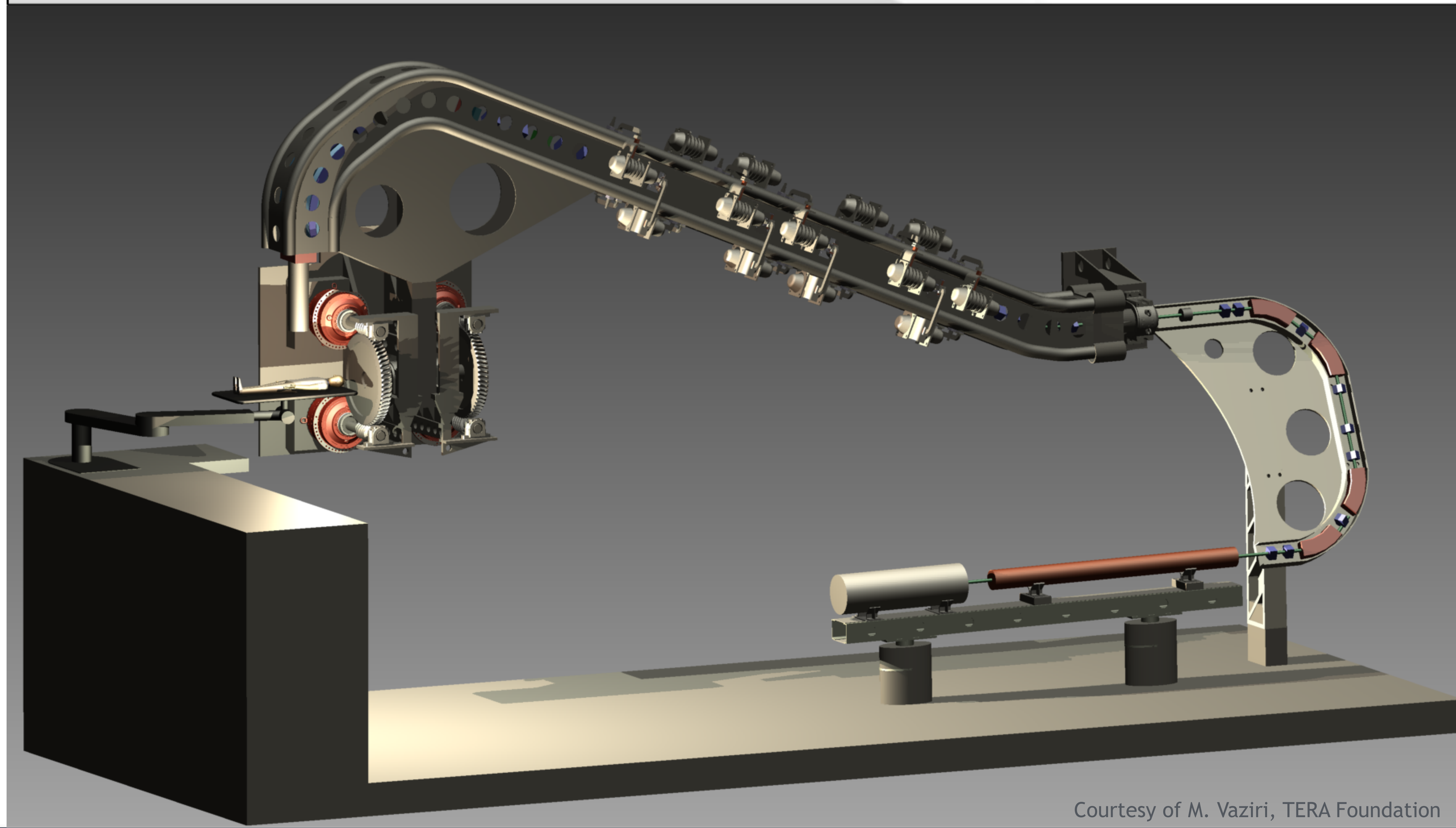
State of the Art Facilities

Projects

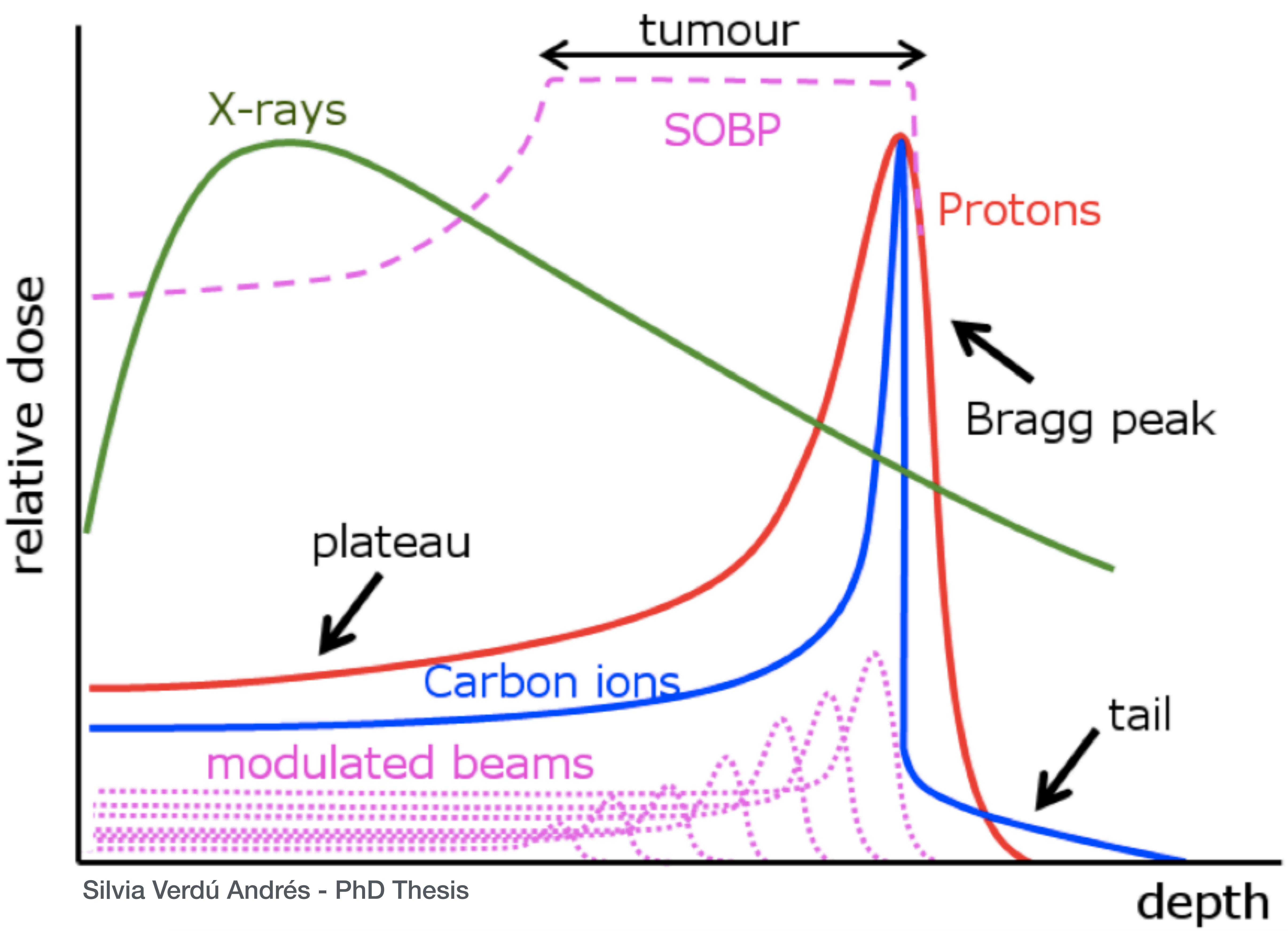
- 750 MHz RFQ for Medical Applications
  - RF Measurements
  - Tuning Algorithm Development
  - Tuning of the RFQ
- 3 GHz BTW Structure for TULIP
  - Conditioning of the Structure
  - Breakdown Studies
  - Data Analysis



Alberto Degiovanni - CAS 2015 / Accelerators for Medical Applications

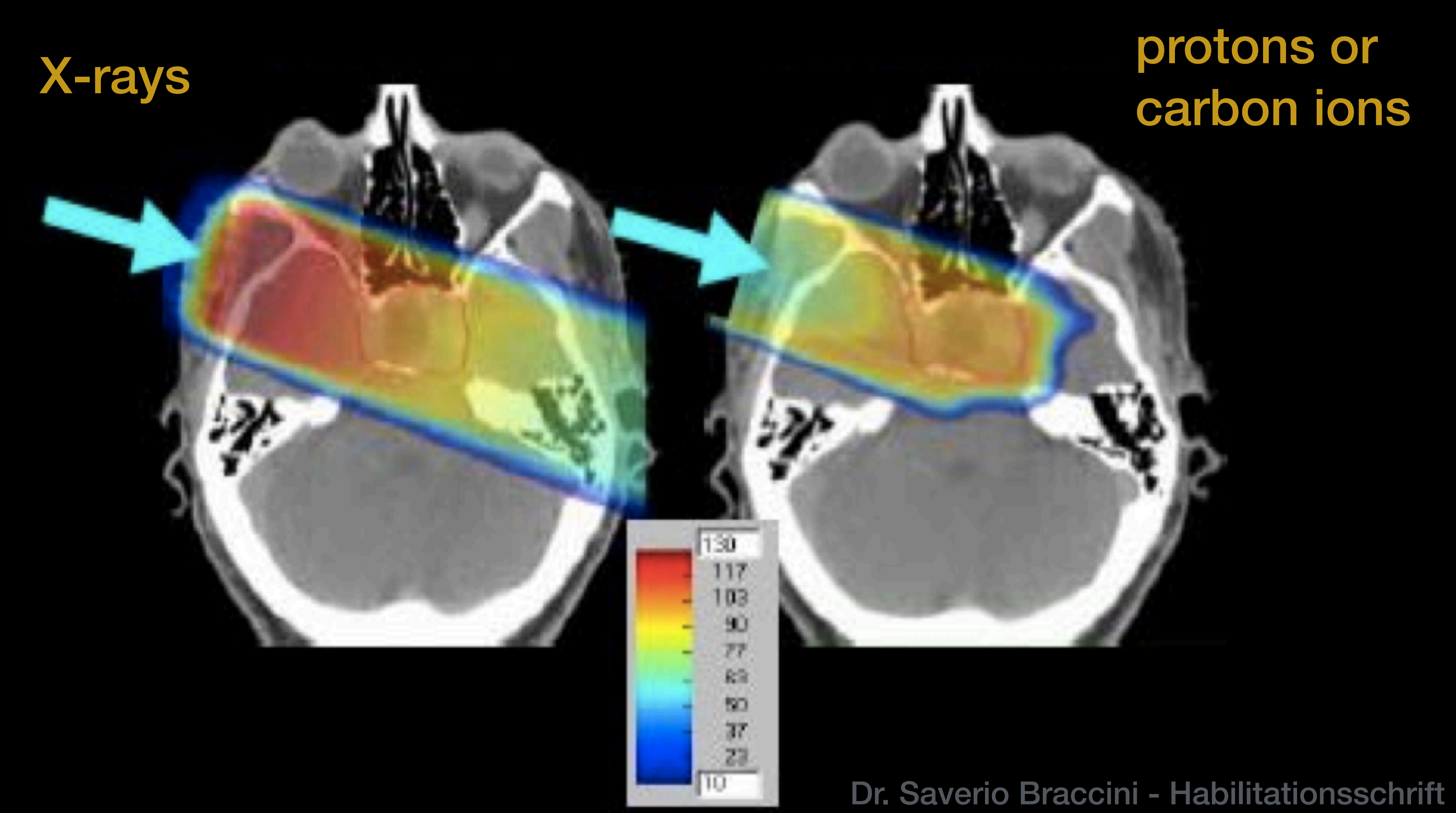

Courtesy of M. Vaziri, TERA Foundation

Hadron Therapy - Basic Concept



Silvia Verdú Andrés - PhD Thesis

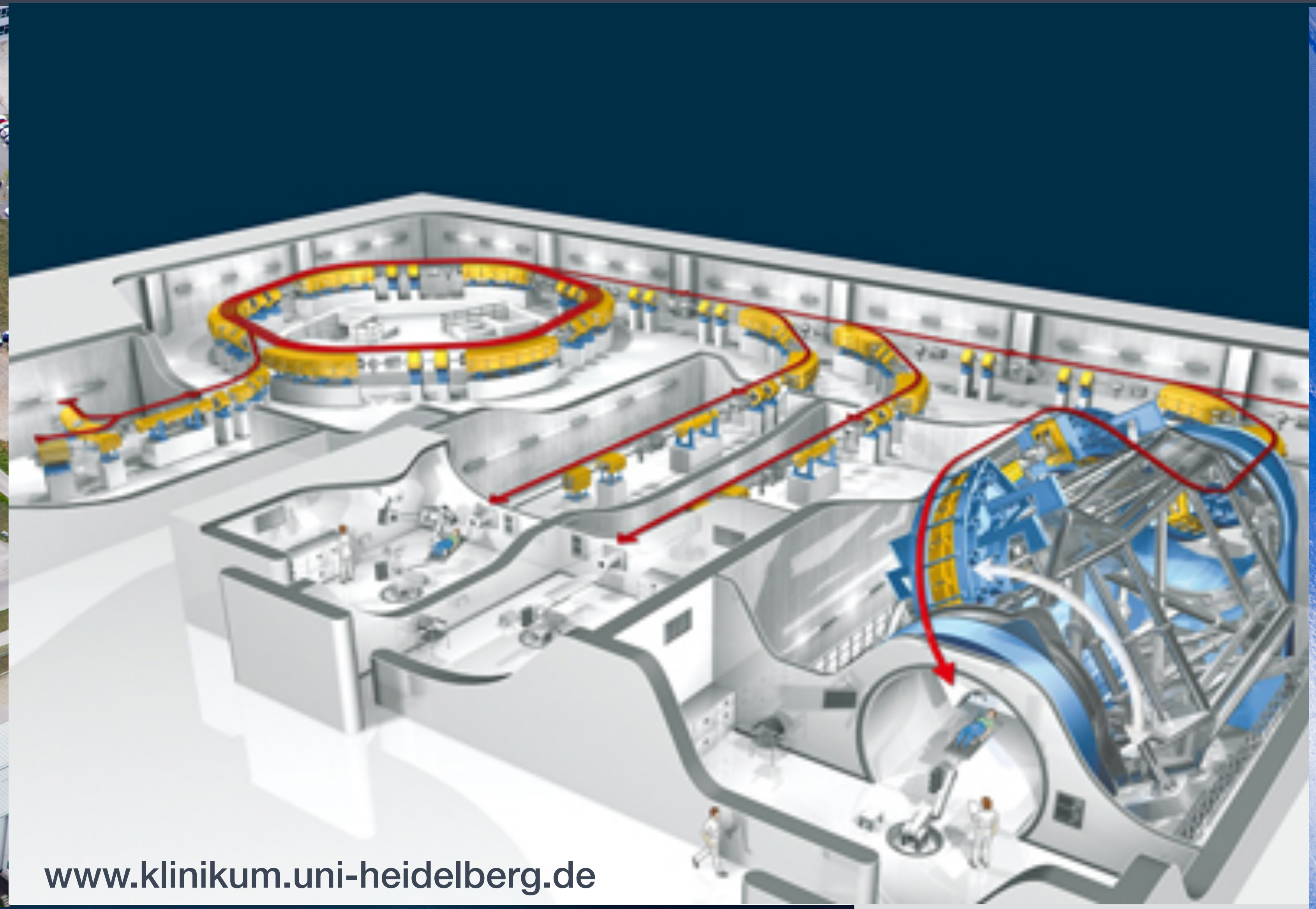
https://www.klinikum.uni-heidelberg.de



Dr. Saverio Braccini - Habilitationsschrift

State of the Art Facilities

Jug Thule / www.medaustron.at



www.klinikum.uni-heidelberg.de

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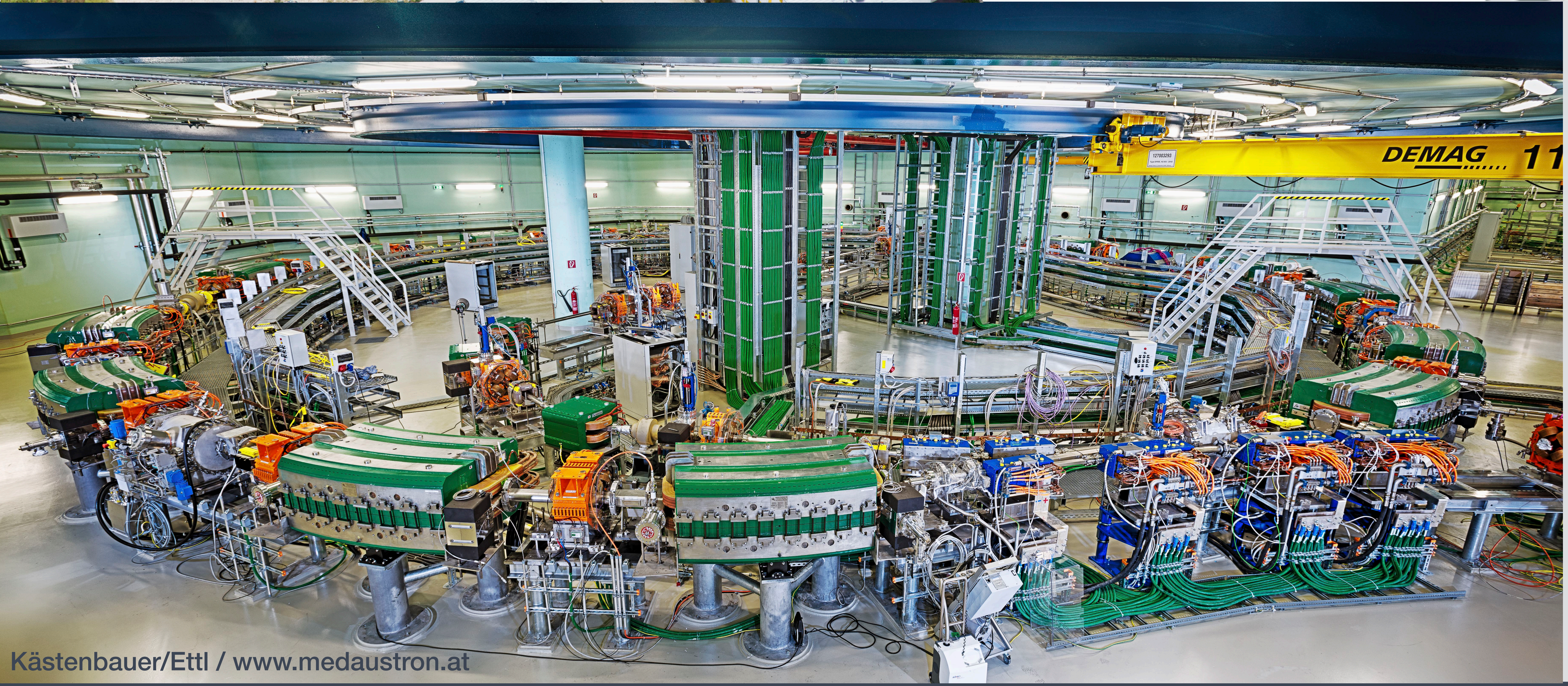
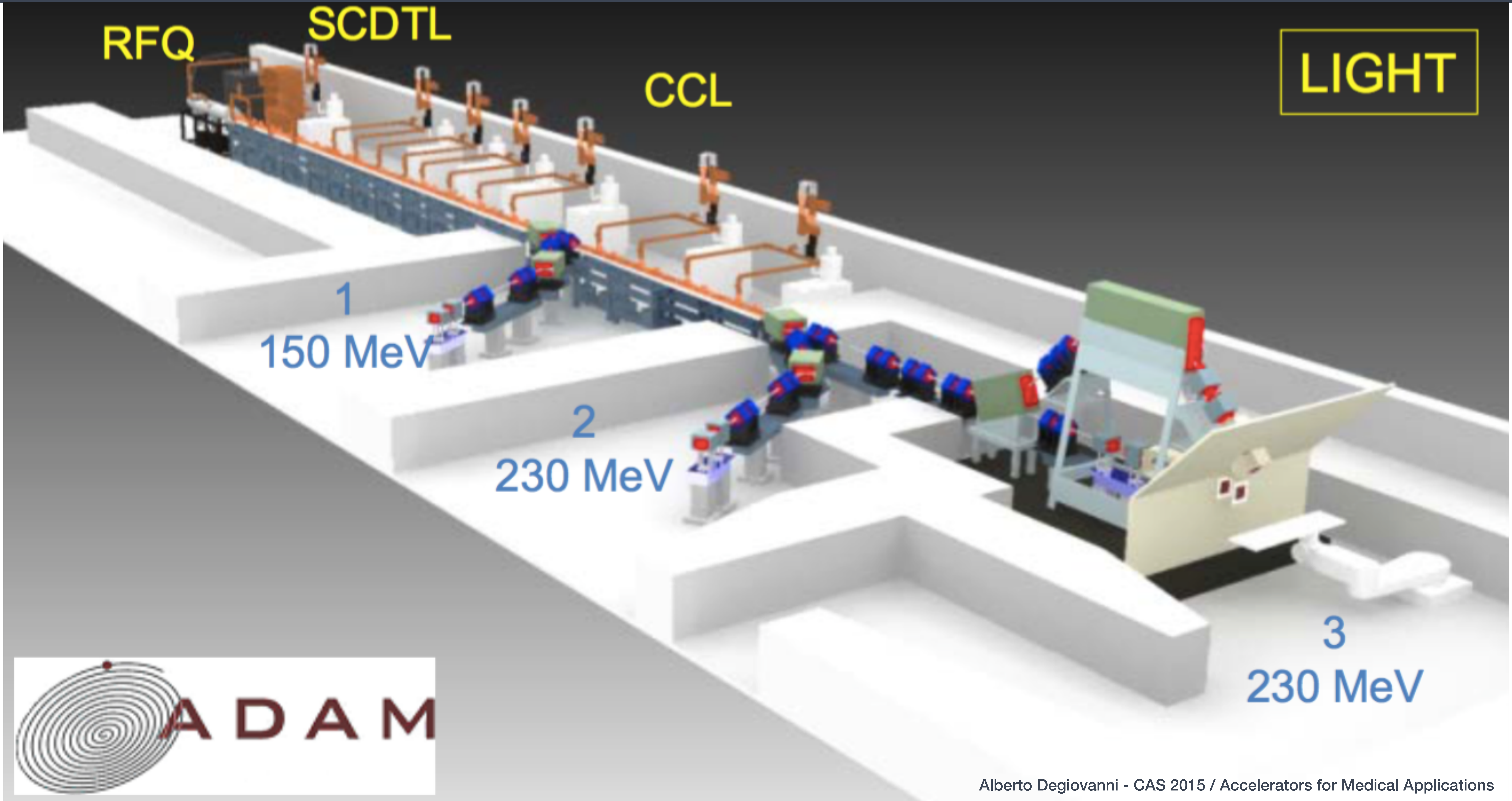


Kästenbauer/Ettl / www.medaustron.at

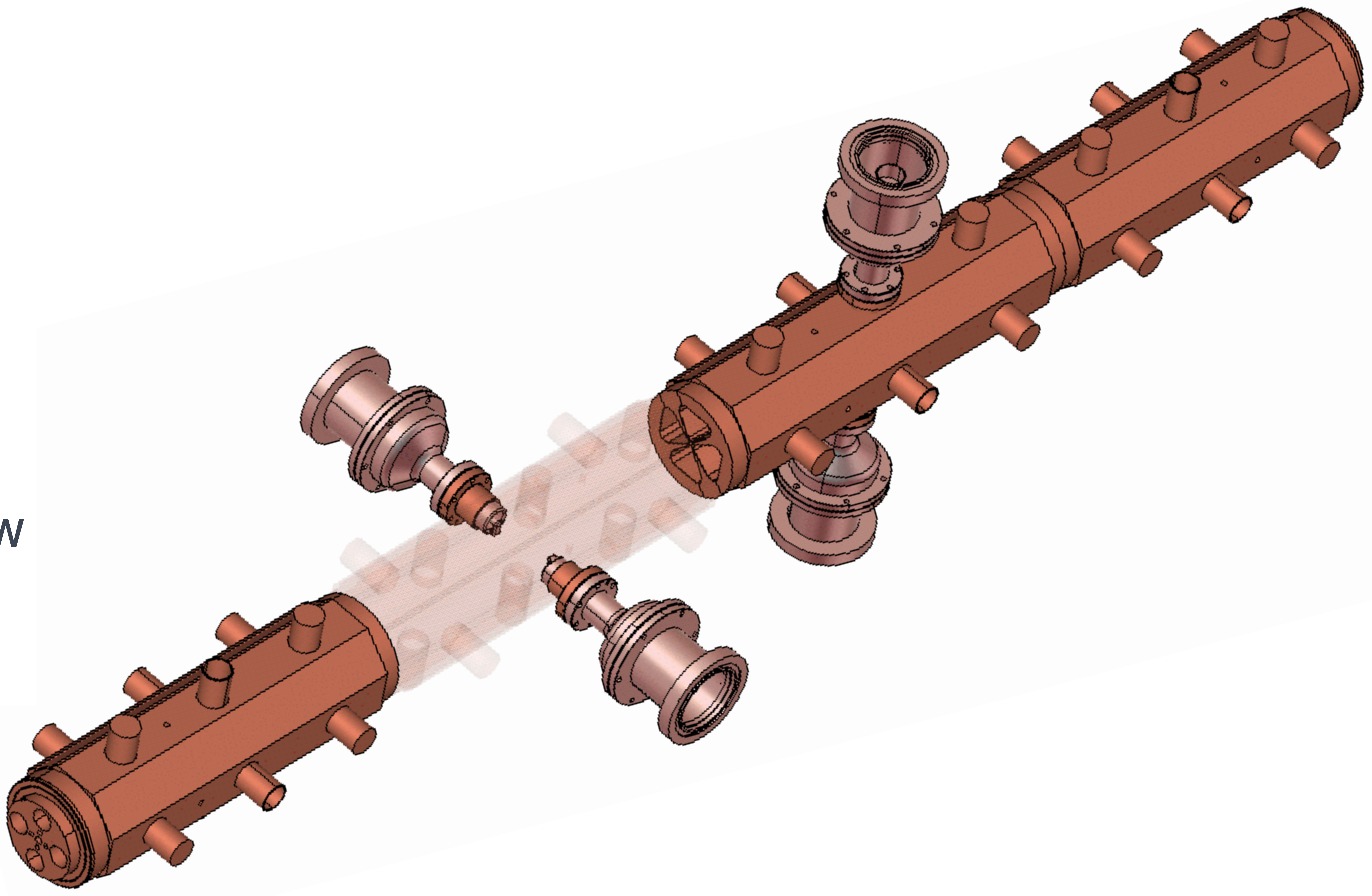
ADAM - LIGHT



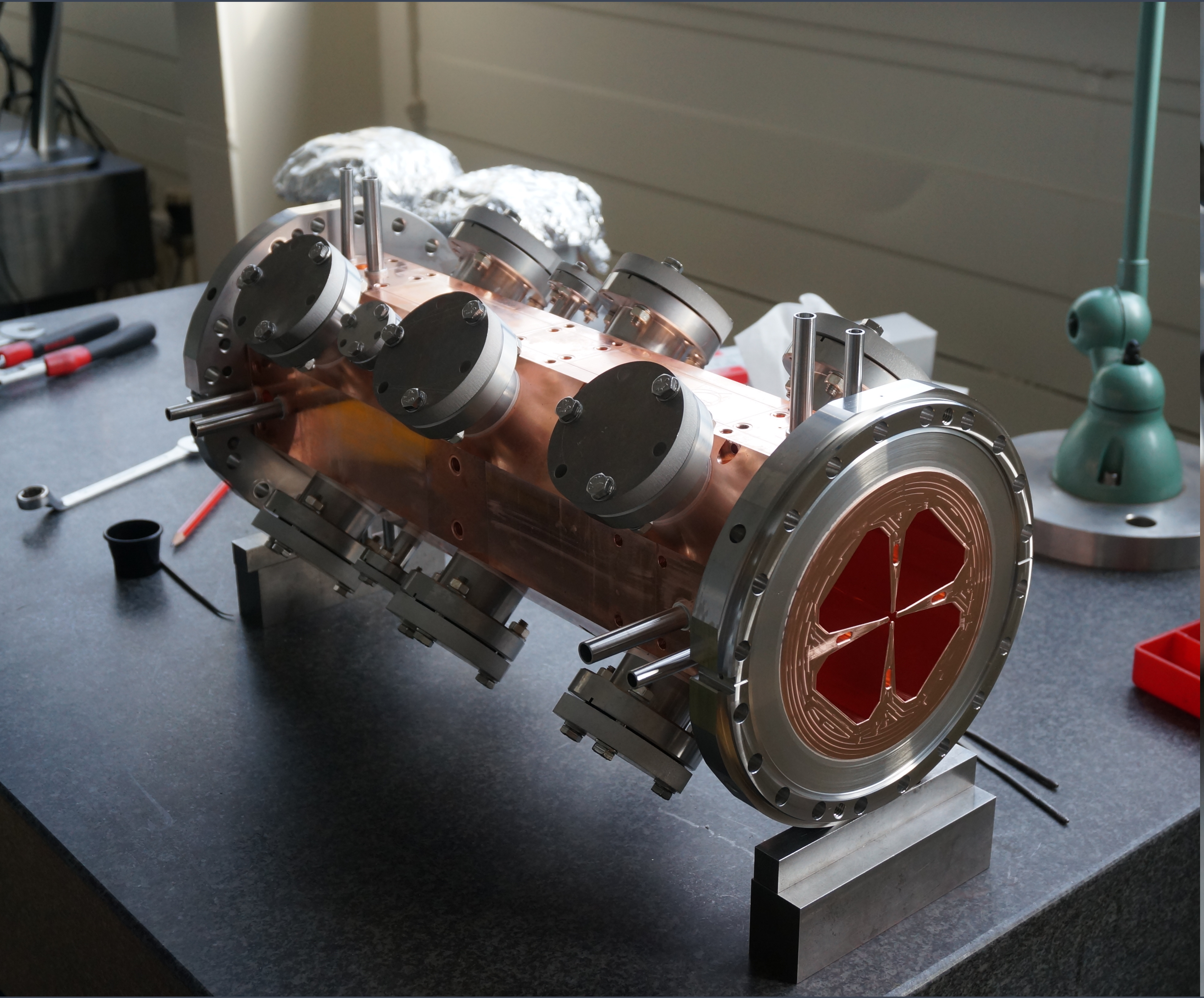
Alberto Degiovanni - CAS 2015 / Accelerators for Medical Applications

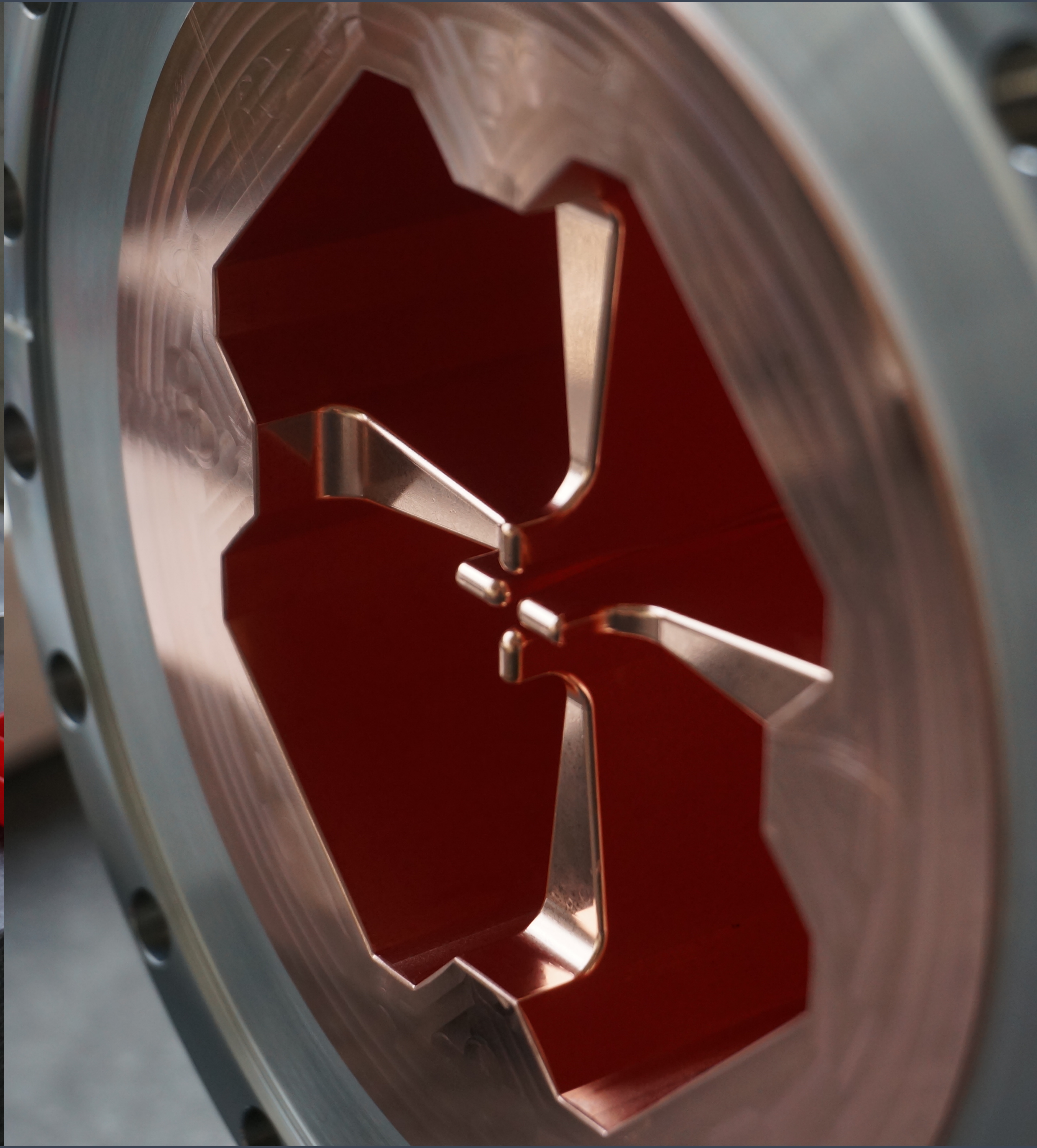
750 MHz RFQ

Frequency	750 MHz
Input Energy	40 keV
Output Energy	5 MeV
Length	2 m
Diameter	0.134 m
# Modules	4
# Tuners	32
Power Supply IOT	4 x 100 kW
# Power Couplers	4
# Pickup Antennas	16

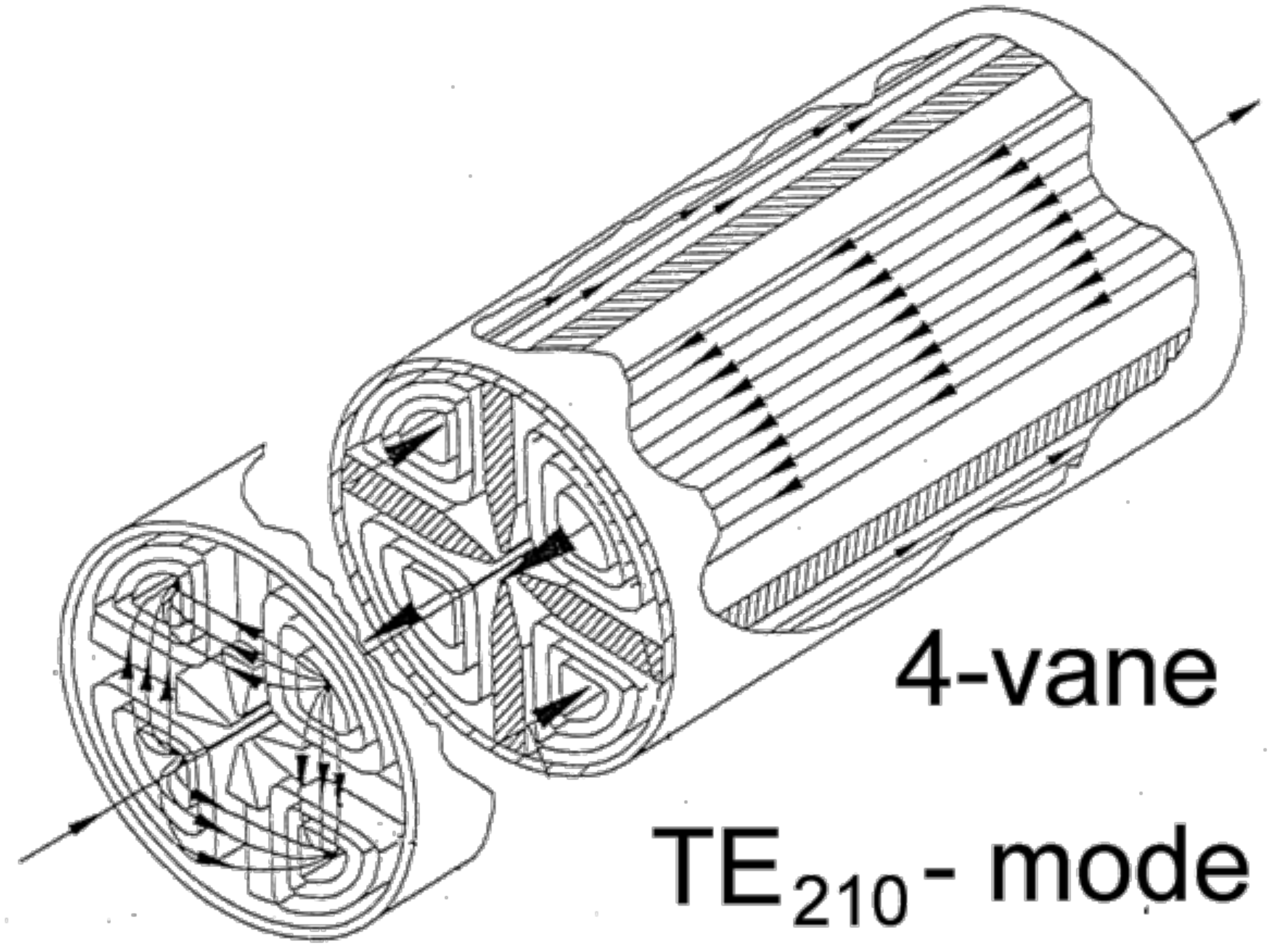


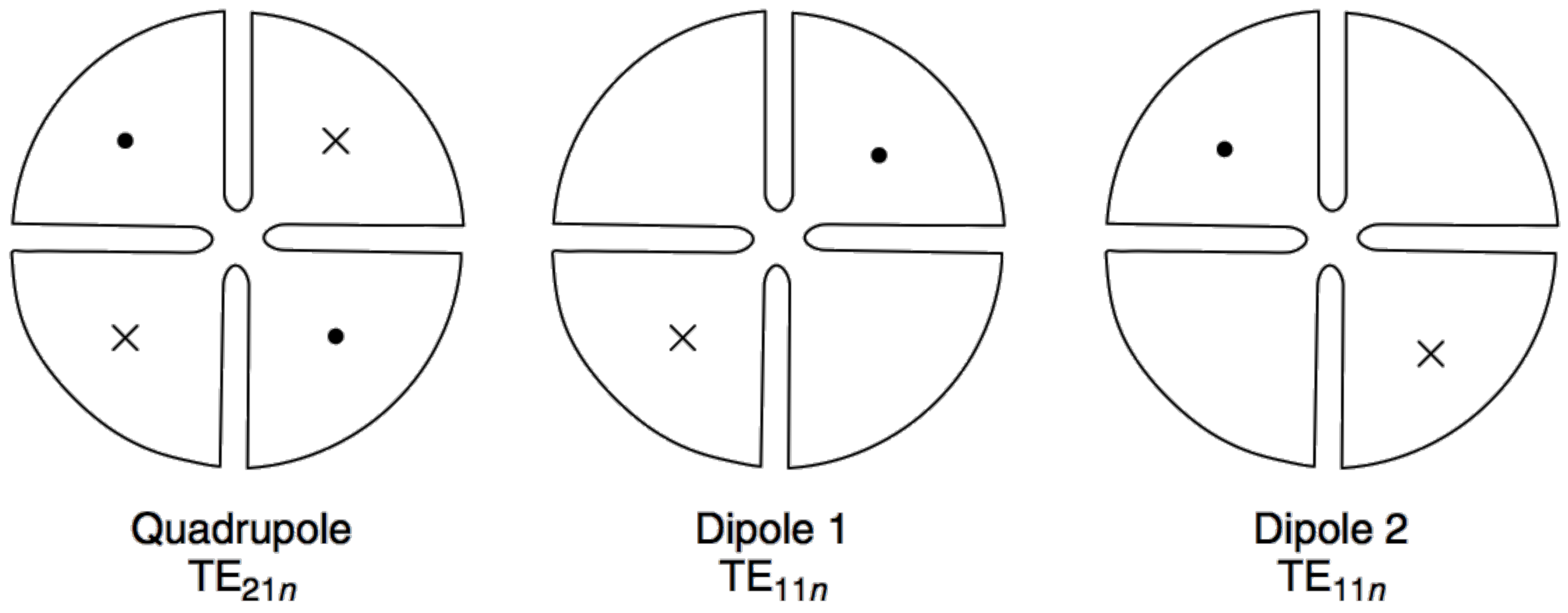
Module Extremities

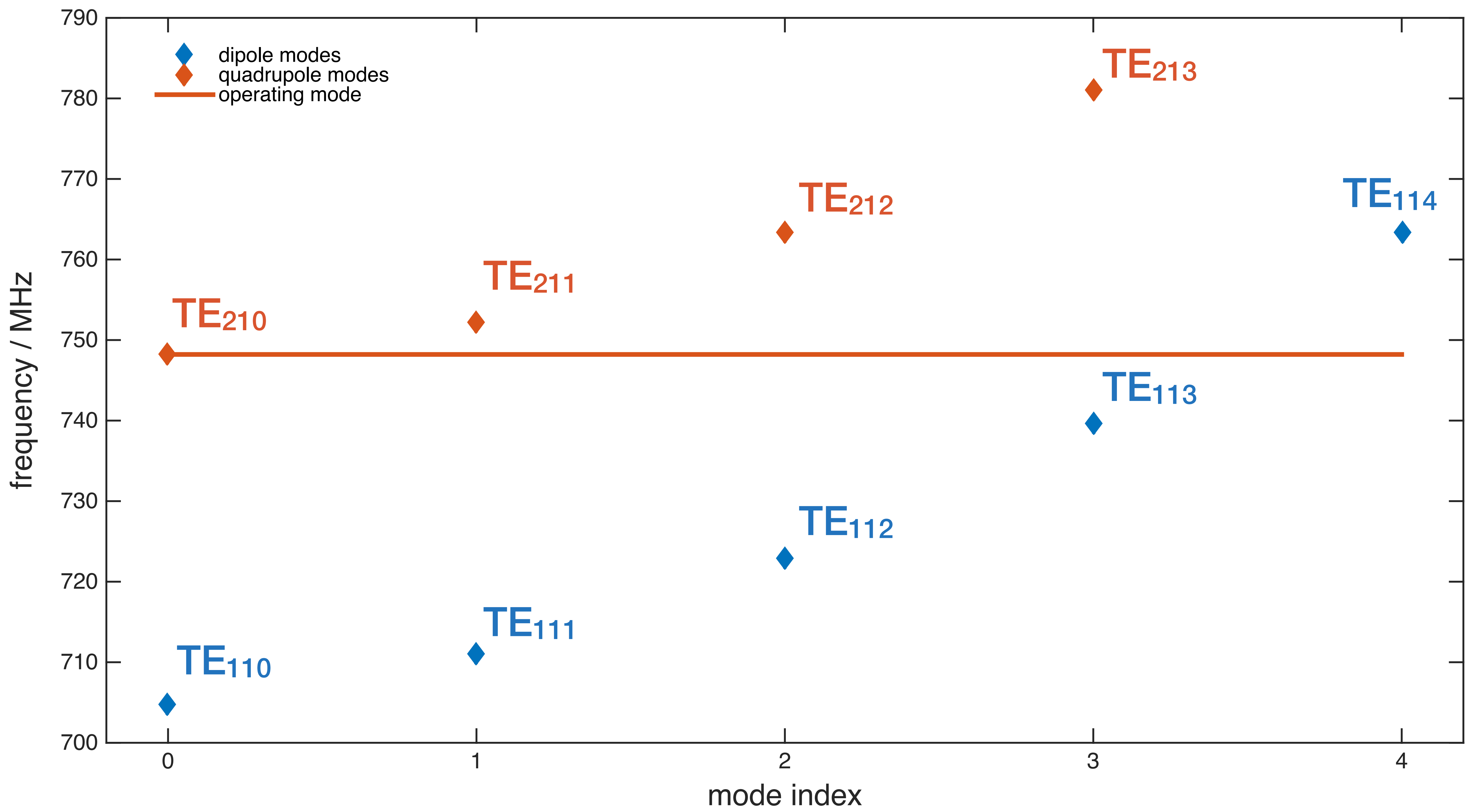




4-vane RFQ



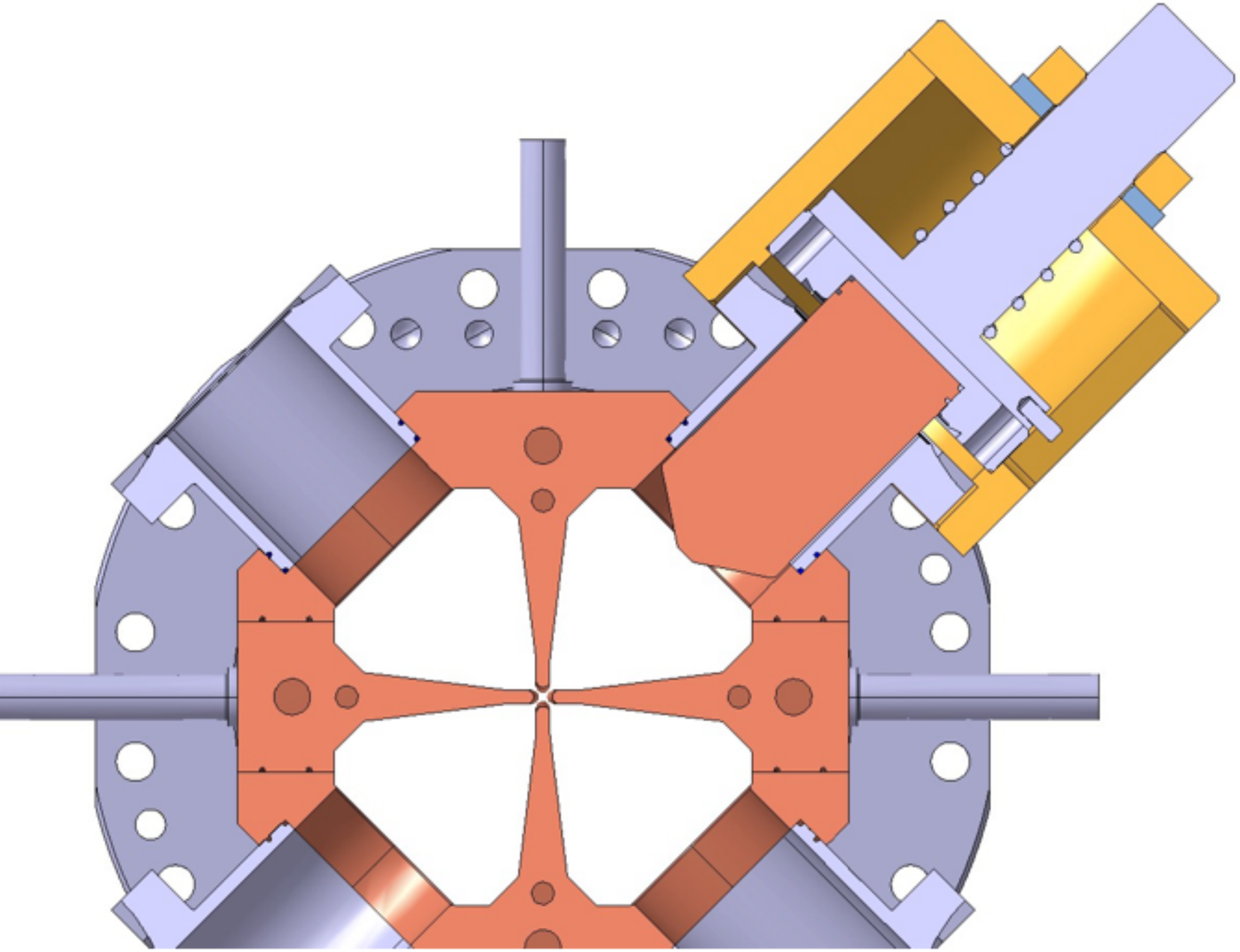


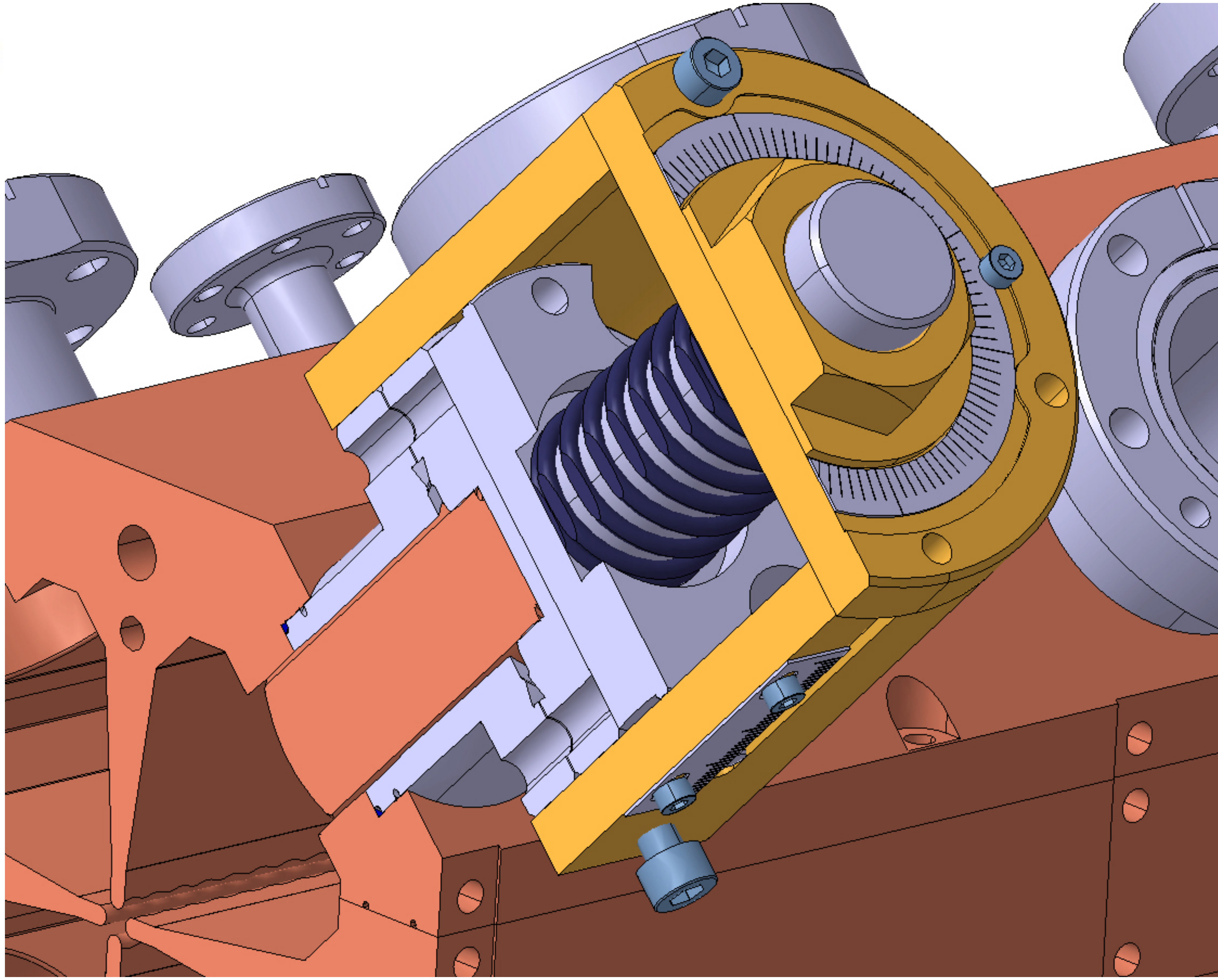


$$Q = (q1 - q2 + q3 - q4) / 4$$
$$Ds = (q1 + q3) / 2$$
$$Dt = (q2 + q4) / 2$$

$$Ds = Dt = 0$$

Tuner Tooling





Bead Pull System

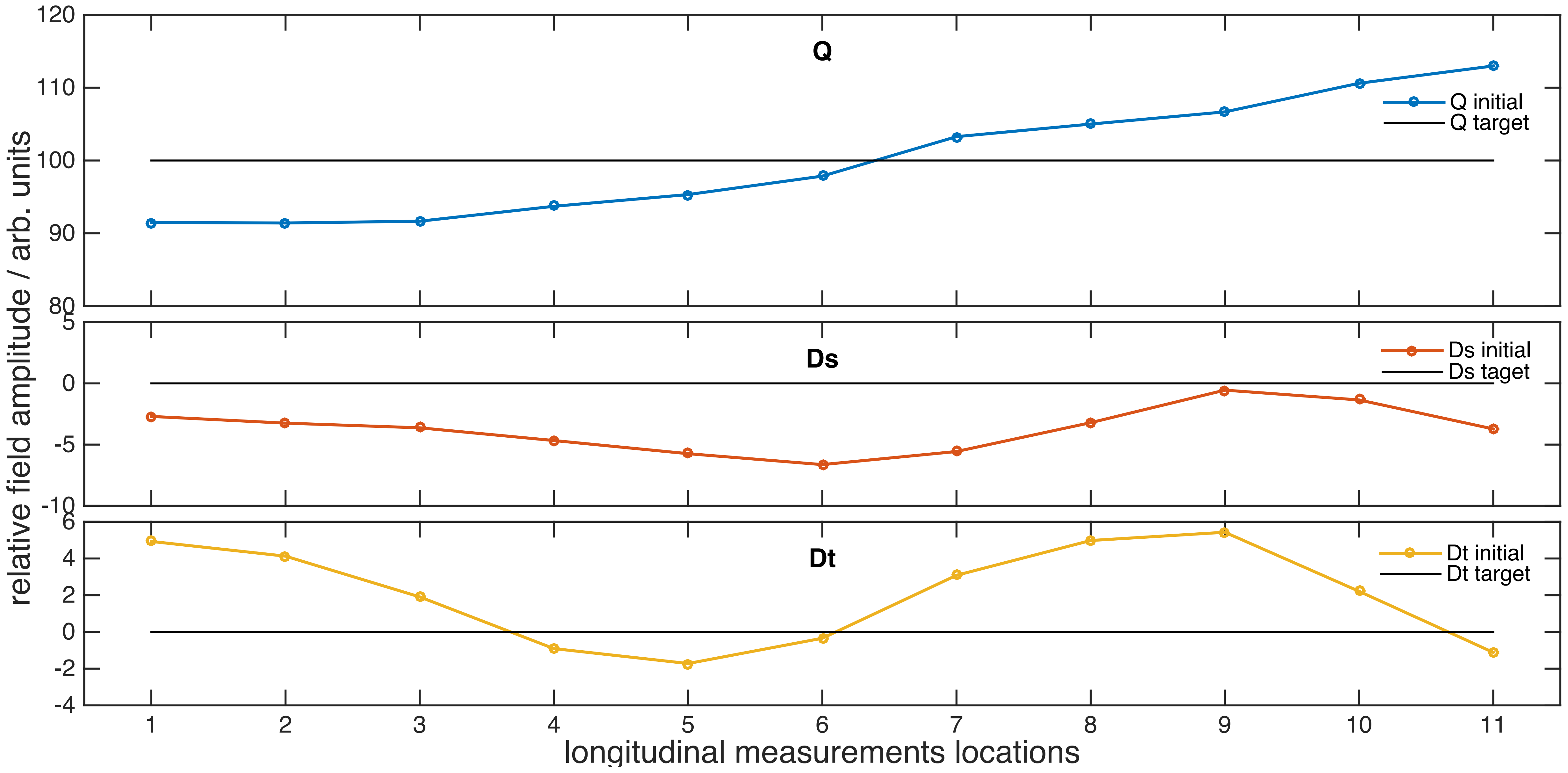
Tuning Algorithm

$$Q = (q_1 - q_2 + q_3 - q_4)/4 = const.$$

$$Ds = (q_1 - q_3)/2 = 0$$

$$Dt = (q_2 - q_4)/2 = 0$$

$$\begin{bmatrix} 100 - V_1 \\ \vdots \\ 100 - V_{11} \\ 0 \quad - V_{12} \\ \vdots \\ 0 \quad - V_{22} \\ 0 \quad - V_{23} \\ \vdots \\ 0 \quad - V_{33} \end{bmatrix}$$



Tuning Algorithm

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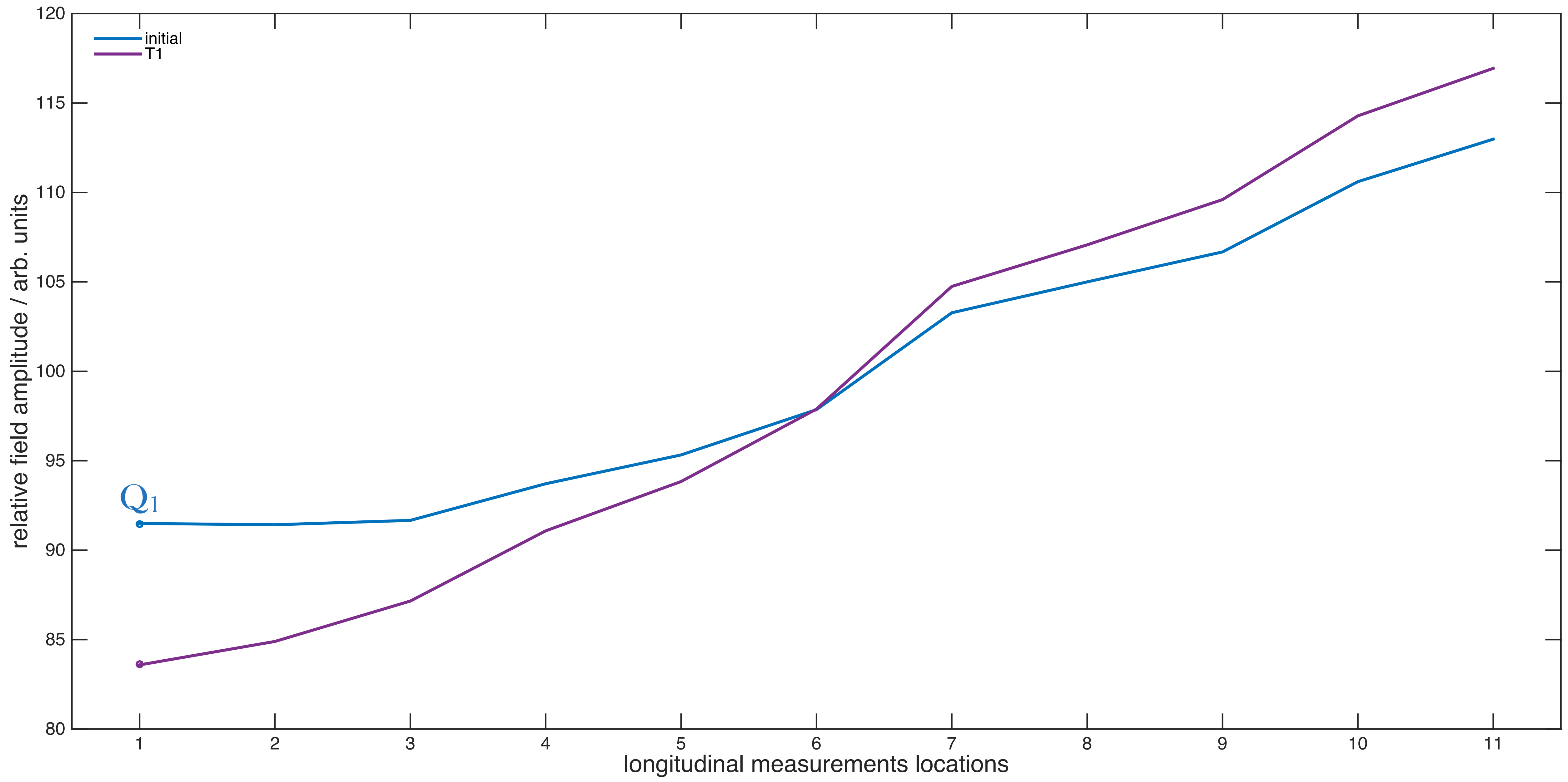
$$\begin{bmatrix} 100 - V_1 \\ \vdots \\ 100 - V_{11} \\ 0 - V_{12} \\ \vdots \\ 0 - V_{22} \\ 0 - V_{23} \\ \vdots \\ 0 - V_{33} \end{bmatrix} \qquad \frac{\partial Q_1}{\partial T_1}$$



Tuning Algorithm

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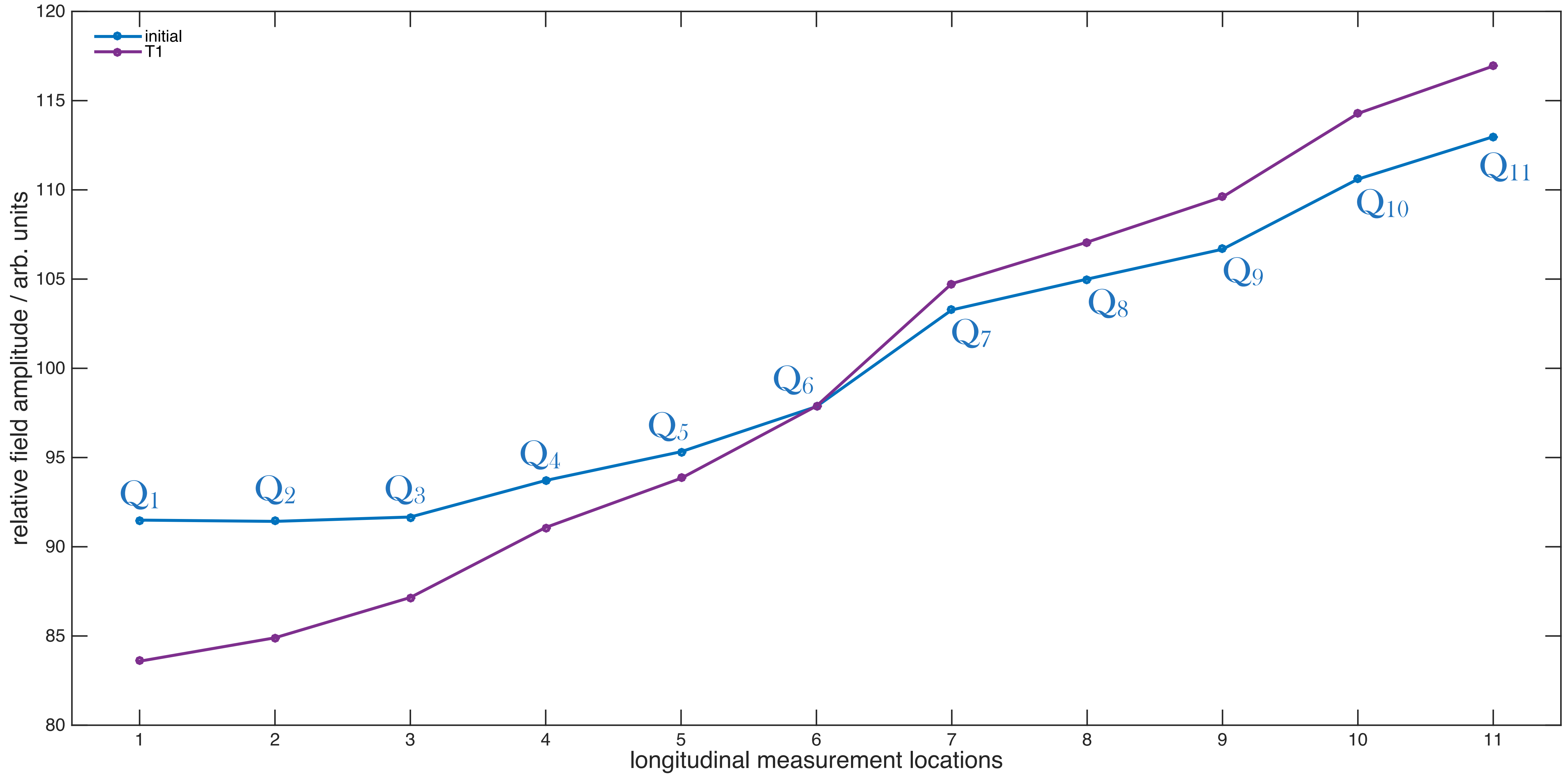

Tuning Algorithm

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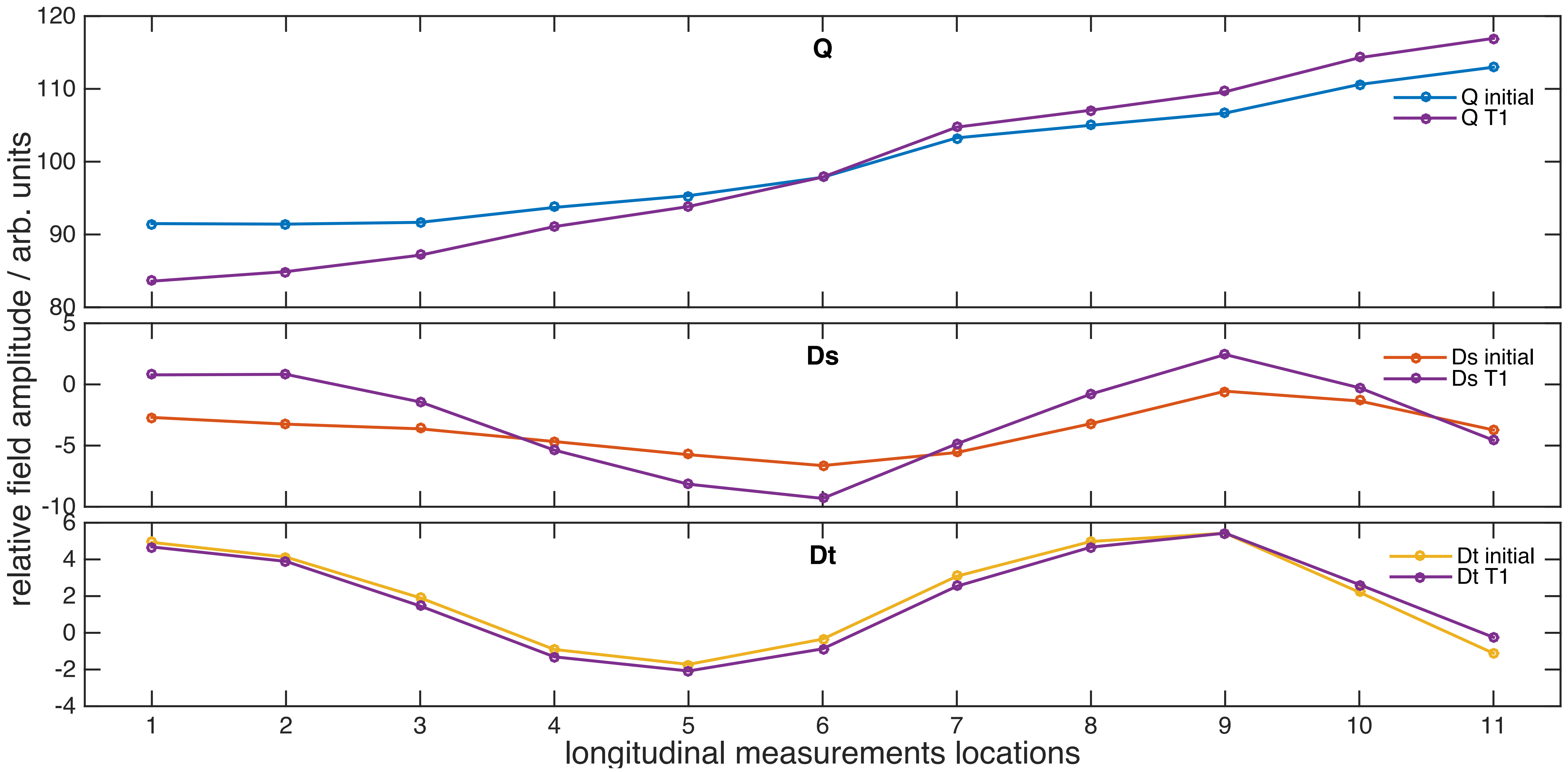
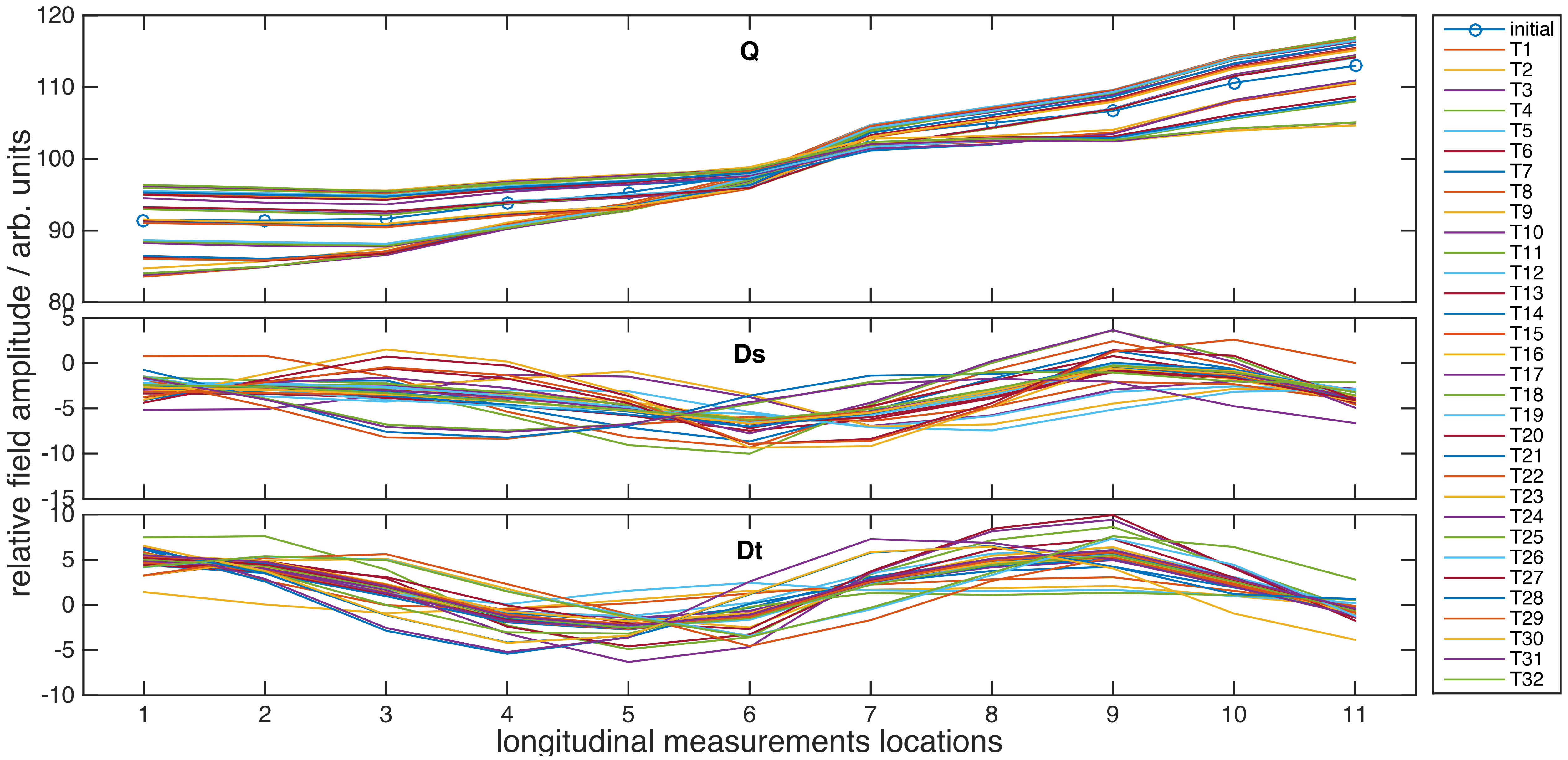


Tuning Algorithm

$$
\begin{aligned}
Q &= (q_1 - q_2 + q_3 - q_4)/4 &&= const. \\
Ds &= (q_1 - q_3)/2 &&= 0 \\
Dt &= (q_2 - q_4)/2 &&= 0
\end{aligned}
$$

$$
\begin{bmatrix}
100 - V_1 \\
\vdots \\
100 - V_{11} \\
0 \quad - V_{12} \\
\vdots \\
0 \quad - V_{22} \\
0 \quad - V_{23} \\
\vdots \\
0 \quad - V_{33}
\end{bmatrix}
\qquad
\begin{bmatrix}
\frac{\partial Q_1}{\partial T_1} & \frac{\partial Q_1}{\partial T_2} & \cdots & \cdots & \cdots & \frac{\partial Q_1}{\partial T_{32}} \\
\vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\
\frac{\partial Q_{11}}{\partial T_1} & \frac{\partial Q_{11}}{\partial T_2} & \cdots & \cdots & \cdots & \frac{\partial Q_{11}}{\partial T_{32}} \\
\frac{\partial Ds_1}{\partial T_1} & \frac{\partial Ds_1}{\partial T_2} & \cdots & \cdots & \cdots & \frac{\partial Ds_1}{\partial T_{32}} \\
\vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\
\frac{\partial Ds_{11}}{\partial T_1} & \frac{\partial Ds_{11}}{\partial T_2} & \cdots & \cdots & \cdots & \frac{\partial Ds_{11}}{\partial T_{32}} \\
\frac{\partial Dt_1}{\partial T_1} & \frac{\partial Dt_1}{\partial T_2} & \cdots & \cdots & \cdots & \frac{\partial Dt_1}{\partial T_{32}} \\
\vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\
\frac{\partial Dt_{11}}{\partial T_1} & \frac{\partial Dt_{11}}{\partial T_2} & \cdots & \cdots & \cdots & \frac{\partial Dt_{11}}{\partial T_{32}}
\end{bmatrix}
$$



Tuning Algorithm

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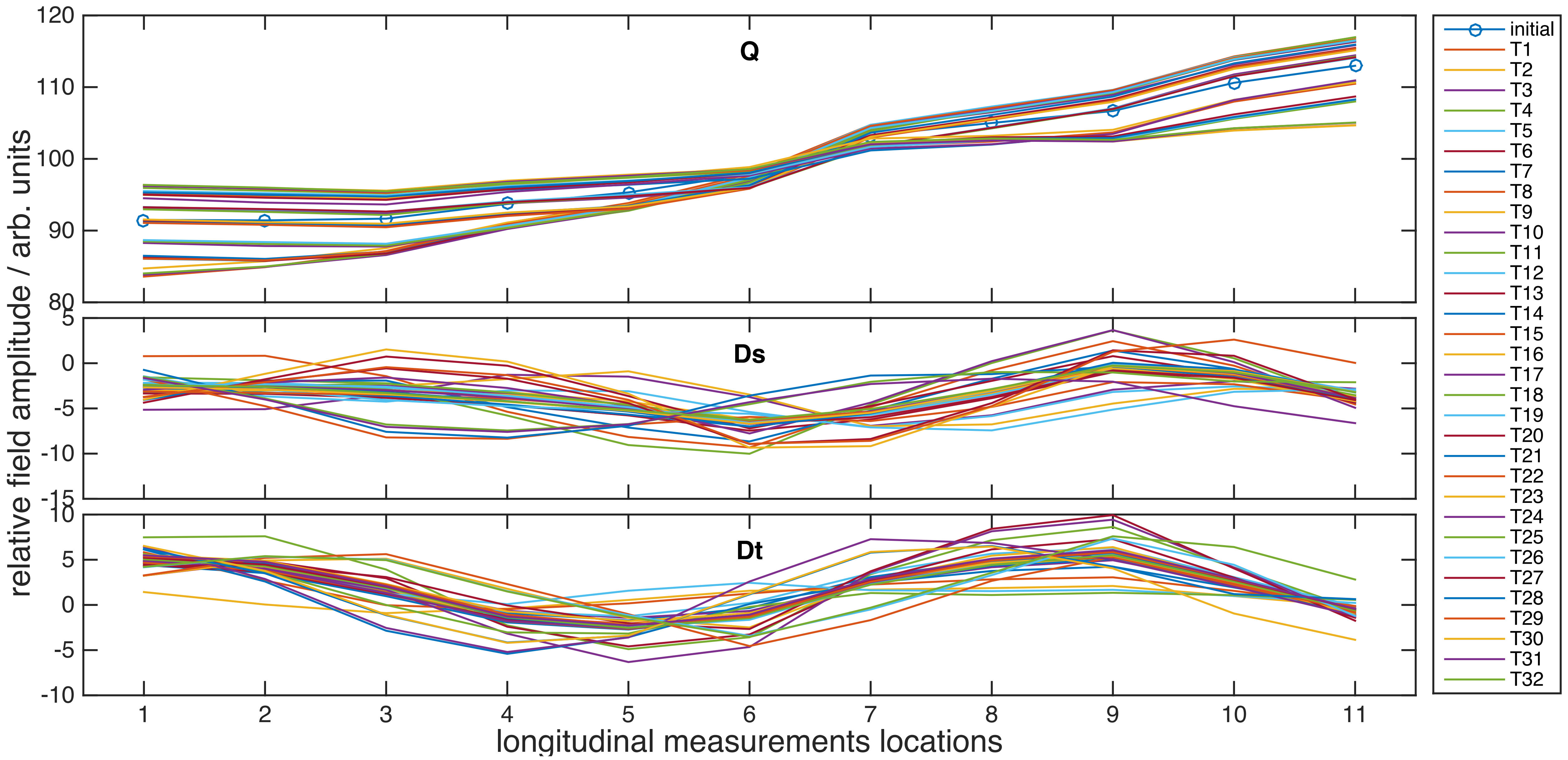


$$\vec{V} = \mathbf{M} \cdot \vec{T}$$

$$\Downarrow$$

$$\vec{T} = \mathbf{M}^{-1} \cdot \vec{V}$$

SVD - Singular Value Decomposition

$$\boxed{\vec{V}} = \mathbf{M} \cdot \vec{T} \qquad \boxed{\vec{T}} = \mathbf{M^{-1}} \cdot \vec{V}$$

$$\mathbf{M^{-1}} = (\mathbf{U} \cdot \mathbf{S} \cdot \mathbf{V^T})^{-1} \approx \mathbf{V} \cdot \mathbf{S_0^{-1}} \cdot \mathbf{U^T}$$

$$\mathbf{M} = \mathbf{U} \cdot \mathbf{S} \cdot \mathbf{V^T}$$

$$\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & M & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix} = \begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & U & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix} \begin{bmatrix} \sigma_1 & & \\ & \sigma_2 & \\ & & \sigma_3 \\ & & \\ & & \end{bmatrix} \begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & V^T & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}$$

$$\mathbf{S_0^{-1}} = \begin{cases} 1/\sigma_i & \text{if } \sigma_i > t \\ 0 & \text{otherwise} \end{cases}$$

$$\mathbf{S} = \mathbf{diag}(\sigma_\mathbf{1}, \sigma_\mathbf{2}, ..., \sigma_\mathbf{n}) \qquad \sigma_1 \geq \sigma_2 \geq ... \geq \sigma_n$$

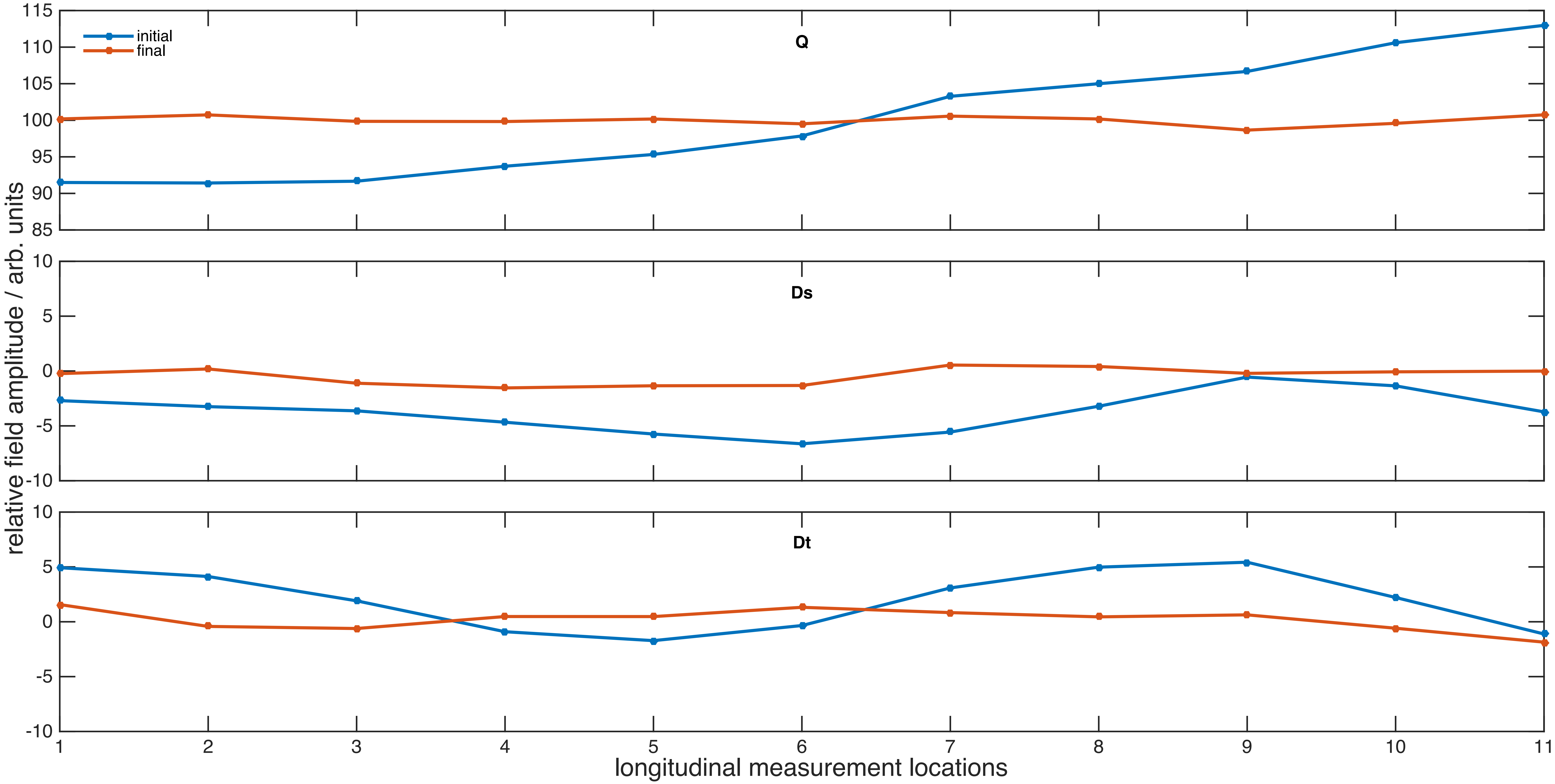
$$\boxed{\vec{T}_{svd}i} = \overbrace{(\mathbf{V} \cdot \mathbf{S_i^{-1}} \cdot \mathbf{U^T})}^{\mathbf{M_i^{-1}}} \cdot \vec{V}$$

$$\mathbf{S^{-1}} = \begin{bmatrix} 1/\sigma_1 & & & \\ & 1/\sigma_2 & & \\ & & \ddots & \\ & & & 1/\sigma_n \\ & & & \end{bmatrix}$$

$$\boxed{\vec{V}} \approx \vec{V}_{svd}i = \mathbf{M} \cdot \vec{T}_{svd}i$$

$$\mathbf{M^{-1}} = \mathbf{V} \cdot \mathbf{S^{-1}} \cdot \mathbf{U^T}$$

Results



Component	Q	Ds	Dt
Initial	±10.8 %	±3.0 %	±3.6 %
Target	±2 %	±2 %	±2 %
Final	±1.0 %	±1.0 %	±1.7 %

Status

- tuning of 4-vane RFQs
  - tuning algorithm / matrix inversion SVD
  - tuning procedure / tuner tooling
- frequency tuning
- Q-values (multiple power couplers)
- antenna calibration

Status

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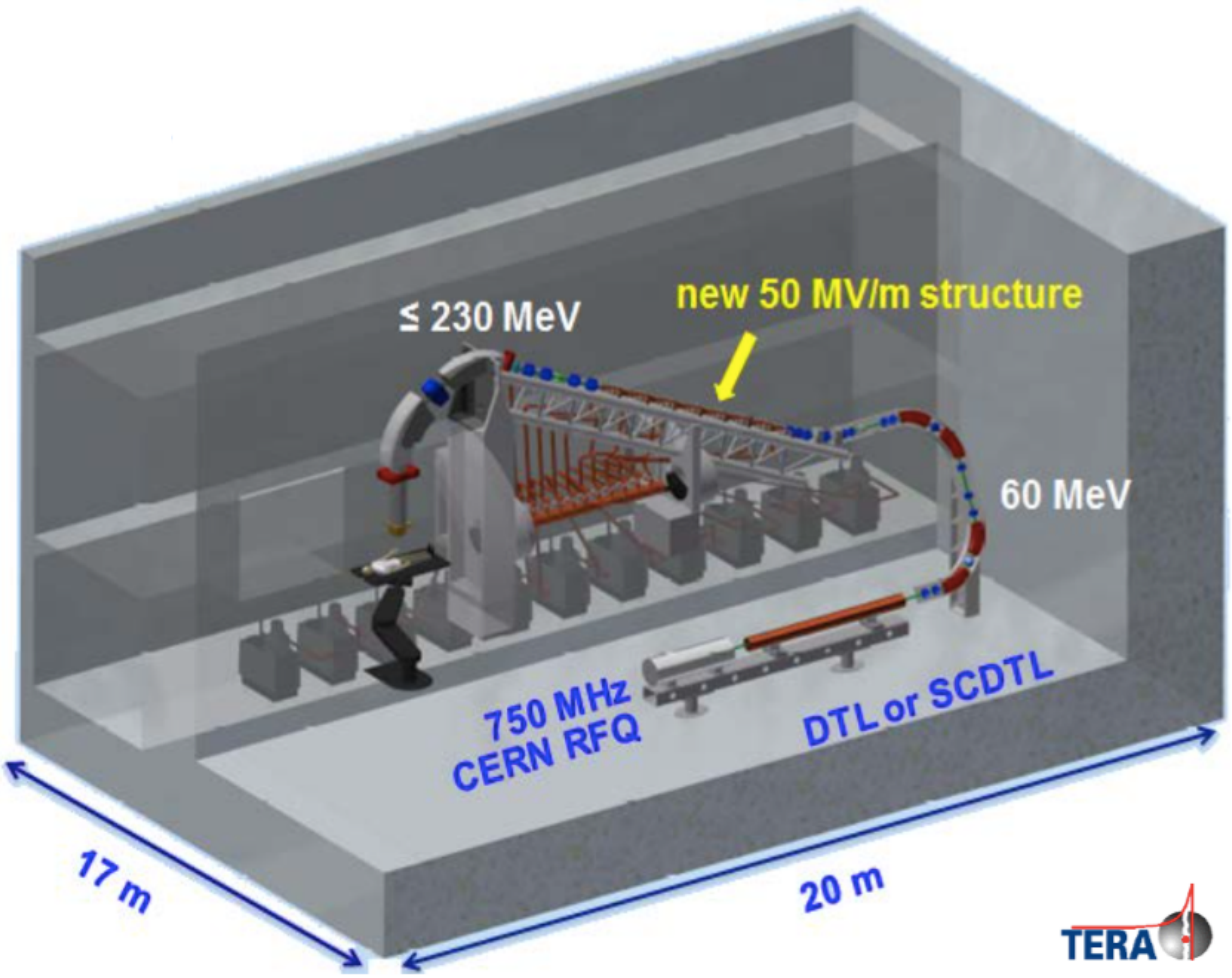
- RFQ does accelerate protons to 5 MeV
- measured transverse beam properties match expectations from simulations

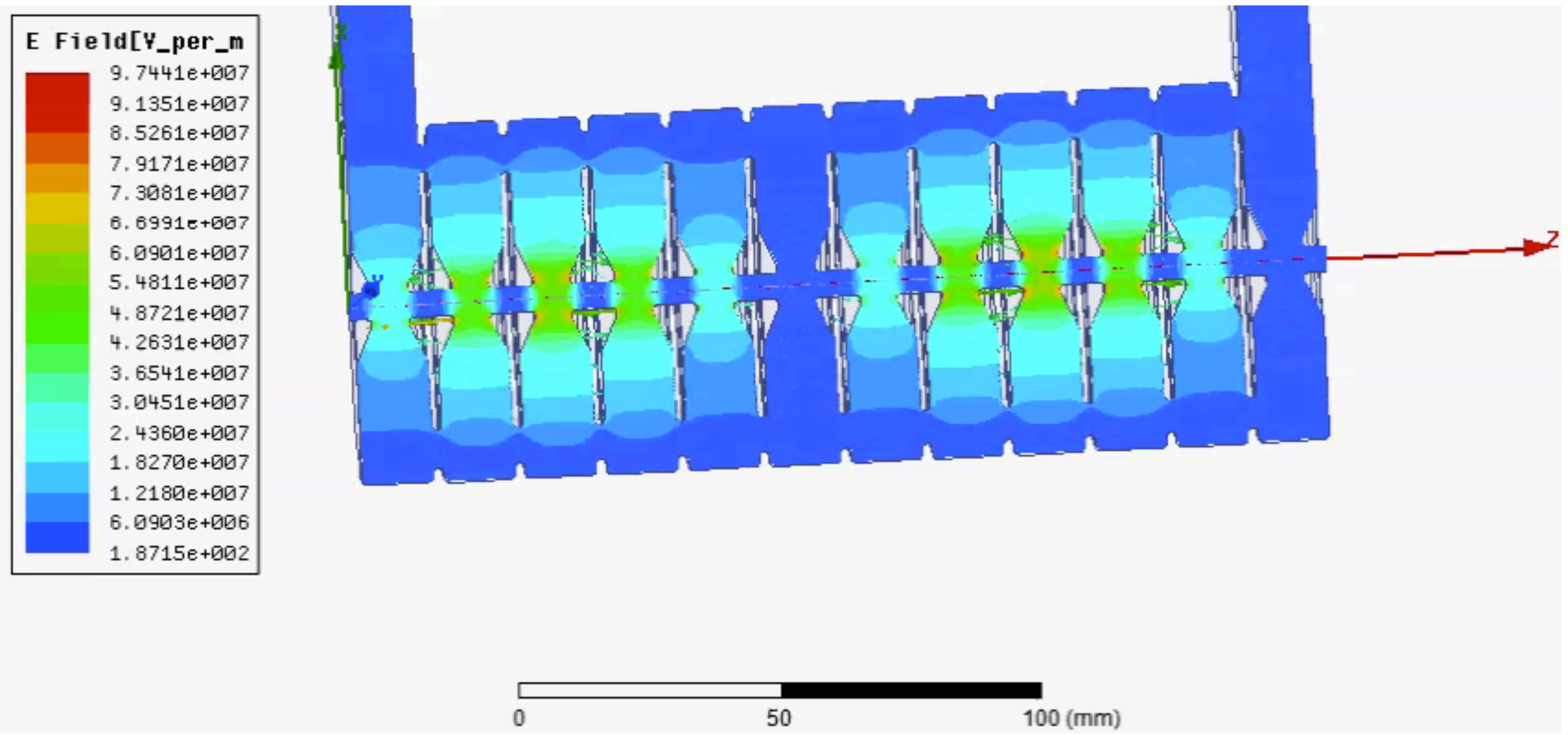
Tera Foundation - TULIP



short linac requires

high gradient & high frequency

- 3 GHz BTW structure
- max gradient of about 50 MV/m
- 20 cm long structure
- 10 MeV energy gain



S-Band BTW Structure - Conditioning

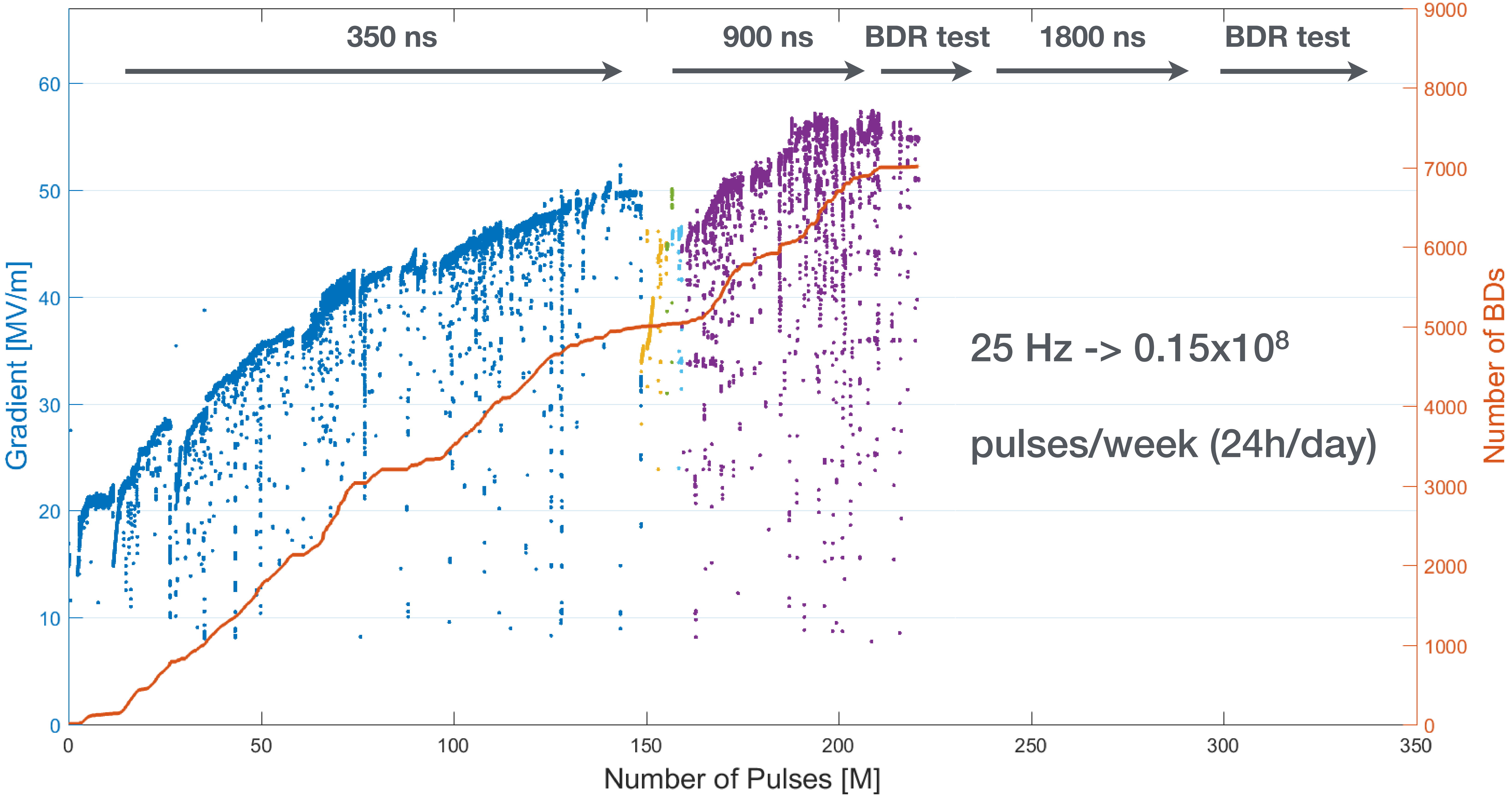
Stefano Benedetti

Conditioning of the structure

Breakdown studies

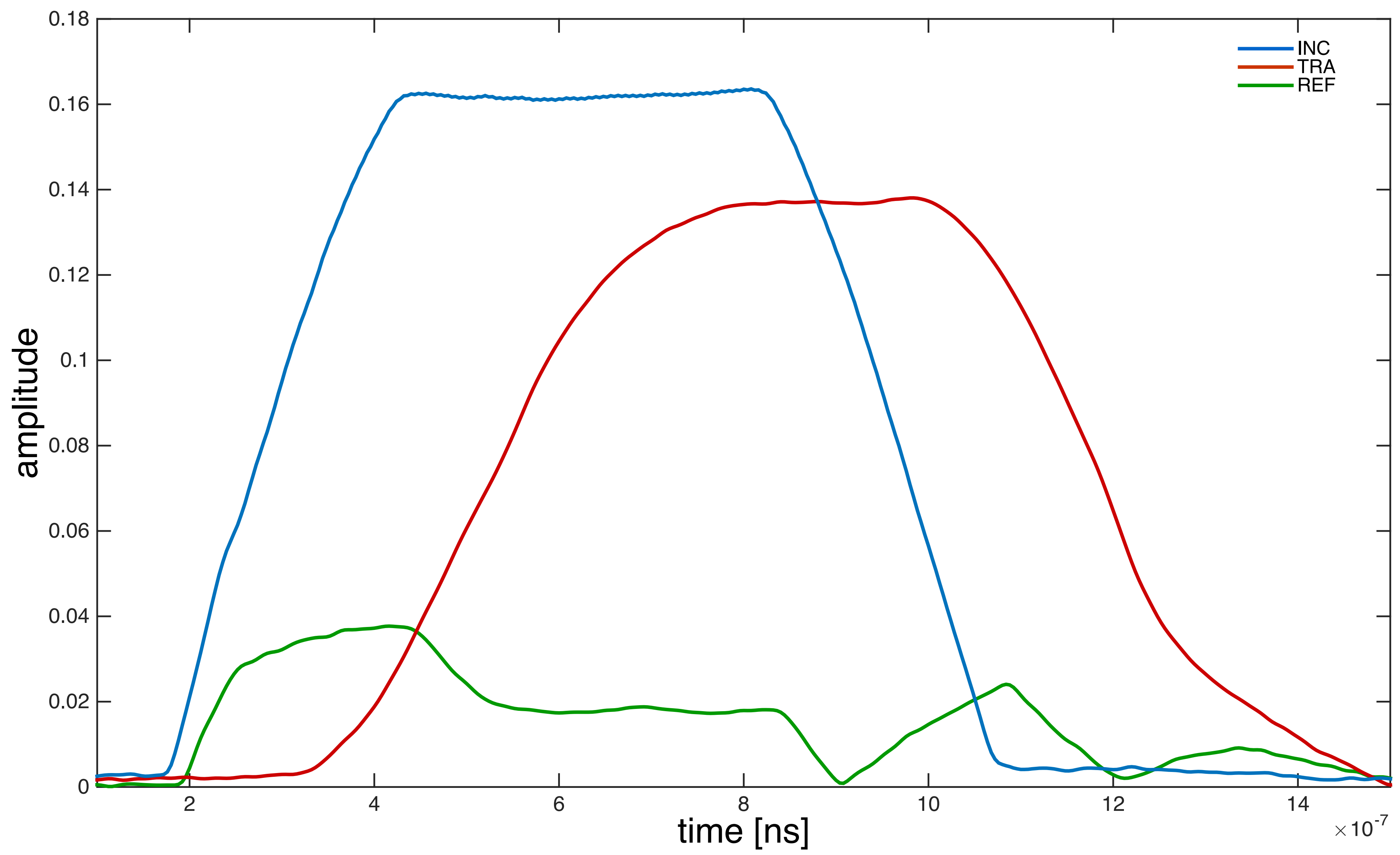
Data analysis

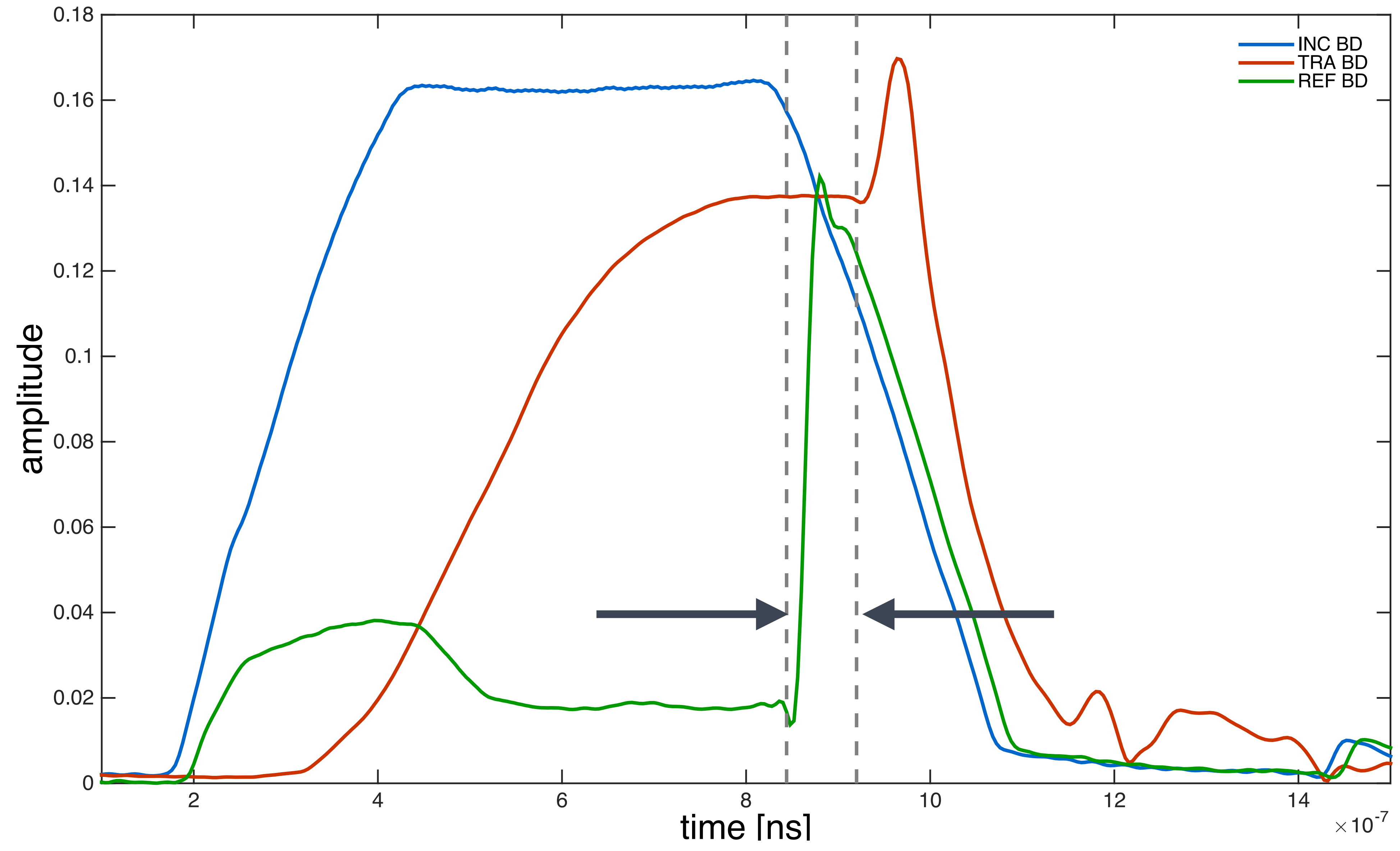
→ define high gradient limits of S-band cavities in terms of BDs

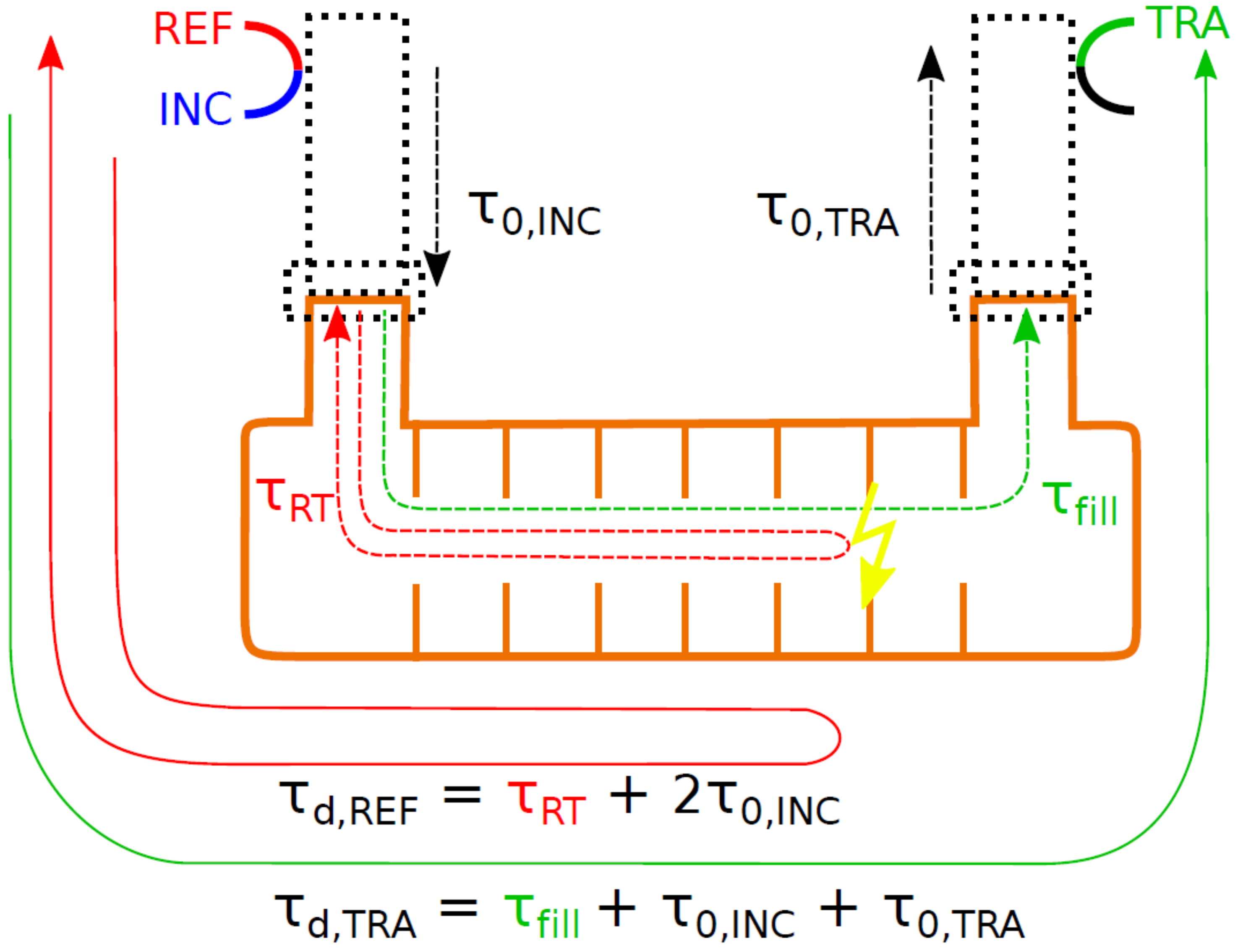


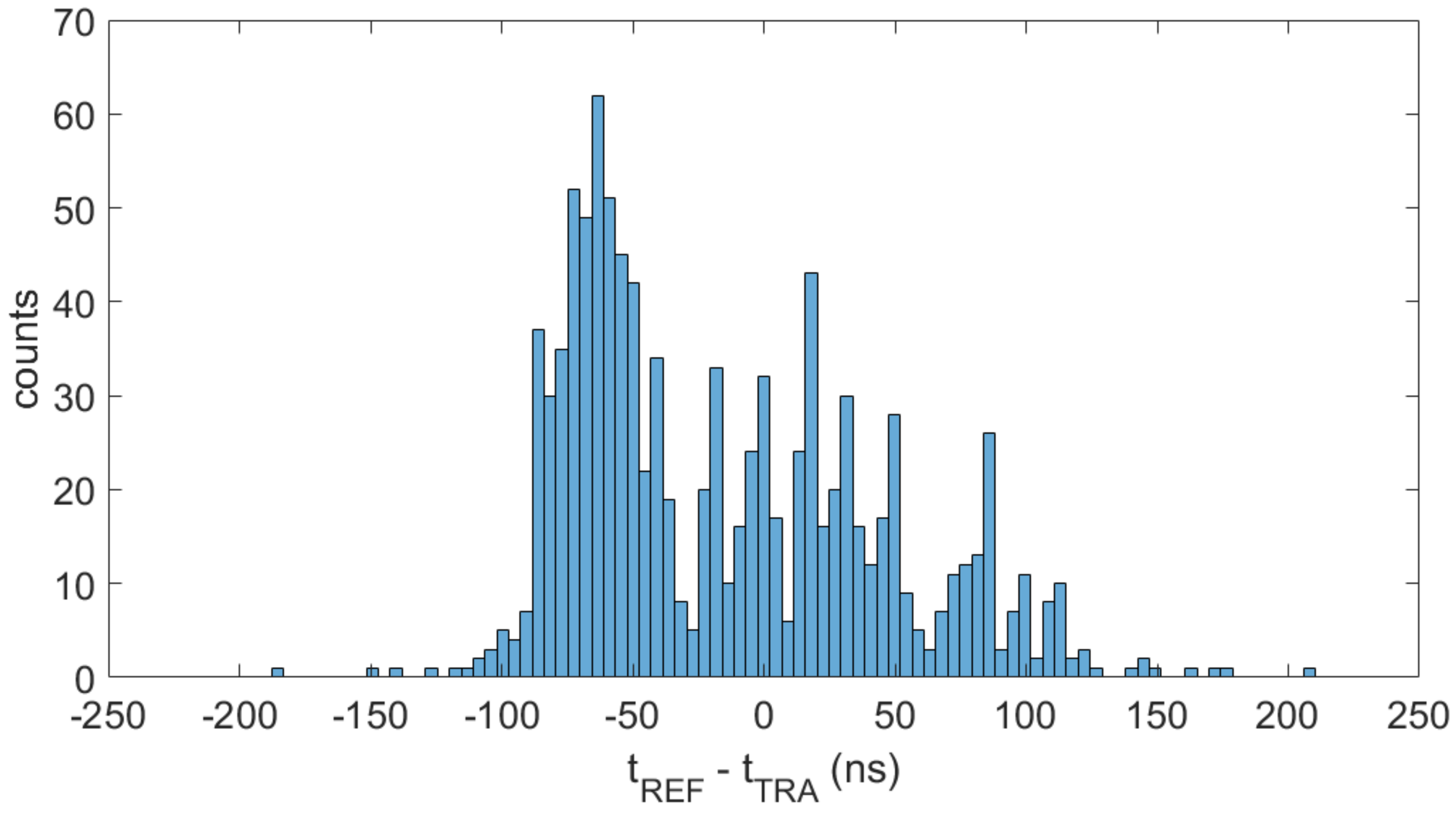
25 Hz -> 0.15×10^8 pulses/week (24h/day)

S-Band BTW - breakdown location










Thank you very much
for your attention!

Extra Slides

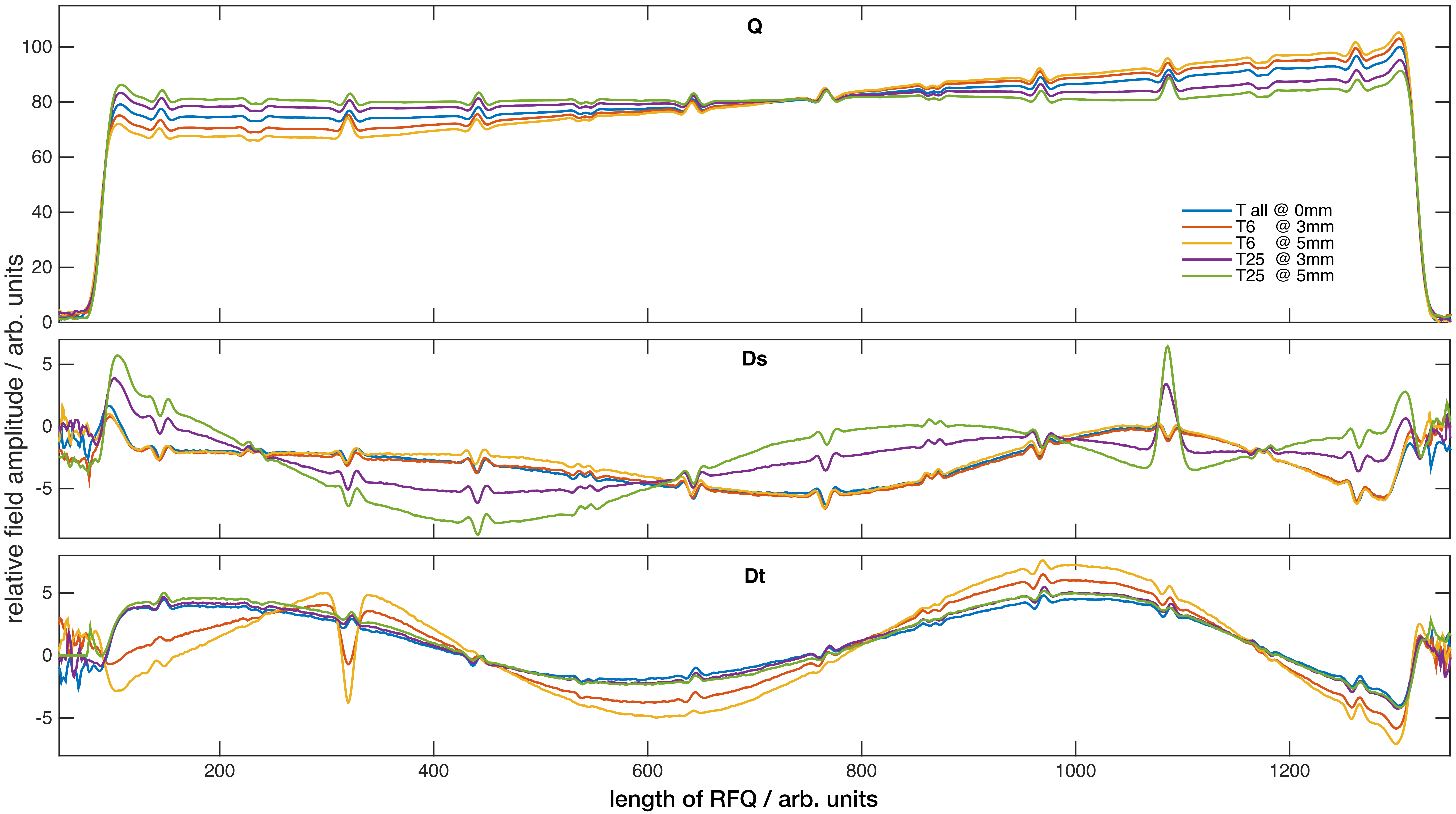
Modulation

Other Applications

Application	Hadrontherapy Injector	Compact PET Isotope Production	99mTc & Brachytherapy Production	IBA Ion Beam Analysis
General Design	1 RFQ (4 modules)	2 RFQ	2 RFQ + 1 DTL	1 RFQ
Particles	p+	p+	p+ / d+ / α	p+ / α
Frequency	750 MHz	750MHz	704 MHz	750 MHz
Output Energy	5 MeV	10 MeV	18 MeV	3 MeV
Total Length	2 m	4 m	10 m	1 m
Peak Power	400 kW	800 kW	1.5 MW	average current 0.1 mA
RF system	IOT (x4)	solid state amplifier / magnetron	klystrons	

Tuner Influence on Different Components

T6 → q2
T25 → q1



SVD - Singular Value Decomposition

T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16

$\vec{V}_{svd}i \approx \vec{V}$

$\vec{T}_{svd}i \gg \text{tuning range}$

T17
T18
T19
T20
T21
T22
T23
T24
T25

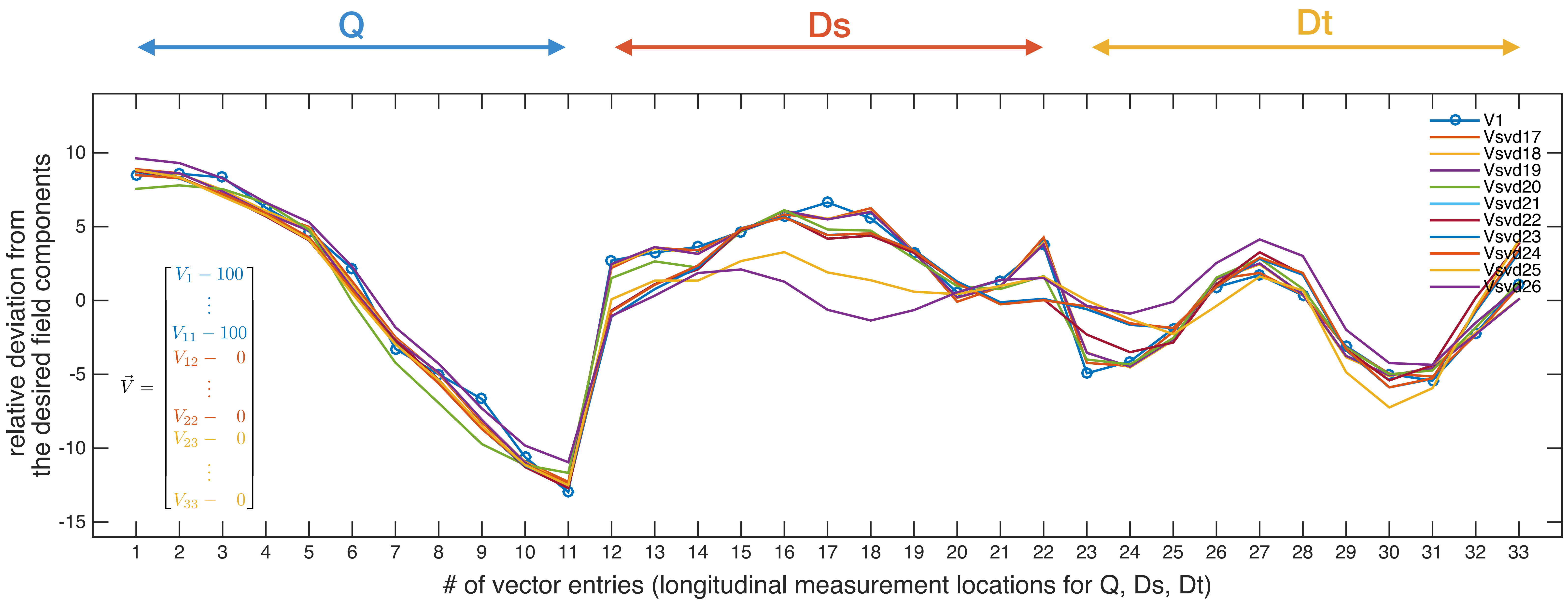
$\vec{V}_{svd}i \approx \vec{V}$

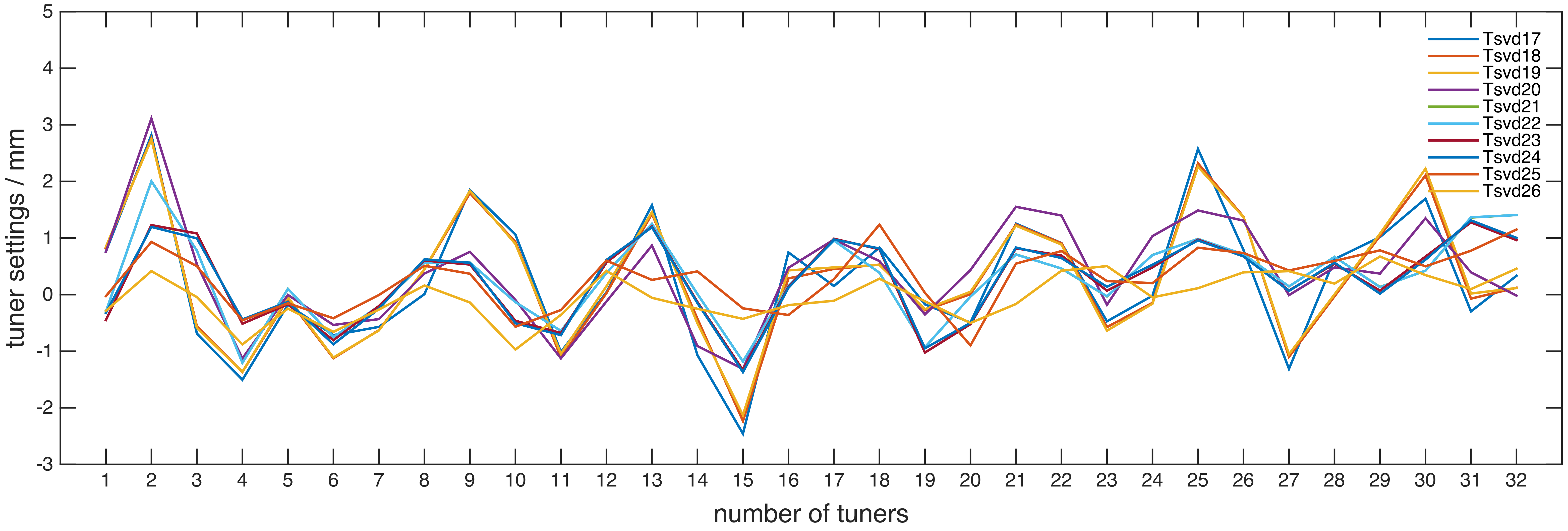
$\vec{T}_{svd}i = \text{ok}$

T26
T27
T28
T29
T30
T31
T32

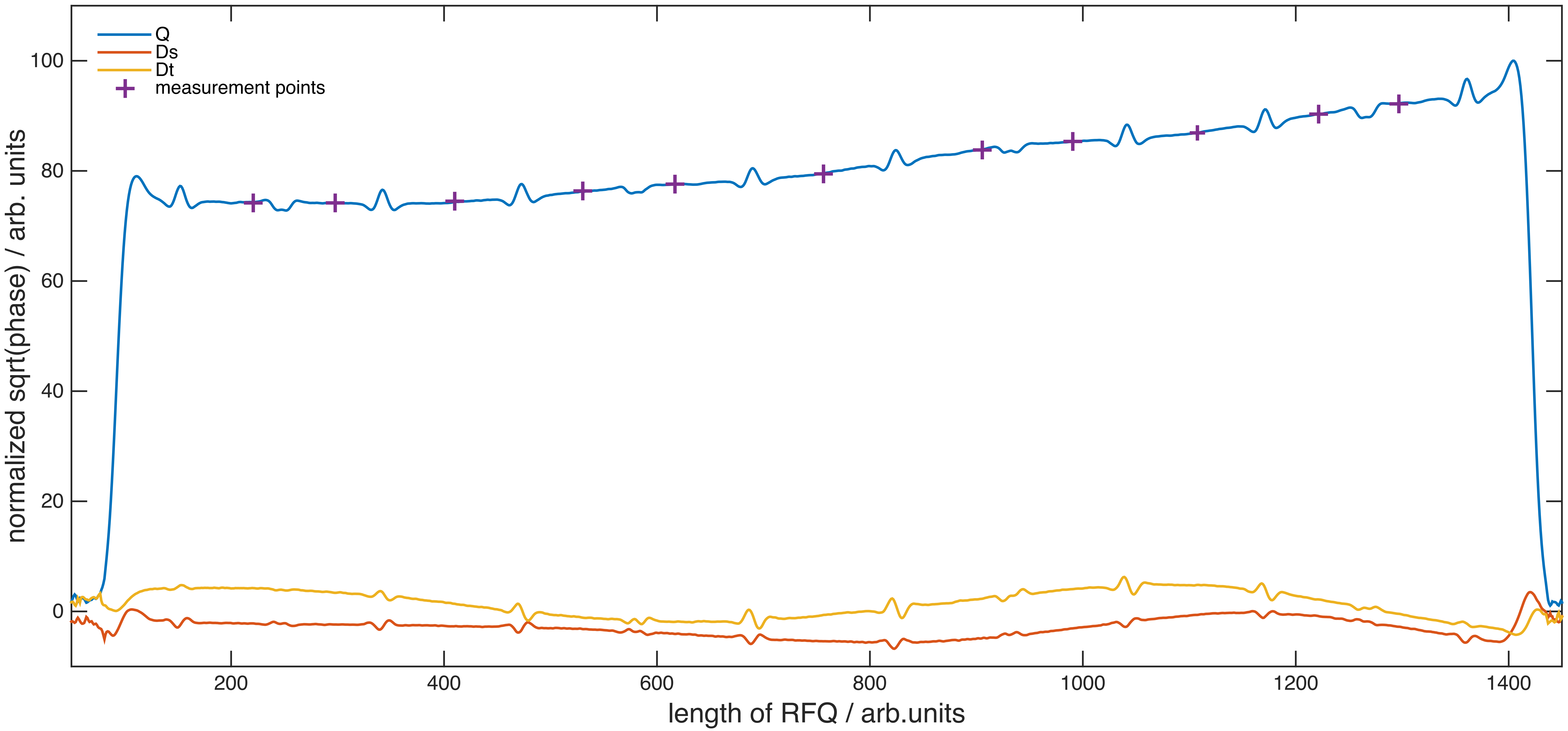
$\vec{V}_{svd}i \neq \vec{V}$

$\vec{T}_{svd}i = \text{ok}$



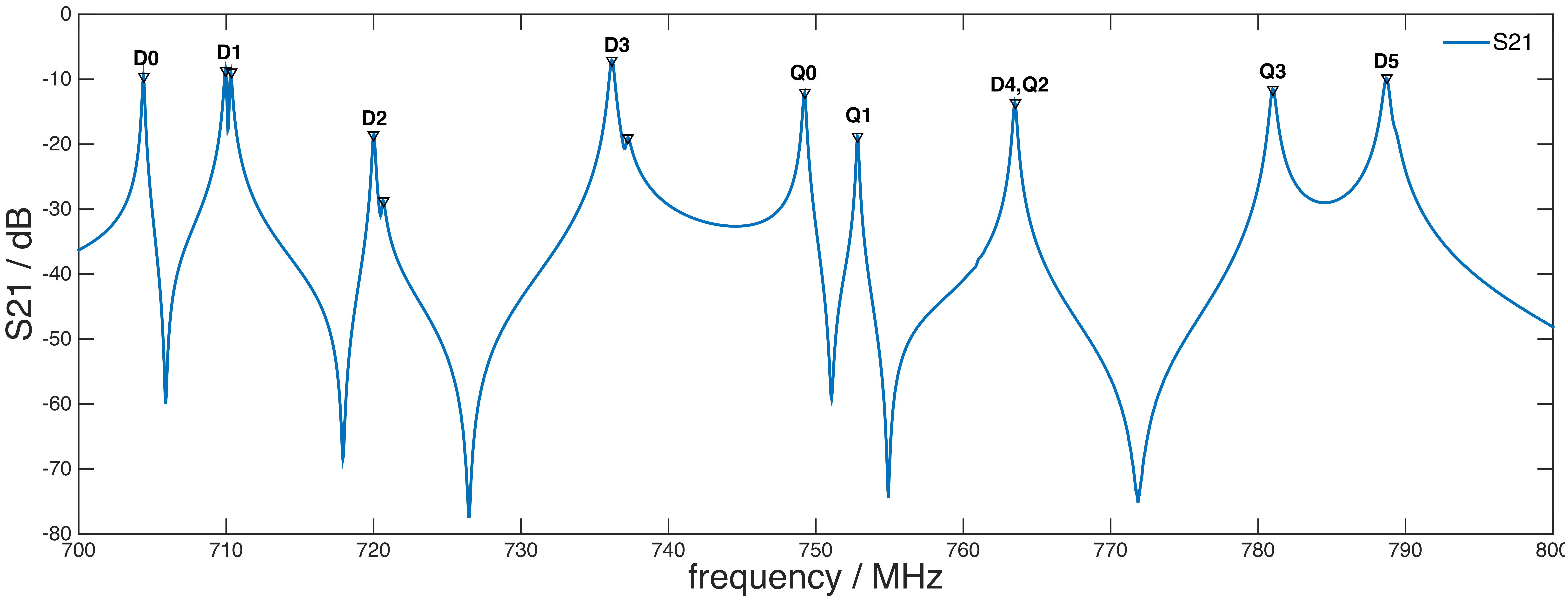


Field Tuning

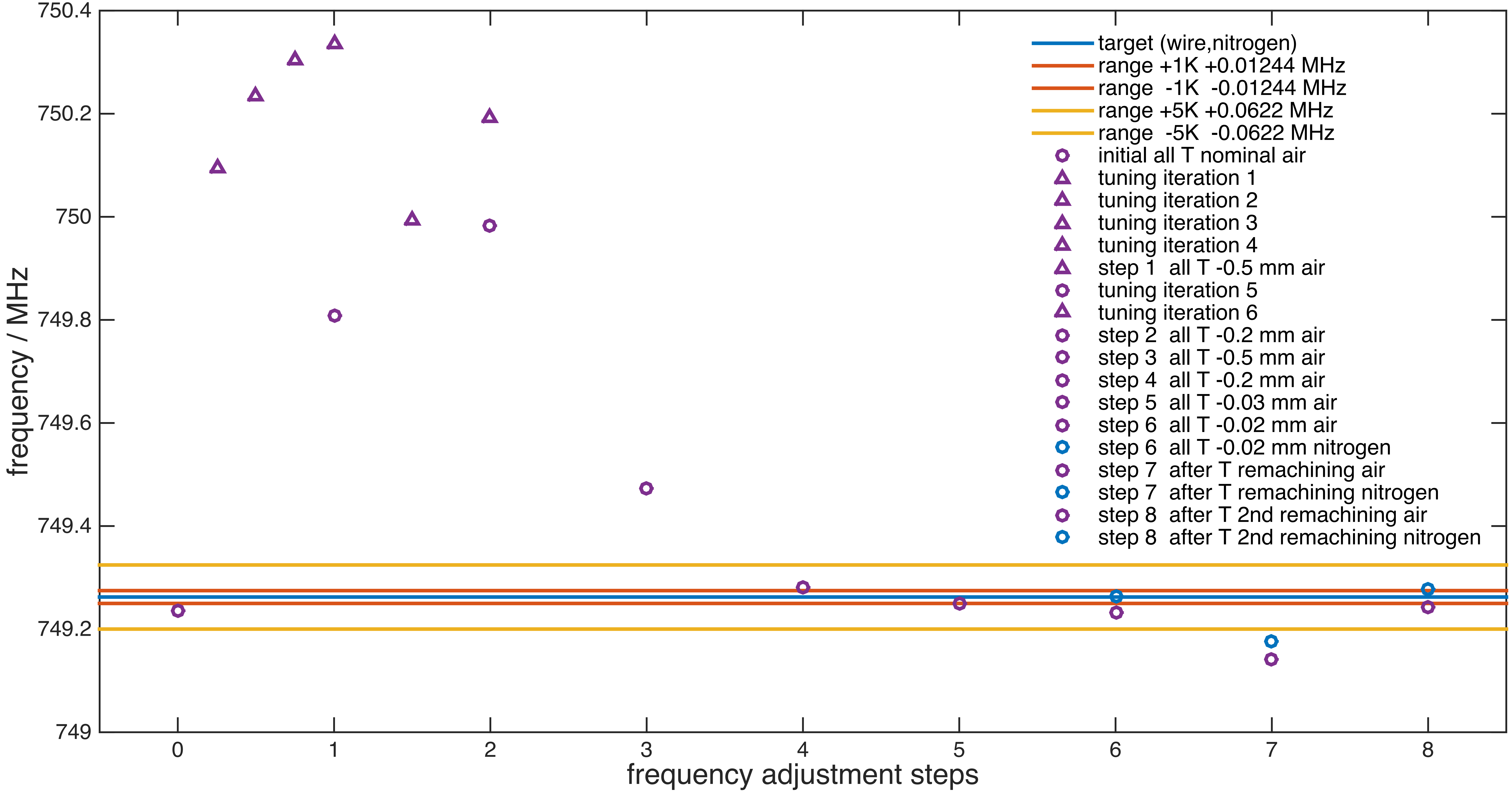


Component	Initial
Q	±10.8 %
Ds	±3.0 %
Dt	±3.6 %

Mode Spectra



Frequency Tuning



Dipole Stabiliser Rods / Modulation