EUROPEAN SPALLATION SOURCE

# ESS Normal Conducting Linac Commissioning Results

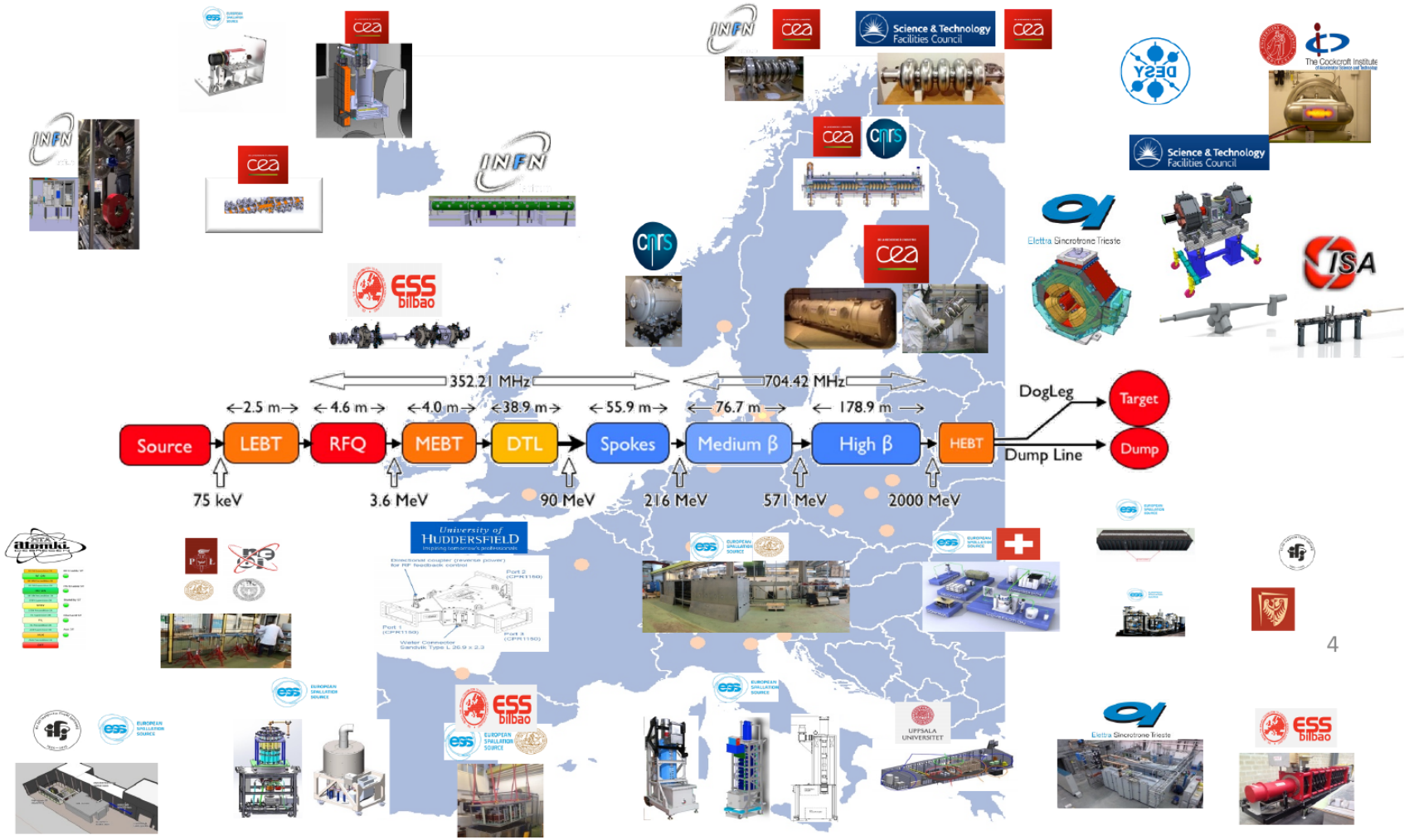
## HB 2023, Geneva, Switzerland

## TUA3I3

Dr. Yngve Levinsen
Accelerator Scientist, ESS
On behalf of the ESS Accelerator Collaboration

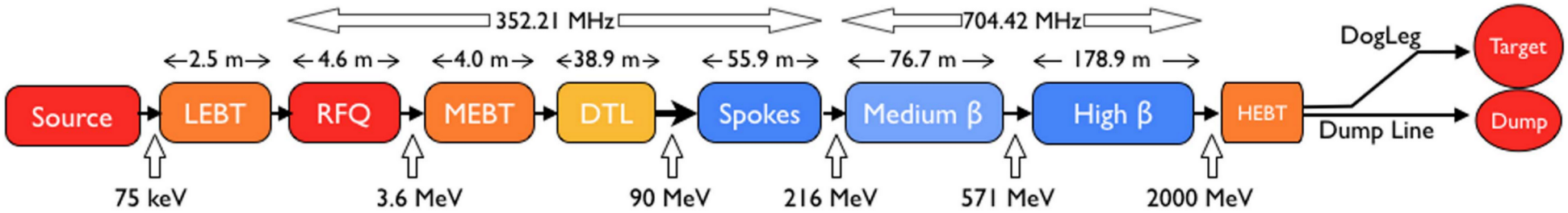
# The ESS In-Kind model

## With a lot of help from our friends



# ESS Project

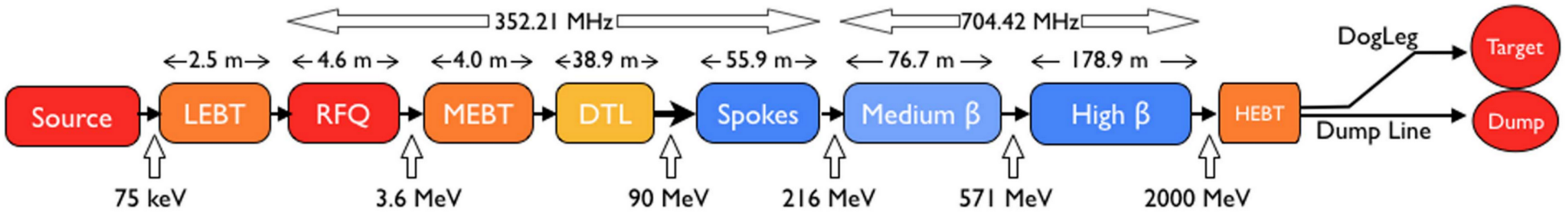
## A world leading spallation source




| Parameter | Value |
|---|---|
| Proton beam power | 5 MW |
| Proton beam energy | 2 GeV |
| Peak current | 62.5 mA |
| Pulse length | 2.86 ms |
| Rep rate | 14 Hz |
| Duty factor | 4 % |
| Bunching frequency | 352.21 MHz |

# Beam Diagnostics

## Beam modes and pulse structure



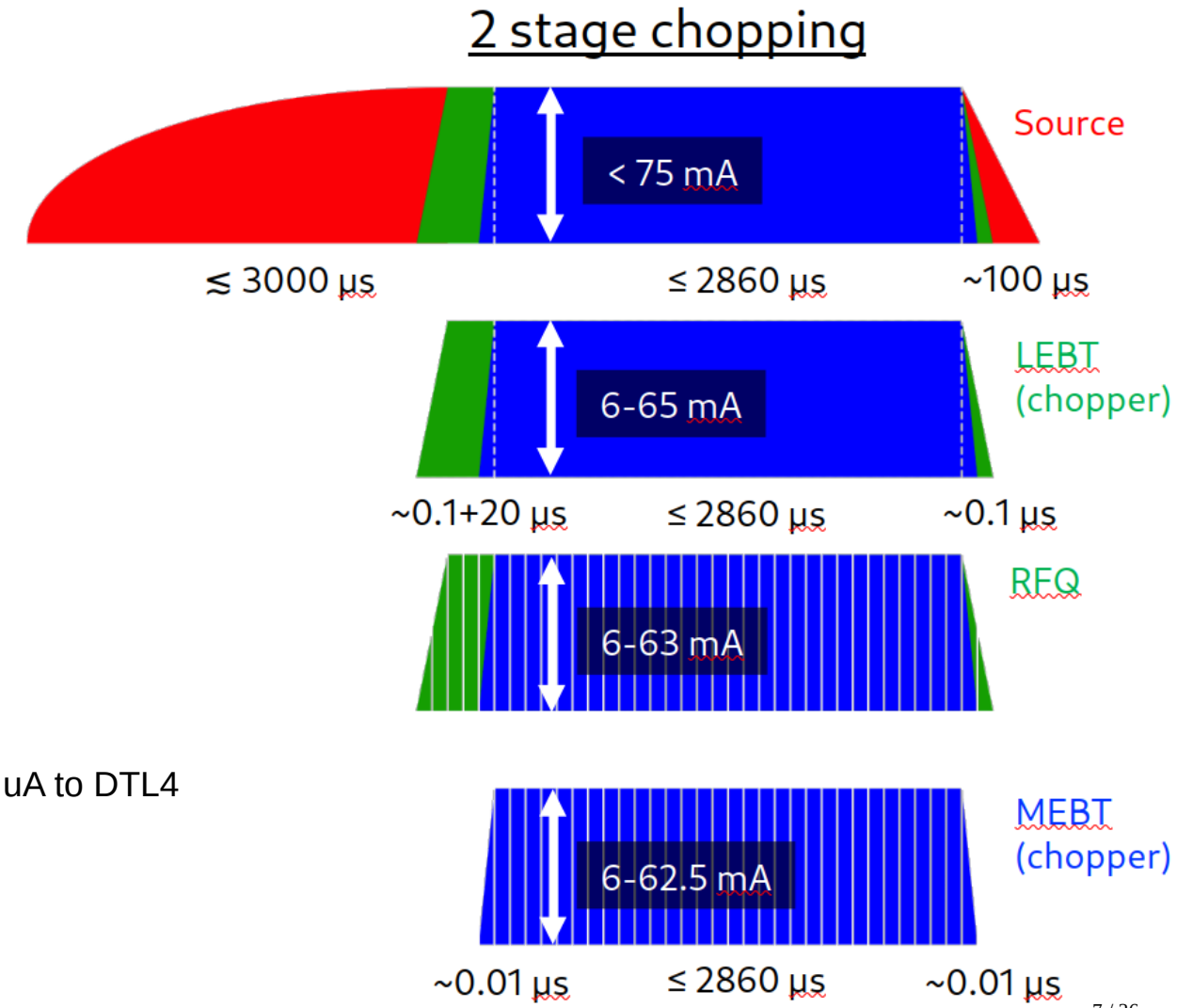

| Device | Type | IS | LEBT | RFQ | MEBT | DTL | SPK | MBL | HBL | HEBT | A2T | DmpL | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Faraday cup | Current | | 1 | | 1 | 2 | | | | | | | 4 |
| BCM | | 1 | 1 | 1 | 2 | 5 | | 1 | 1 | 2 | 3 | 2 | 19 |
| Fast BCM | | | | | 2 | | | | | | | | 2 |
| Doppler | | | 1 | | | | | | | | | | 1 |
| BPM | Parasitic transverse | | | | 7 | 15 | 14 | 9 | 21 | 16 | 12 | 4 | 98 |
| Non-invasive profile | | | 2 | | 2 | | 1 | 3 | 1 | | 1 | | 10 |
| Imaging | Parasitic target/dump transverse | | | | | | | | | | 2 | 1 | 3 |
| Grid | | | | | | | | | | | 1 | | 1 |
| Aperture | | | | | | | | | | | 3 | 1 | 4 |
| Emittance | Non-parasitic | | 1 | | 1 | | | | | | | | 2 |
| Bunch shape | | | | | 1 | | 1 | | | | | | 2 |
| WS | | | | | 3 | | 3 | 3 | 1 | 3 | 1 | | 14 |
| BLM | Loss | | | | 4 | 47 | 78 | 38 | 86 | 51 | 38 | 6 | 348 |

# Proton beam

## Beam modes and pulse structure

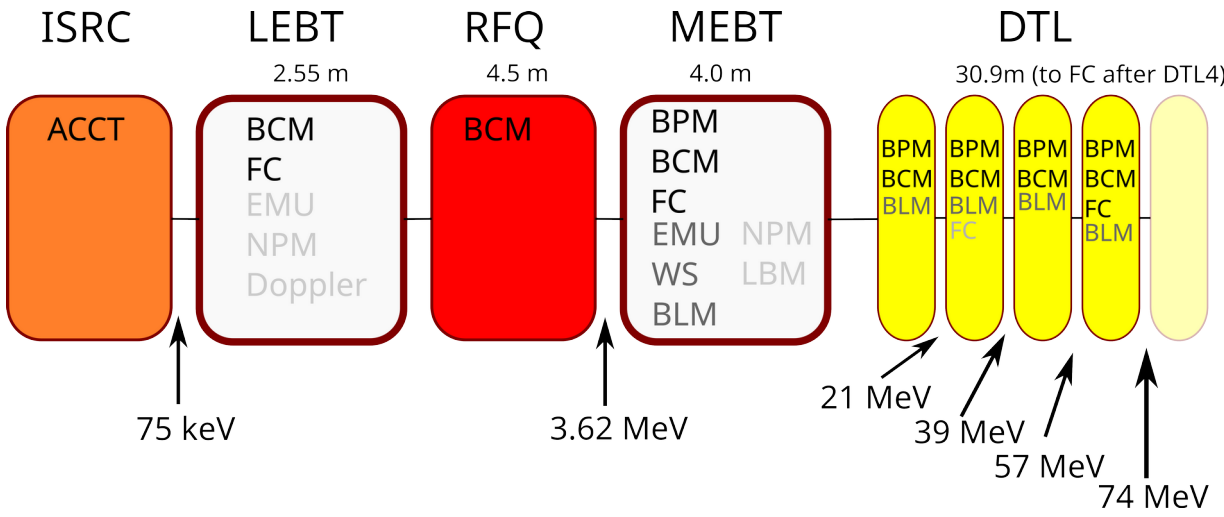
| Mode | Current [mA] | Length [µs] | Rep [Hz] |
|---|---|---|---|
| Probe | ≤ 6 | ≤ 5 | ≤ 1 |
| Fast commissioning | ≤ 6 | ≤ 5 | ≤ 14 |
| Slow commissioning | ≤ 62.5 | ≤ 5 | ≤ 1 |
| Fast tuning | ≤ 62.5 | ≤ 5 | ≤ 14 |
| Slow tuning | ≤ 62.5 | ≤ 50 | ~~≤ 1~~ ≤ 0.2 |
| Long pulse verification | ≤ 62.5 | ≤ 2860 | ≤ 1/30 |
| Production | ≤ 62.5 | 2860 | 14 |

< 1 uA to DTL4



# NCL Overview

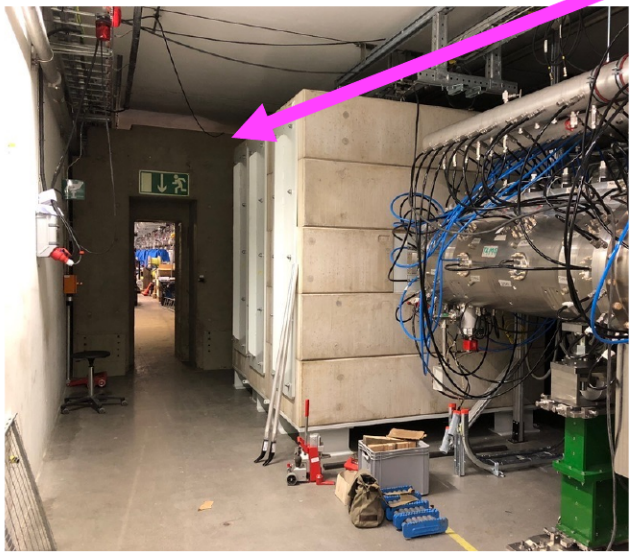
- ISRC & LEBT
  - DC beam > 70 mA @ 75 keV
  - Chop pulse, diagnose, focus & match for RFQ
- RFQ
  - 4.5 m, 5 segments, 4-vane,  accelerate to 3.62 MeV
- MEBT
  - Diagnose beam, fine chop, collimate, match for DTL
- DTL
  - 5 tanks, accelerate to 90 MeV (74 MeV after DTL4)
  - Temporary beam stop & shield wall in place of 5th tank



# Tunnel configuration

## NCL commissioning





# Milestones

## Throughout commissioning

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- January 31st Start of RF commissioning in DTL

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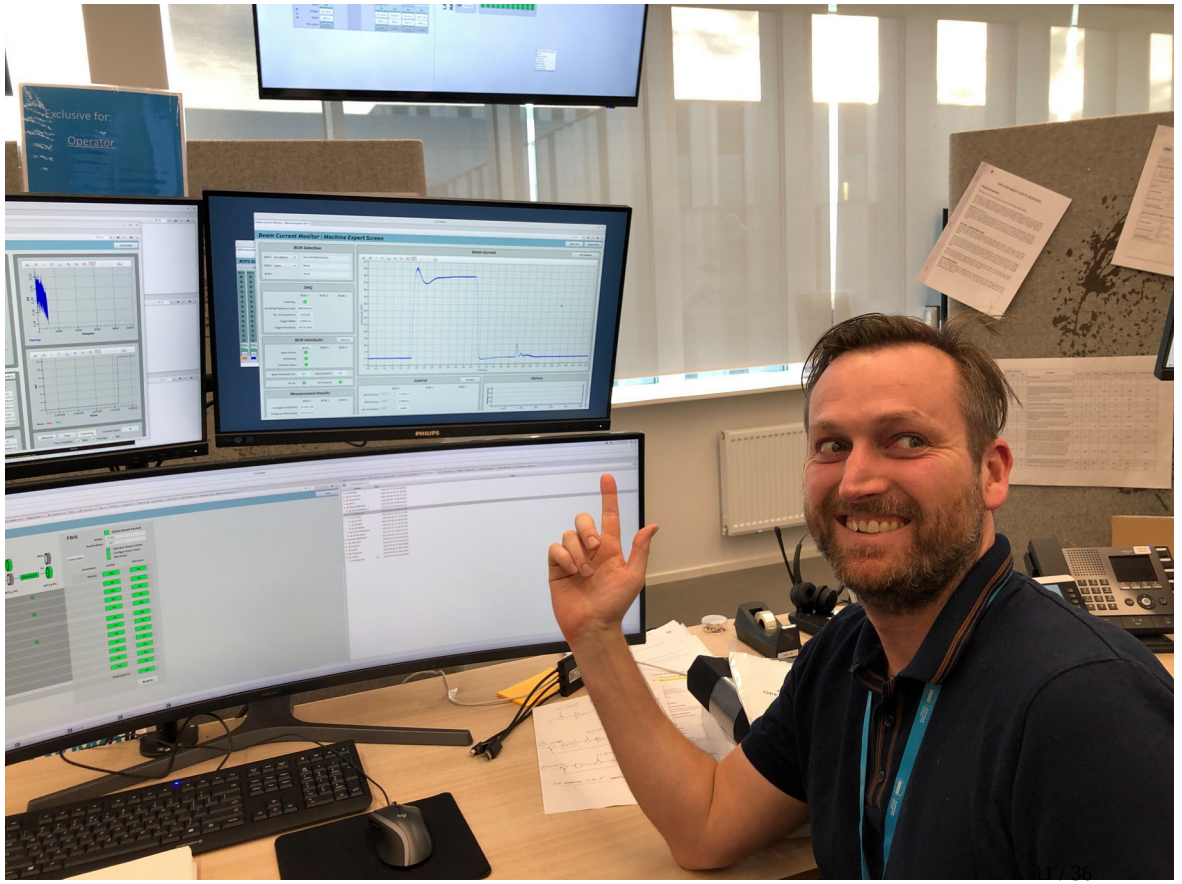
- January 31st Start of RF commissioning in DTL
- April 18th First beam extracted from ion source



# Milestones

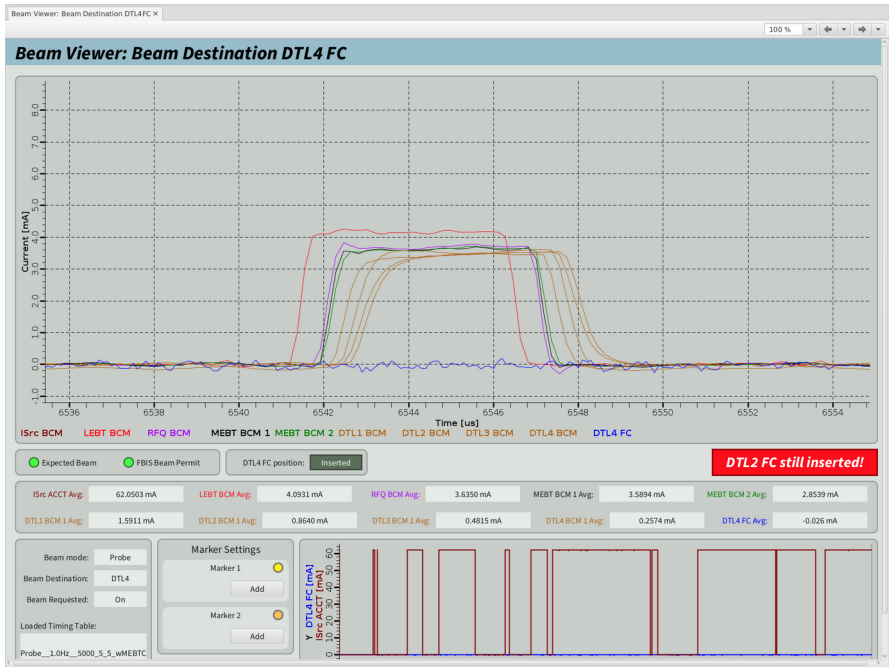
## Throughout commissioning

- January 31st Start of RF commissioning in DTL
- April 18th First beam extracted from ion source
- April 19th First beam to MEBT FC

# Milestones

## Throughout commissioning

- January 31st Start of RF commissioning in DTL
- April 18th First beam extracted from ion source
- April 19th First beam to MEBT FC
- April 20th First beam through DTL4




# Milestones

## Throughout commissioning

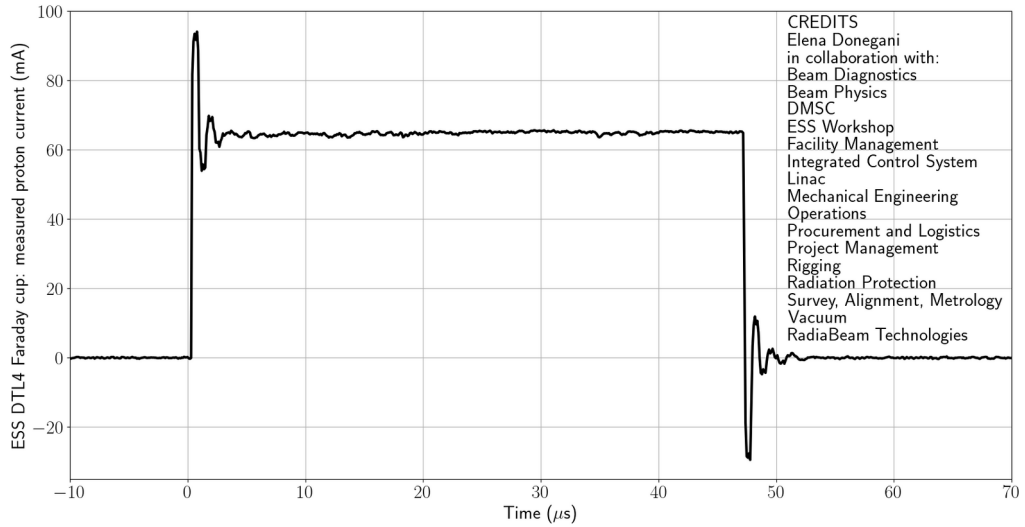
- January 31st Start of RF commissioning in DTL
- April 18th First beam extracted from ion source
- April 19th First beam to MEBT FC
- April 20th First beam through DTL4
- May 4th First beam seen by DTL4 FC

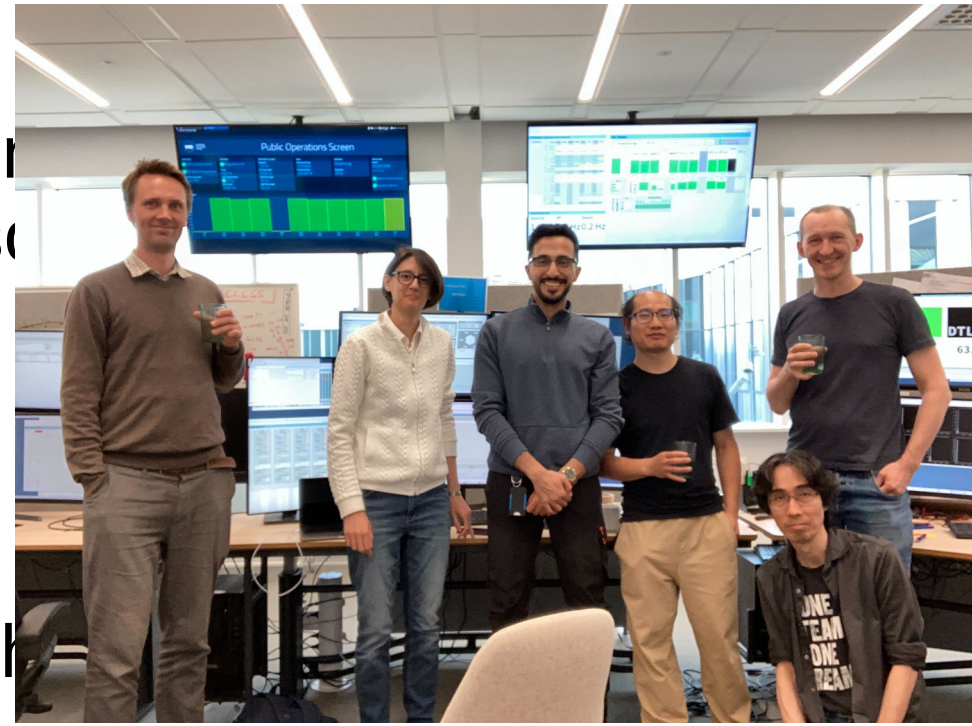
# Milestones

## Throughout commissioning

- January 31st Start of RF commissioning in DTL
- April 18th First beam extracted from ion source
- April 19th First beam to MEBT FC
- April 20th First beam through DTL4
- May 4th First beam seen by DTL4 FC
- May 30th First 50us beam through DTL4

# Milestones




- May 30th First 50us beam through DTL4
- July 6th First 50us, 62.5 mA beam through DTL4

# Milestones

## Throughout commissioning

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- July 6th First 50us, 62.5 mA beam through DTL4
- July 14th End of beam commissioning to DTL4

# Milestones

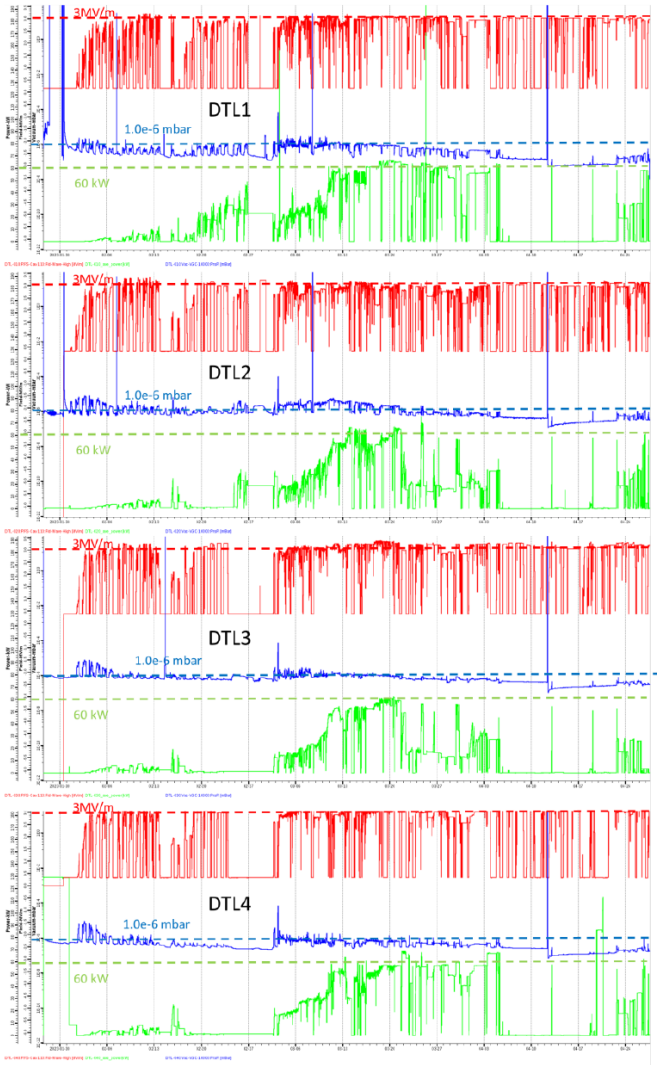
## Throughout commissioning

- January 31st Start of RF commissioning in DTL
- April 18th First beam extracted from ion source
- April 19th First beam to MEBT FC
- April 20th First beam through DTL4
- May 4th First beam seen by DTL4 FC
- May 30th First 50us beam through DTL4
- July 6th First 50us, 62.5 mA beam through DTL4
- July 14th End of beam commissioning to DTL4
- August 1st Last day of beam commissioning run

# RF Commissioning

## A major non-beam goal of the commmissioning

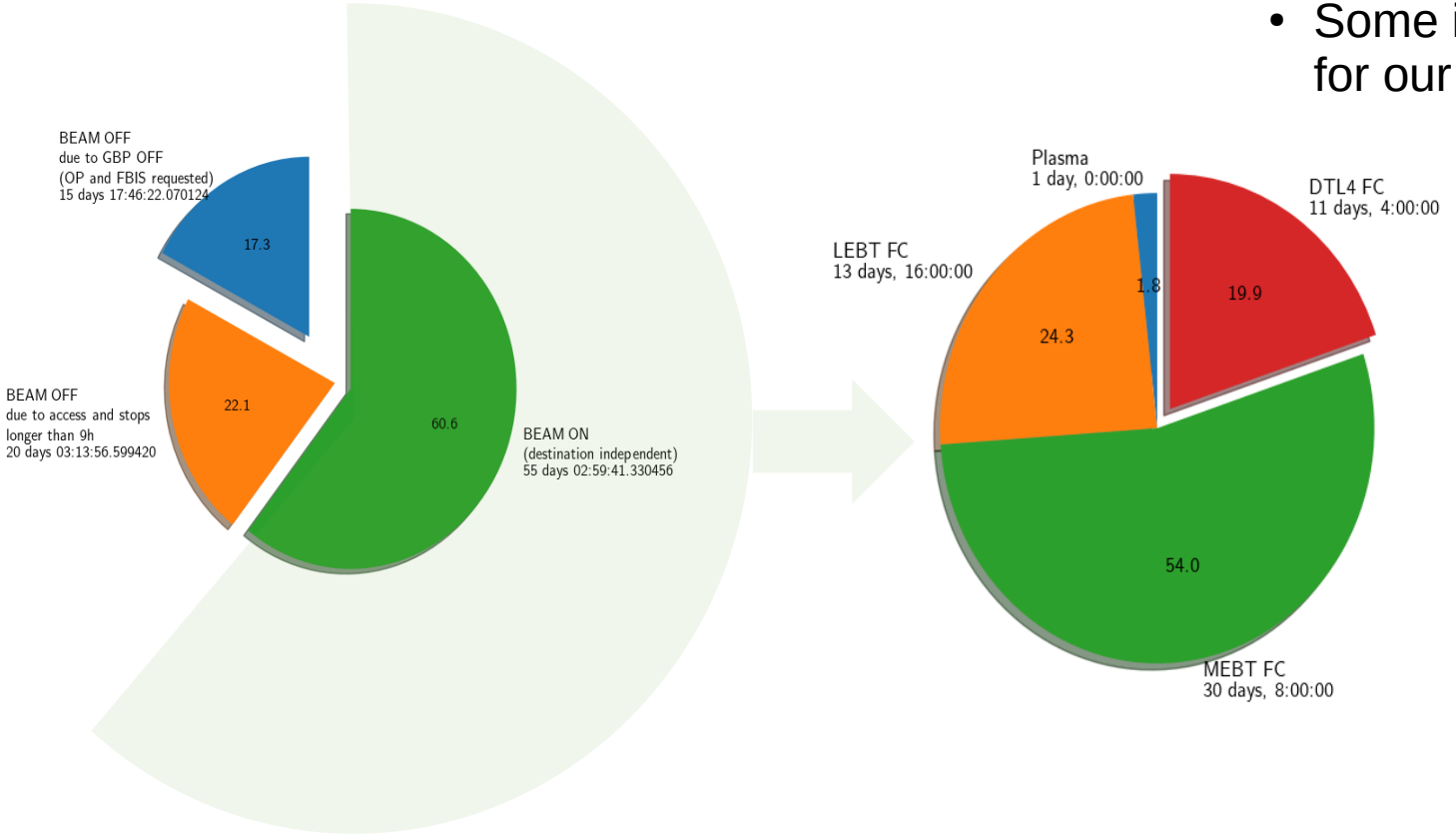
- Overall goal for DTLs was >12hrs with >95% RF at nominal parameters
- Started January 31st (first beam planned mid April)
- One DT replaced in DTL1 after 2022 commissioning
- Quickly reached nominal field for short pulse
- First half of March all DTLs close to reach goals
- Second half of March DTL2&3 RF windows arching




Francesco Grespan/INFN

# Beam Availability

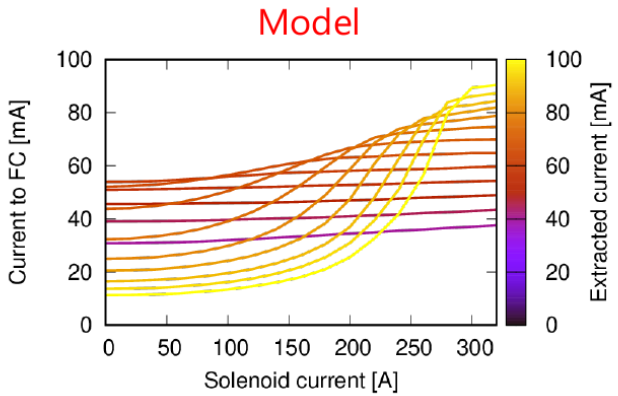
- 24/7 running March – mid July
- Excellent support from the OPs crew
- Beam availability good for early stage
- Some interlock/trip analysis work to be done for our 95% availability goal

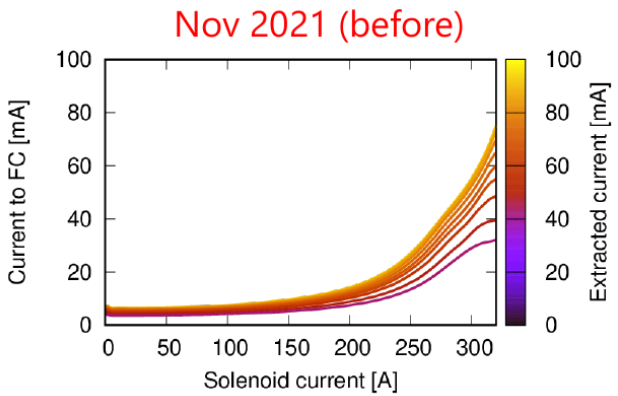


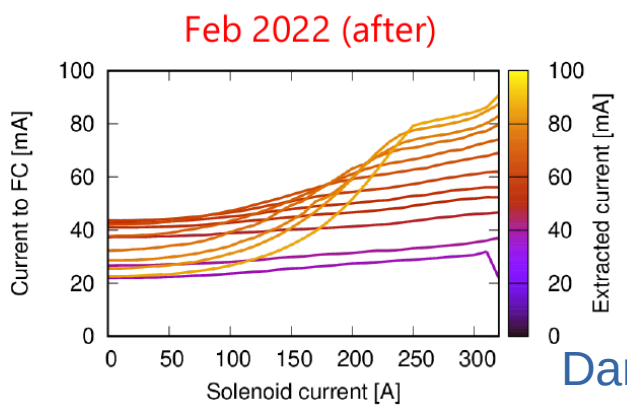

Arkadiusz Gorzawski

# Ion Source extraction

## Repeller issue

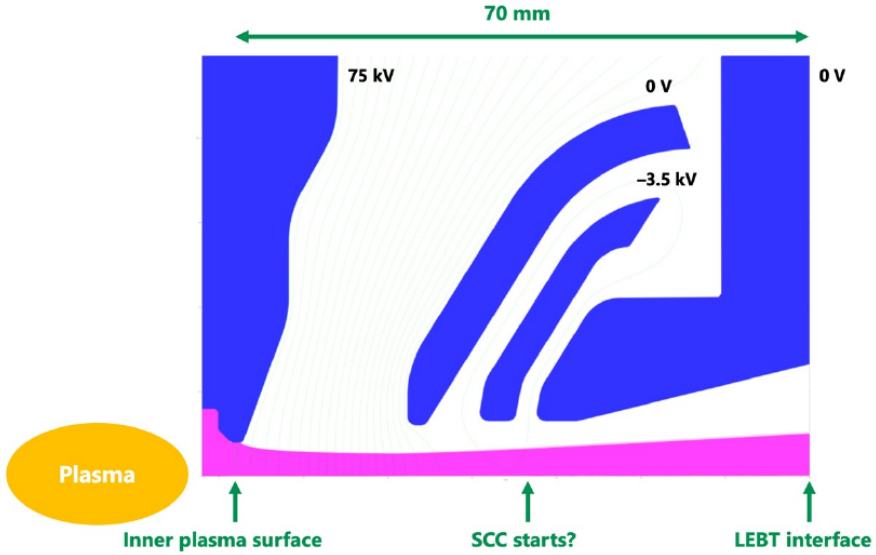


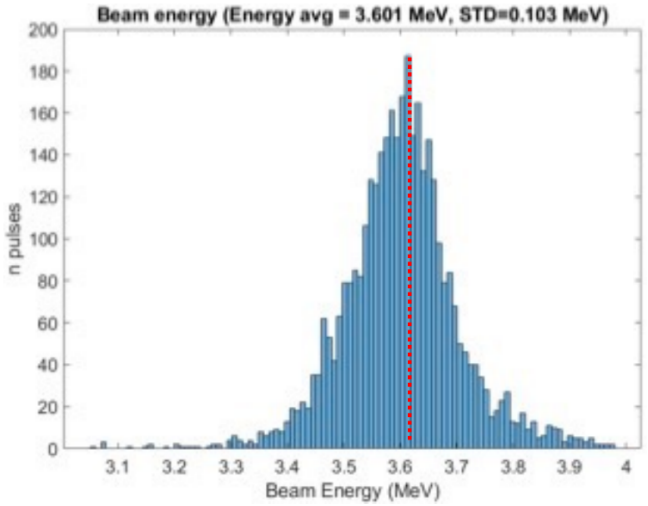

Daniel Noll

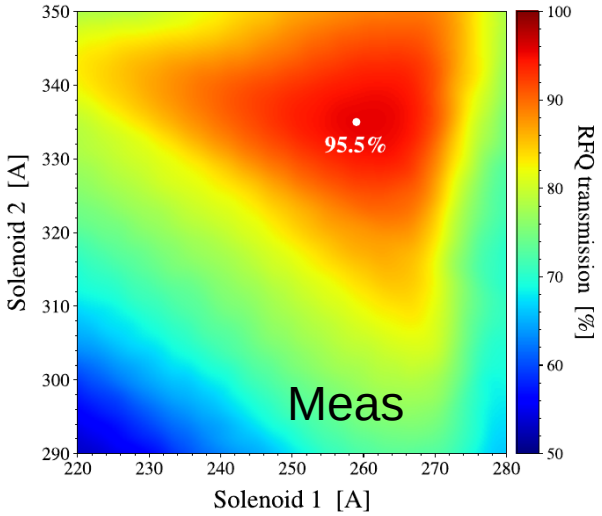
- Large initial divergence and emittance observed during the source+LEBT commissioning in 2019.
- Discovered source repeller was disconnected (maintenance Jan 2022)
- Significantly improved model consistency!
- Data from 2019 less relevant

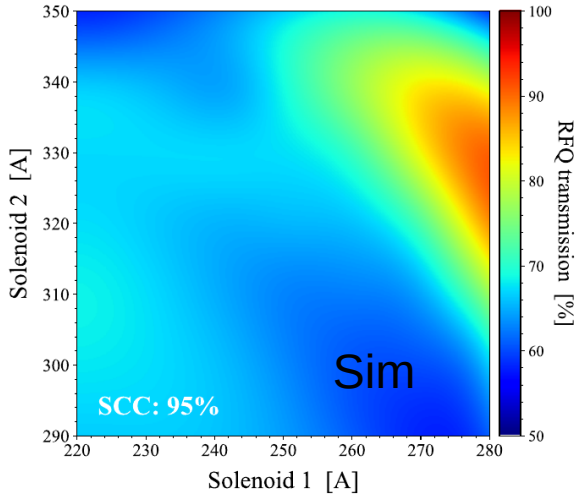


# RFQ Characterization

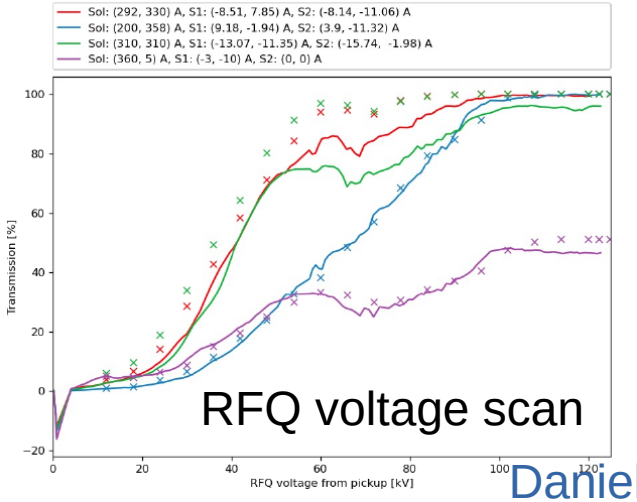
MEBT ToF - FBPM



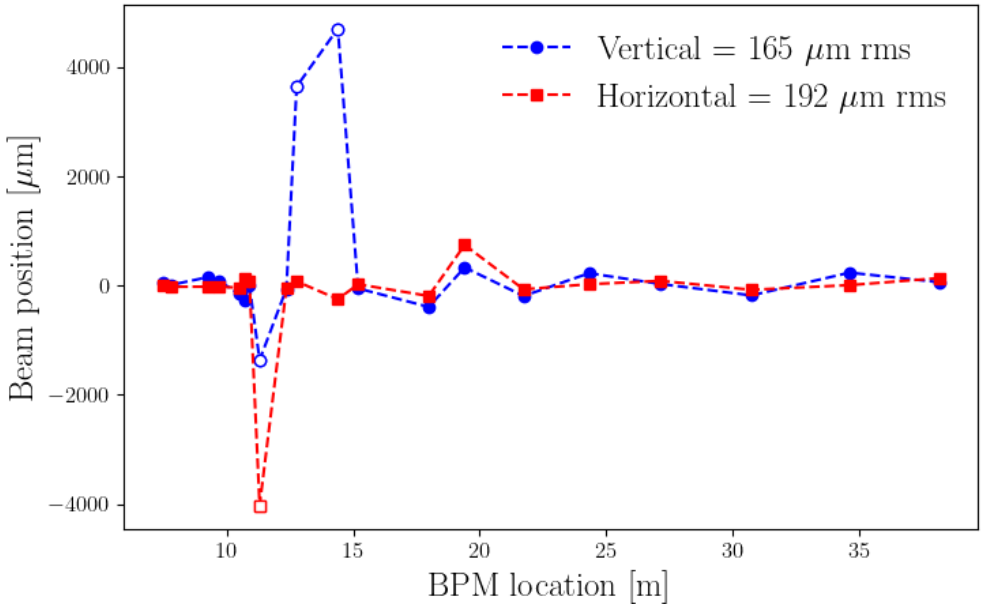

- Time-of-flight confirmed ~3.6 MeV
- Voltage scan matched well to reconstructed model
- Transmission match expectations from model (96-98%), solenoid scan pattern differ




Daniel Noll

# Trajectory Correction

- Total of 20 BPM’s in the NCL
- RF noise challenges on certain DTL BPMs
- Polarity checks BPMs, correctors
- Ignoring a few BPMs we got a good RMS
- We use SVD for matrix inversion




Natalia Milas

# Phase Scans

## 3 MEBT bunchers and 4 DTL tanks

- 3 bunchers
- 4 DTL tanks (3 new)
- 20 BPMs
- Manual set up still achievable
  - For SCL 146 cavities → automation essential
- Frequency jump between Spoke-MBL
  - Amplitude match particularly important

DTL scans

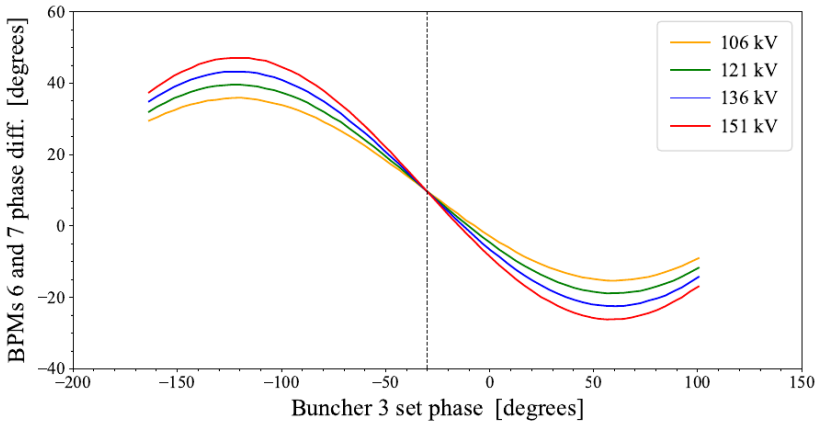
- First (few) internal BPM(s) → sine-like response
- Here we focus on online modelling & fitting
- For more details on DTL measurements, see
  **M. Comunian et al. - THBP07**

Buncher scans

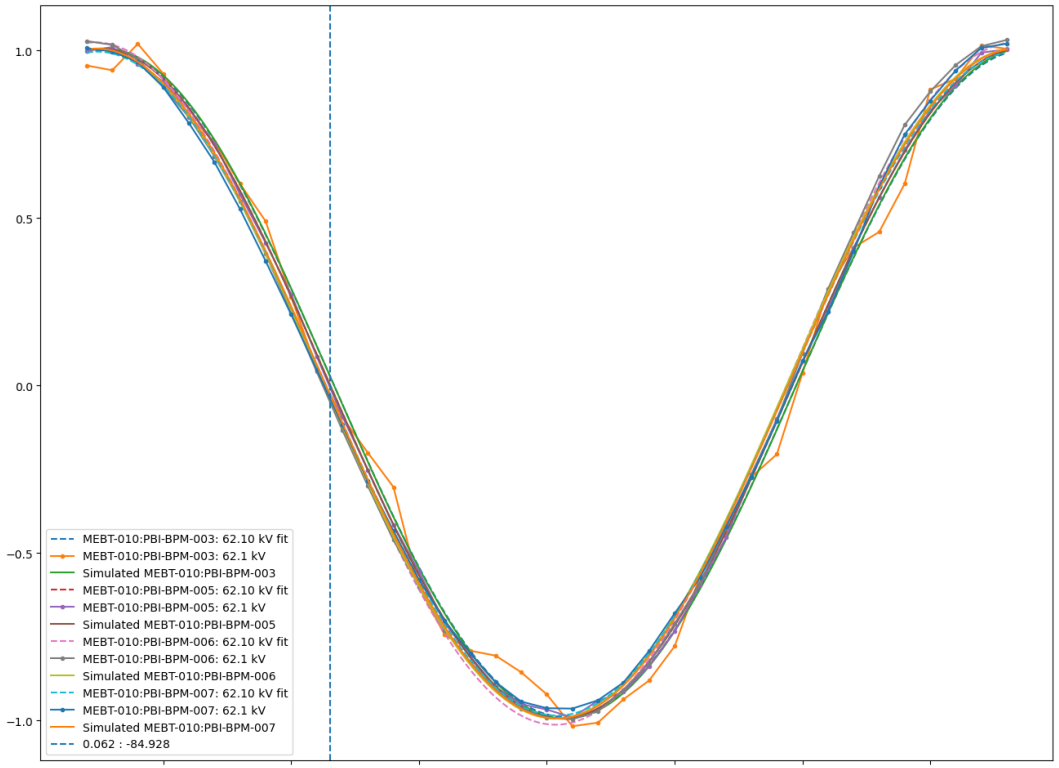
- Closest BPM may observe RF noise
- Model based (OpenXAL) BPM response fitting
- “Turning off” with time delay is fast
- Fully detuning is time consuming
- Aim for scans w/o needing to detune
  - Lowering current
  - Short pulse

# Buncher Phase Scans

- Weighted sum of fit to expected model response of all BPMs
- BPMs close to buncher may see RF noise (orange)
- Automated fit in ~1 min per buncher




Buncher 2 scan

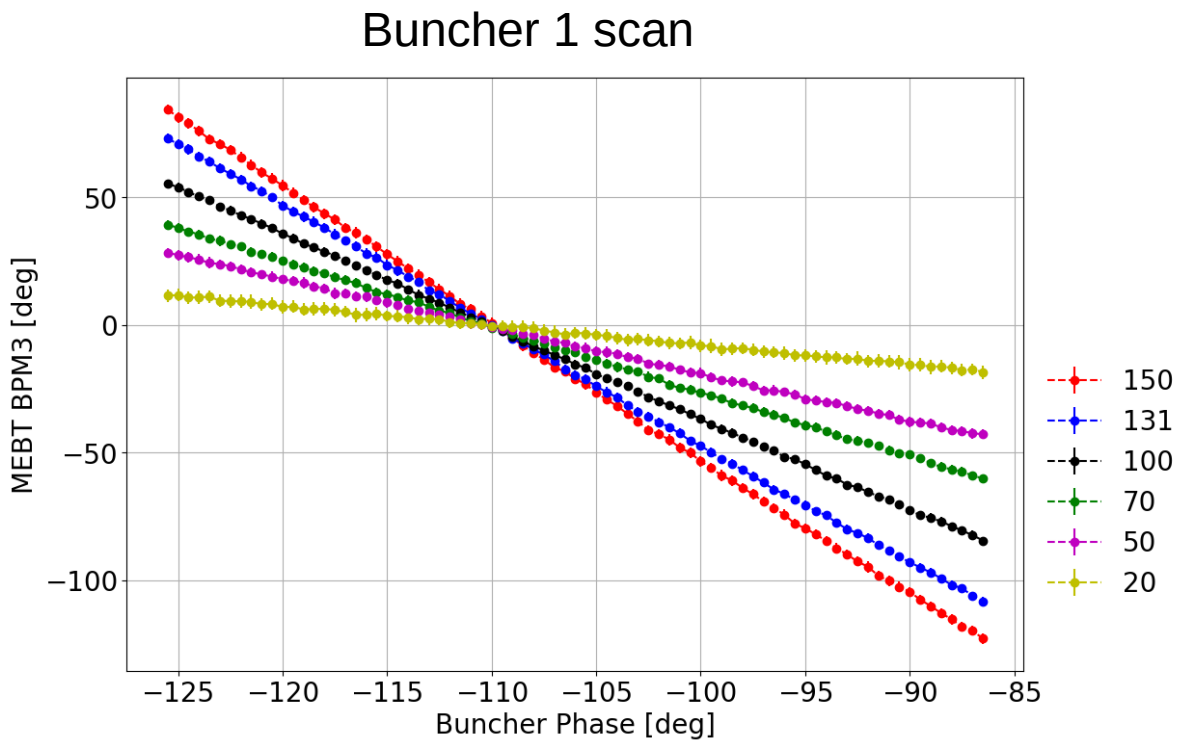


# Buncher Phase Scans

## To detune or not to detune

- Compared to measurements with fully detuned buncher 2
- BPM3 & 5 gave -110.4 & -111.2 deg
- Compared to -110.7 deg with no detuning
- Amplitude still to be fully verified
- Low current and short pulse seems reasonable

But ...

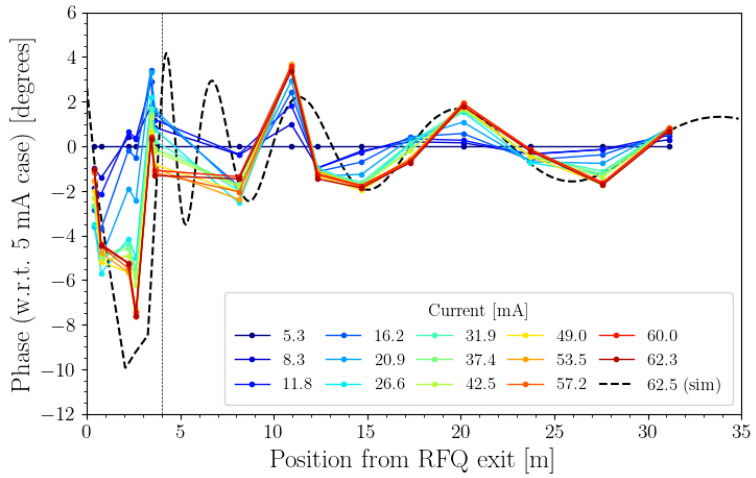


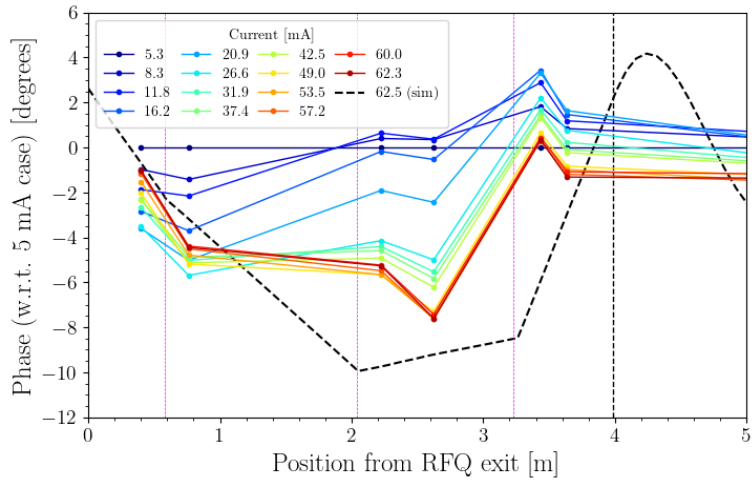
# Phase/current dependence

Significant current dependence on beam phase out of RFQ

- Iris cuts of transverse tails → change energy distribution?
- Less severe when current is lowered by Sol2
- RF phase scan at low current, operations at full current
- Effect dampens with energy but emittance blows up.
- Depends on ISrc HV. (Energy mismatch?)

Note: requirements on the set phase/amp is 1-deg & 1%



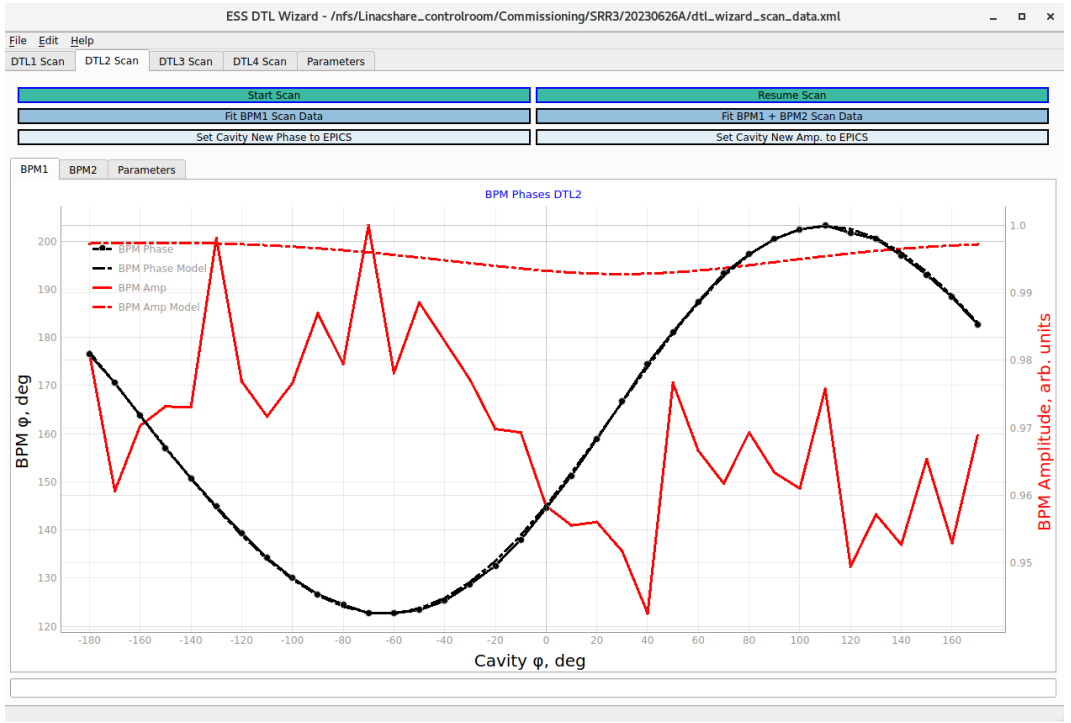




Ryoichi Miyamoto

# DTL Phase Scans

## DTL Wizard application

- Dr. A. Shishlo from SNS visited us for 3 months
- Focus on DTL phase scan strategy
- Developed a new application based on PyORBIT
- Together with Dr. S. Zhukov transitioned PyORBIT from Python2 to Python3
  github.com/PyORBIT-Collaboration/PyORBIT3
- Evaluated fitting strategy
  - Suggest BPM1 for first guess, BPM2 for precise fitting
- Model improvement identified: calibration of cavity amplitude should take into account the longitudinal bunch size




$$\Delta W = qV_0 \cdot TTF \cdot \cos(\phi_0)$$

$$\rho(\phi) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(\phi - \phi_0)^2}{2\sigma^2}}$$

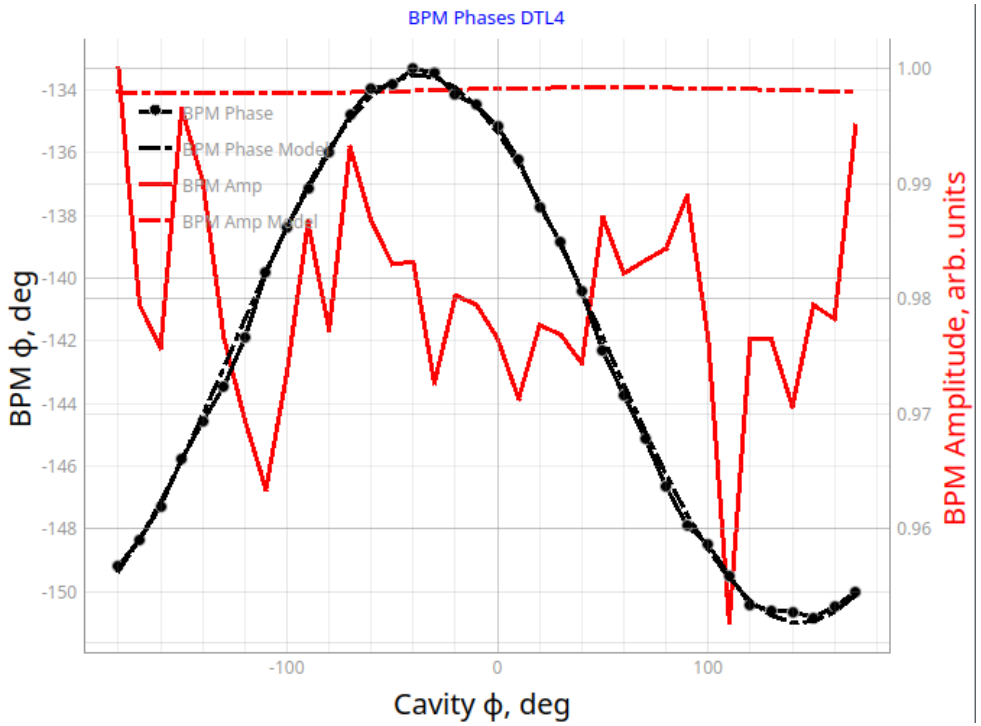
$$\langle \Delta W \rangle = \int \rho(\phi) \cdot qV_0 \cdot TTF \cdot \cos(\phi_0) d\phi = qV_0 \cdot TTF \cdot e^{-\frac{\sigma^2}{2}} \cdot \cos(\phi_0)$$

**J. Müller - TUC2C2**

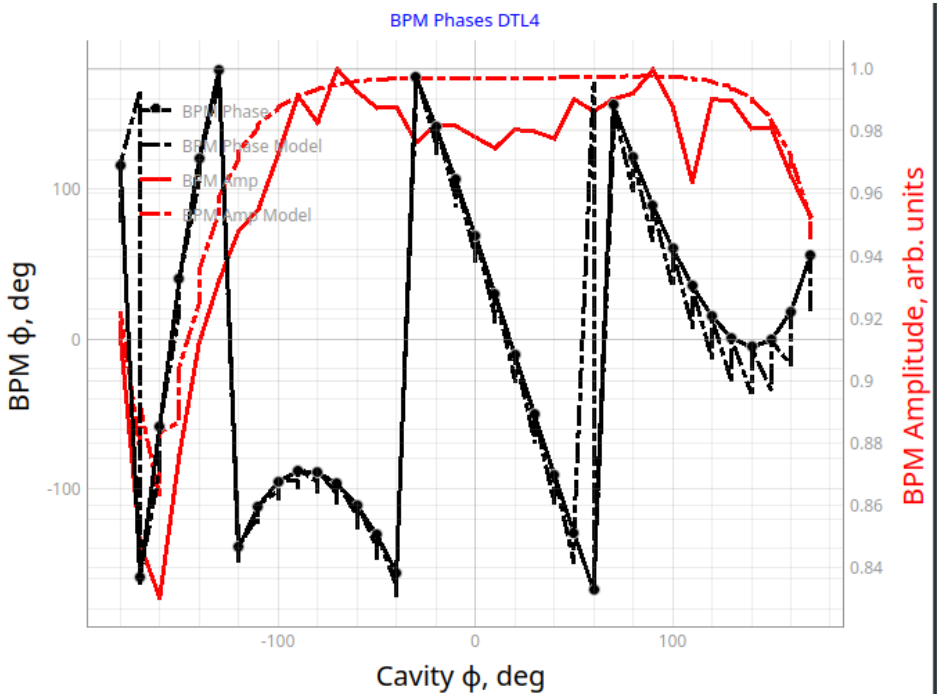
# DTL Phase Scans

## Fitting to internal BPM1 only

BPM1



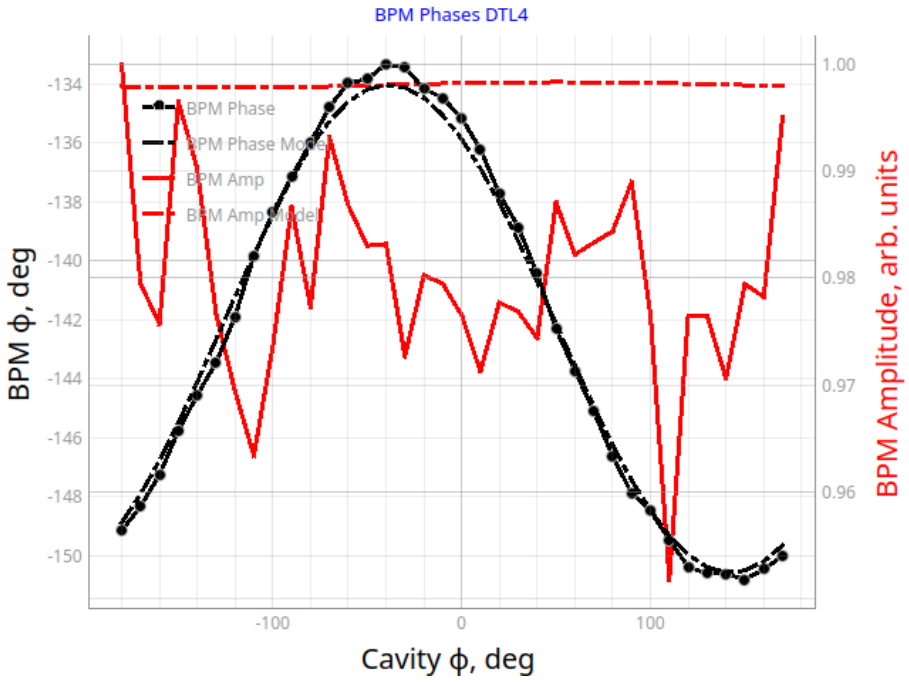

BPM2



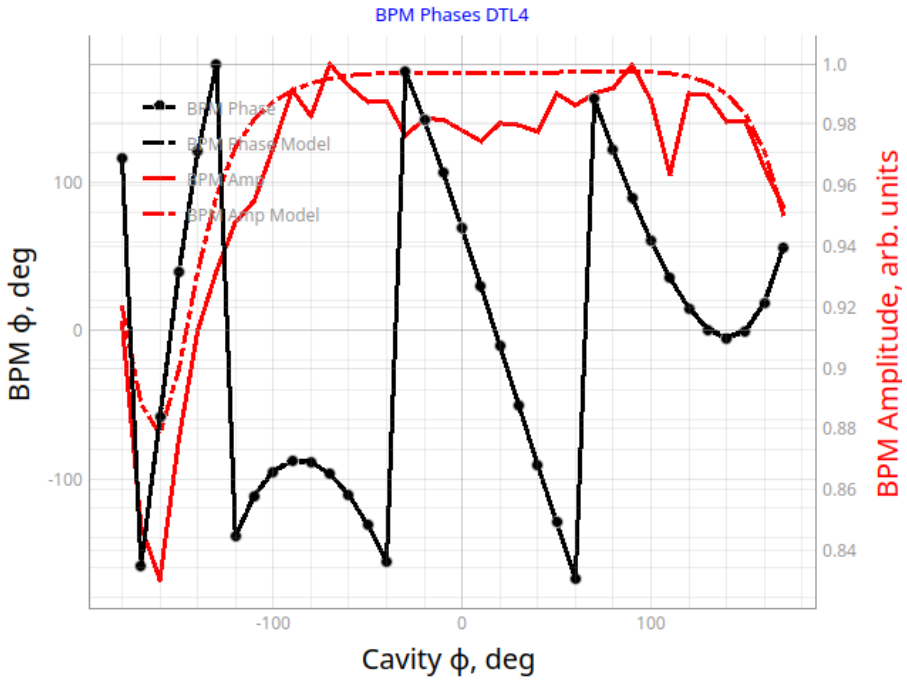
# DTL Phase Scans

## Fitting to internal BPM1 + BPM2

BPM1




BPM2

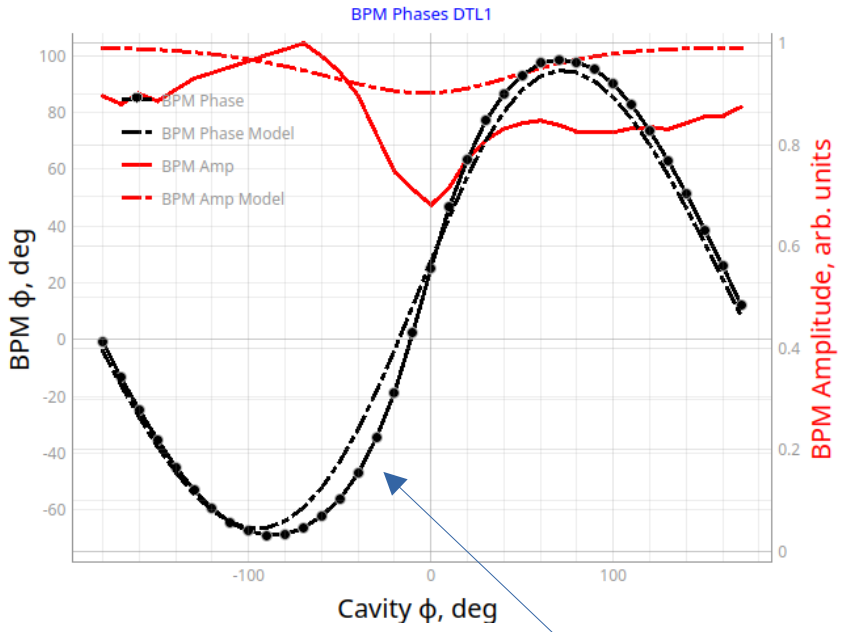



Improved fitting BPM1+2: Use predominantly BPM2 data

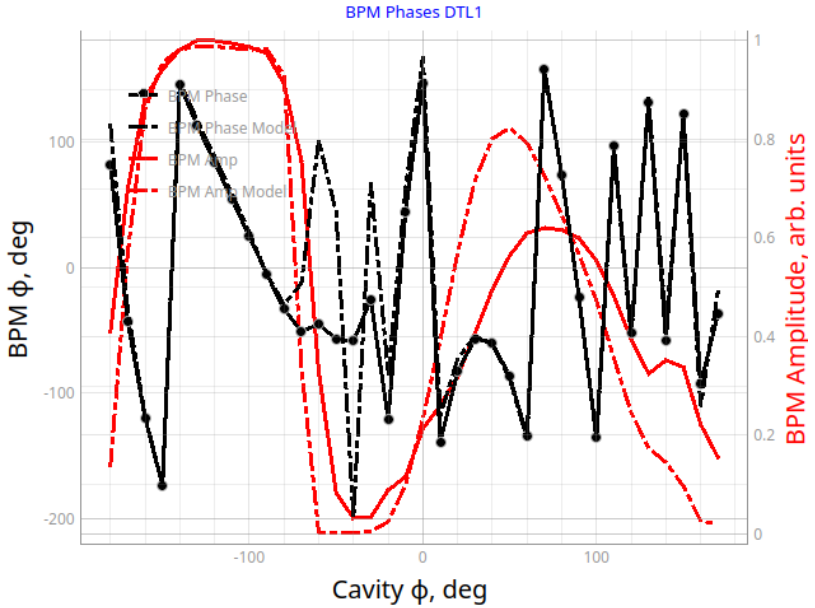
# DTL1 Phase Scans

## Fitting to internal BPM1 + BPM2

BPM1




BPM2




Generally DTL1 harder to fit
- matching issues?

# DTL1 Phase Scans

## Reproducibility?

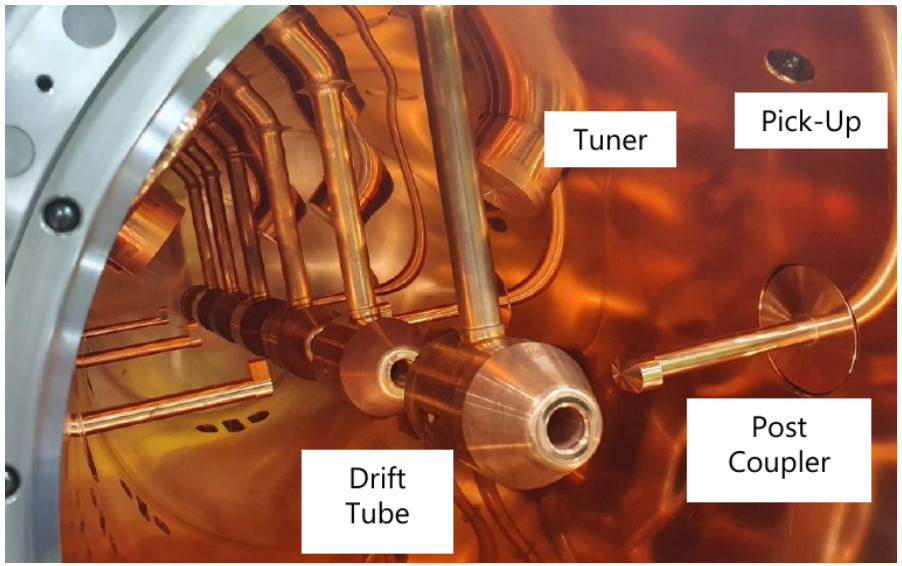
| Shift | DTL1 | DTL2 | DTL3 | DTL4 |
|---|---|---|---|---|
| 20230530B | 2.89/-131.8 | 3.0/-101.4 | 3.25/-198.1 | **2.58**/75.8 |
| 20230602B | N/A | 3.09/-95.1 | 3.24/-162.9 | 2.84/101.0 |
| 20230602B | N/A | 3.11/-99.0 | 3.27/-161.6 | 2.84/101.3 |
| 20230626A | 2.85/-131.3 | 3.08/-96.2 | 3.22/-159.6 | 2.86/109.1 |
| 20230711A | **2.91**/-152.4 | 3.08/-115.2 | 3.22/-179.6 | 2.85/88.01 |
| 20230711A | **2.65**/-155.9 | 3.09/-122.9 | 3.22/-180.3 | 2.84/90.2 |

# DTL1 Phase Scans

## Reproducibility?

| Shift | DTL1 | DTL2 | DTL3 | DTL4 |
|---|---|---|---|---|
| 20230530B | 2.89/-131.8 | 3.0/-101.4 | 3.25/-198.1 | **2.58**/75.8 |
| 20230602B | N/A | 3.09/-95.1 | 3.24/-162.9 | 2.84/101.0 |
| 20230602B | N/A | 3.11/-99.0 | 3.27/-161.6 | 2.84/101.3 |
| 20230626A | 2.85/-131.3 | 3.08/-96.2 | 3.22/-159.6 | 2.86/109.1 |
| 20230711A | **2.91**/-152.4 | 3.08/-115.2 | 3.22/-179.6 | 2.85/88.01 |
| 20230711A | **2.65**/-155.9 | 3.09/-122.9 | 3.22/-180.3 | 2.84/90.2 |

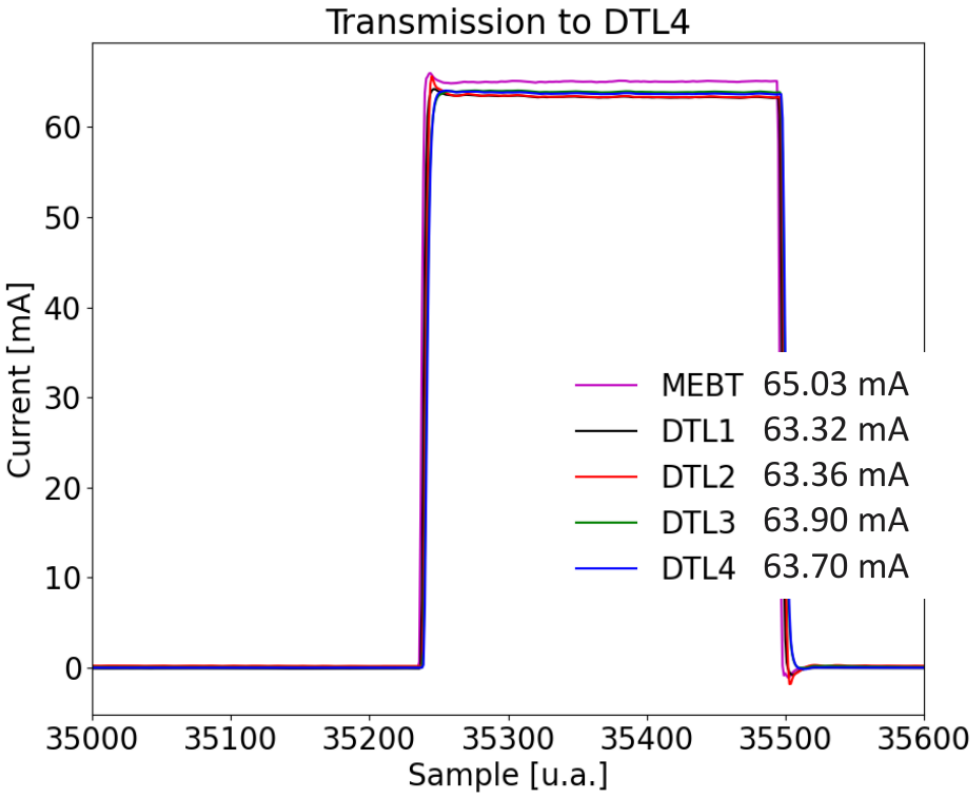
Selecting a different reference pickup?




Francesco Grespan/INFN

# DTL Transmission

- Transmission in DTL ~100%
- Lose beam into DTL1
  - Input conditions?
  - Alignment issues?
  - Beam phase dependency on current in RFQ?




Natalia Milas

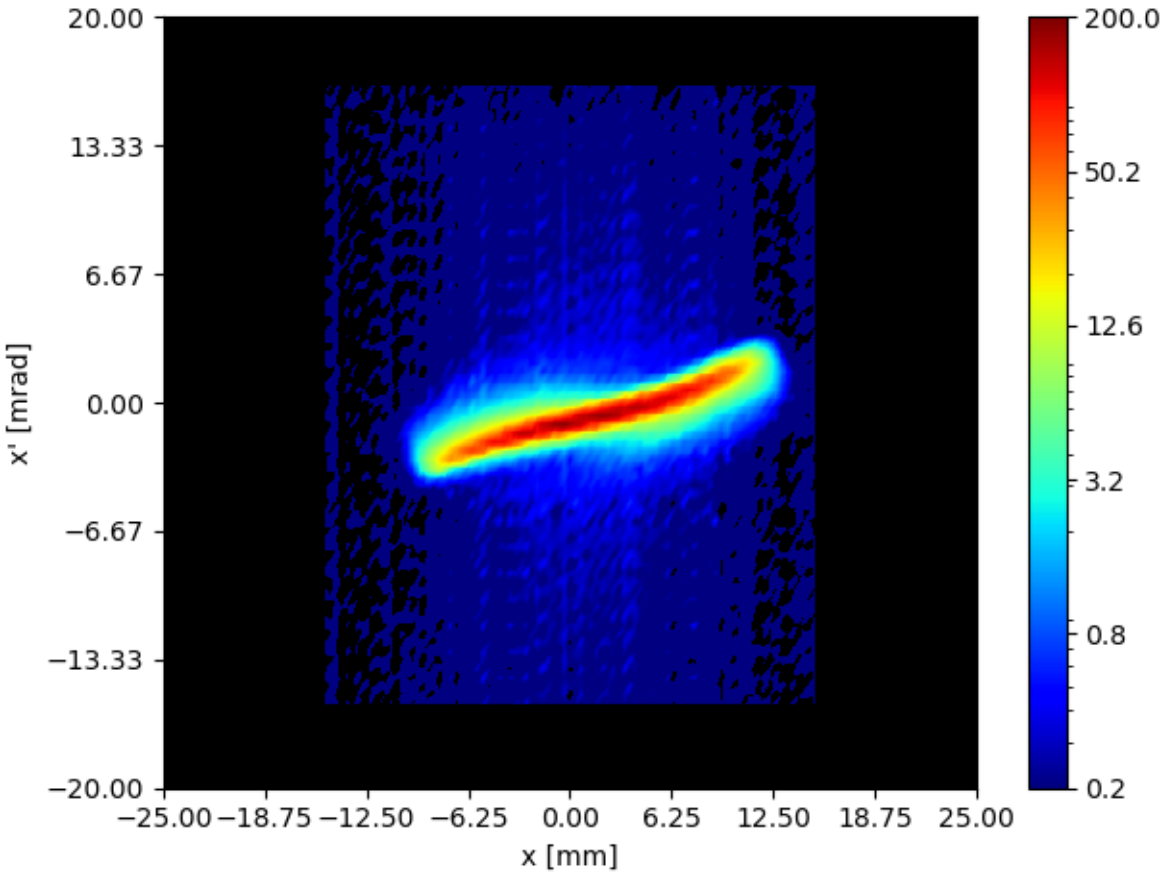
# EMU H data

We had horizontal EMU available last days

Technical hurdles and resource limitations

**Results fit very well with model predictions!**

- very encouraging but we need more data

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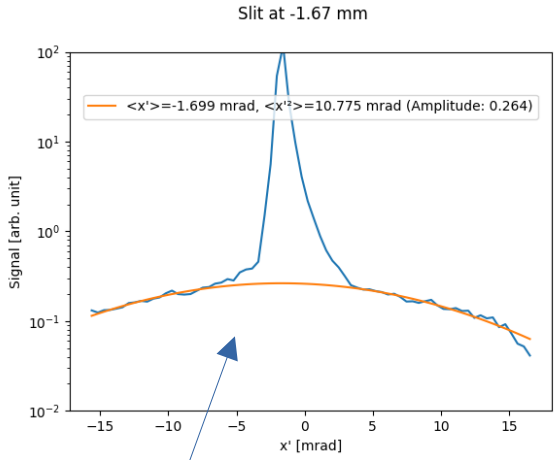
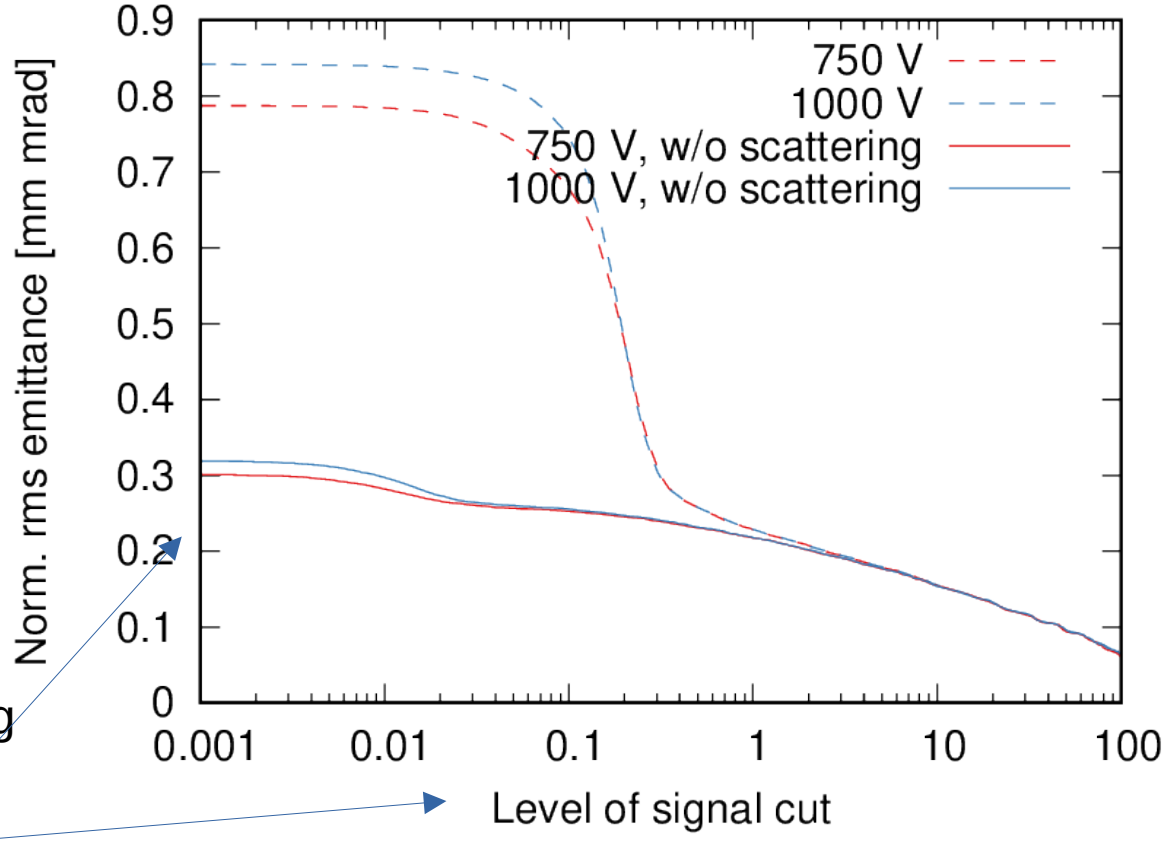
# EMU H data

## Background subtraction




- Assumes background comes from slit scattering
  - Gaussian distributed
- Fit Gaussian to background and subtract
- Then apply flat signal cut
- ESS design 0.25 mm mrad out of RFQ

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# Full NCL installed

End of September we had the entire NCL installed

A particular congratulations and thanks to the INFN Legnaro colleagues!

# Summary

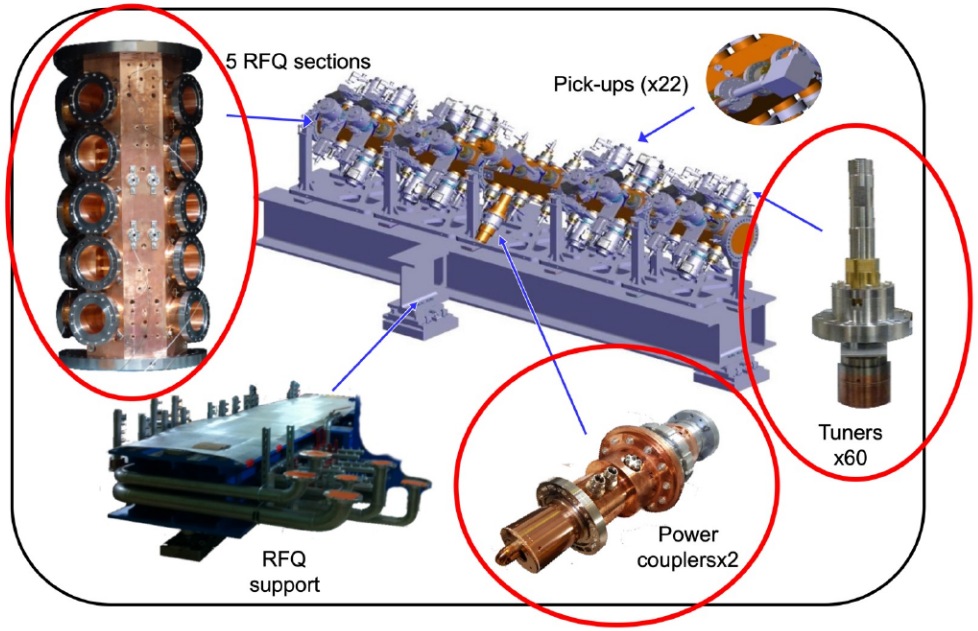
- **Nominal, 50us beam transported through DTL4**
- Trajectory correction worked well
- Phase scan strategy works well
  - Seems precise, uncertain accuracy?
- Transverse measurement – encouraging
- More attention needed...
  - Matching into DTL1
  - Phase out of RFQ
  - Source characterization
  - 50 us → 2860 us
  - ...
- **A successful commissioning campaign**
  - **Many systems come together**
  - **Learn how to operate**
  - **Learn where attention is needed**

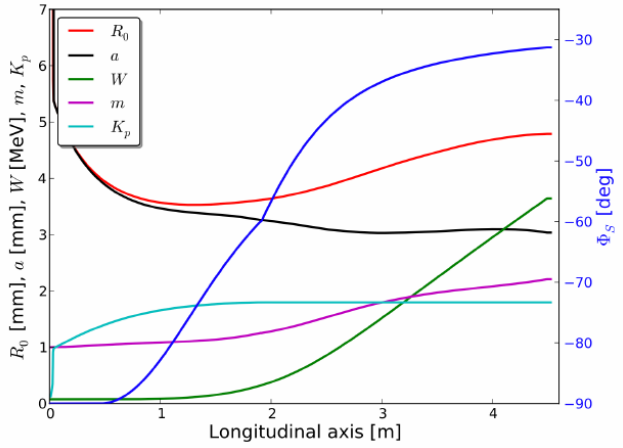
# Backup slides

# RFQ

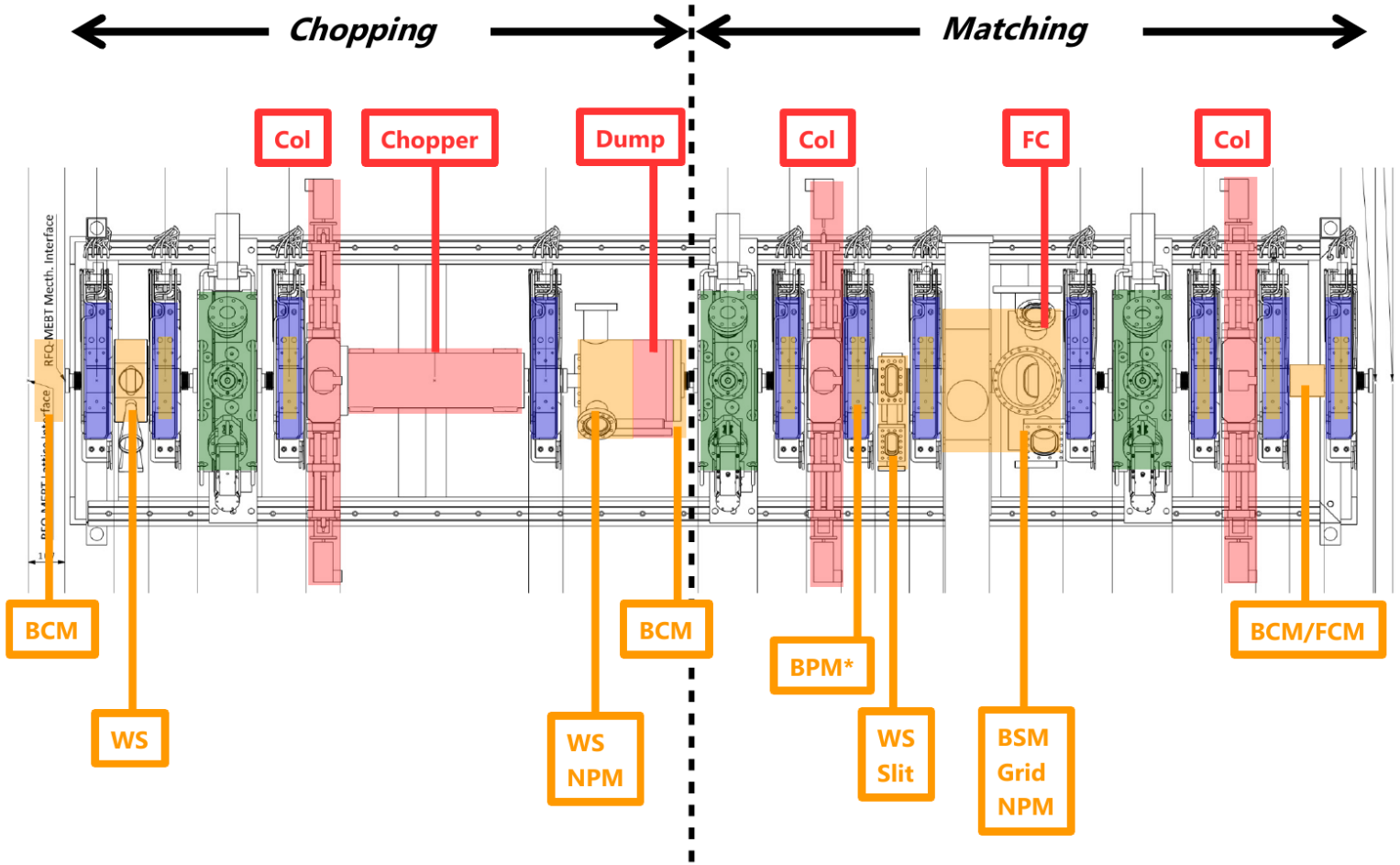
The numbers

- 75 keV to 3.62 MeV
- 4.6 m long
- 4 vanes
- 2 coaxial power couplers
- 5 segments
- 22 field pickups
- 60 static tuners
- 66 cooling circuits
- 80-120 kV intervane voltage
- <TODO Power>
- 352.21 MHz



# The MEBT


Chopping
Matching
Col
Chopper
Dump
Col
FC
Col
BCM
WS
WS
NPM
BCM
BPM*
WS
Slit
BSM
Grid
NPM
BCM/FCM