Measurements of the energy chirp induced by “self-fields” in the injector section

Igor Zagorodnov and Sergey Tomin

XFEL Beam Dynamics Meeting

DESY, Hamburg

2.06.20

Motivation

Measurements of the on-crest phase of A1 from 29.10.2019 have shown a disagreement of about 1 degree between:

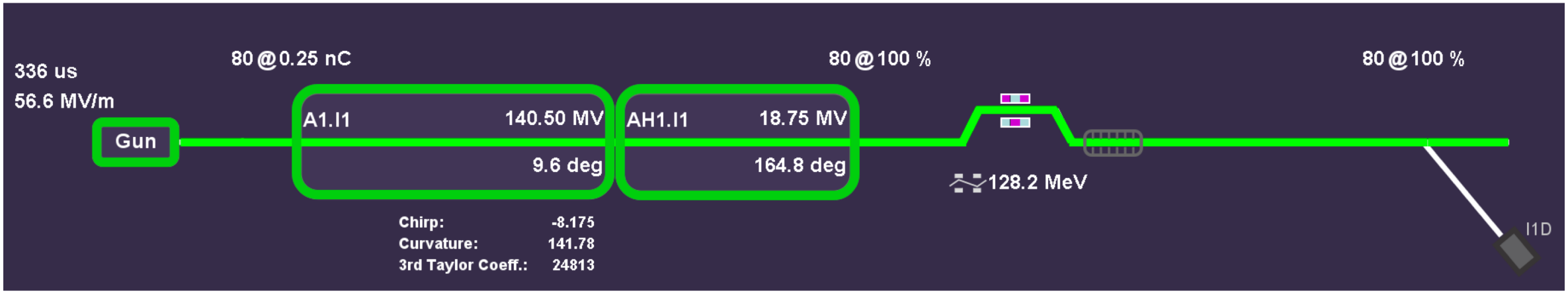
- the on-crest phase defined by maximal energy scan (“IntelliPhase” software),
- the on-crest phase defined from RF curvature of the longitudinal phase space measured with TDS.

Questions

- How accurate is the RF phase definition by energy scan (“IntelliPhase” software)?
- Are we able to subtract the RF curvature and to see the “self fields” phase space (due to the self-fields only)?
- How does energy chirp depend on the charge?

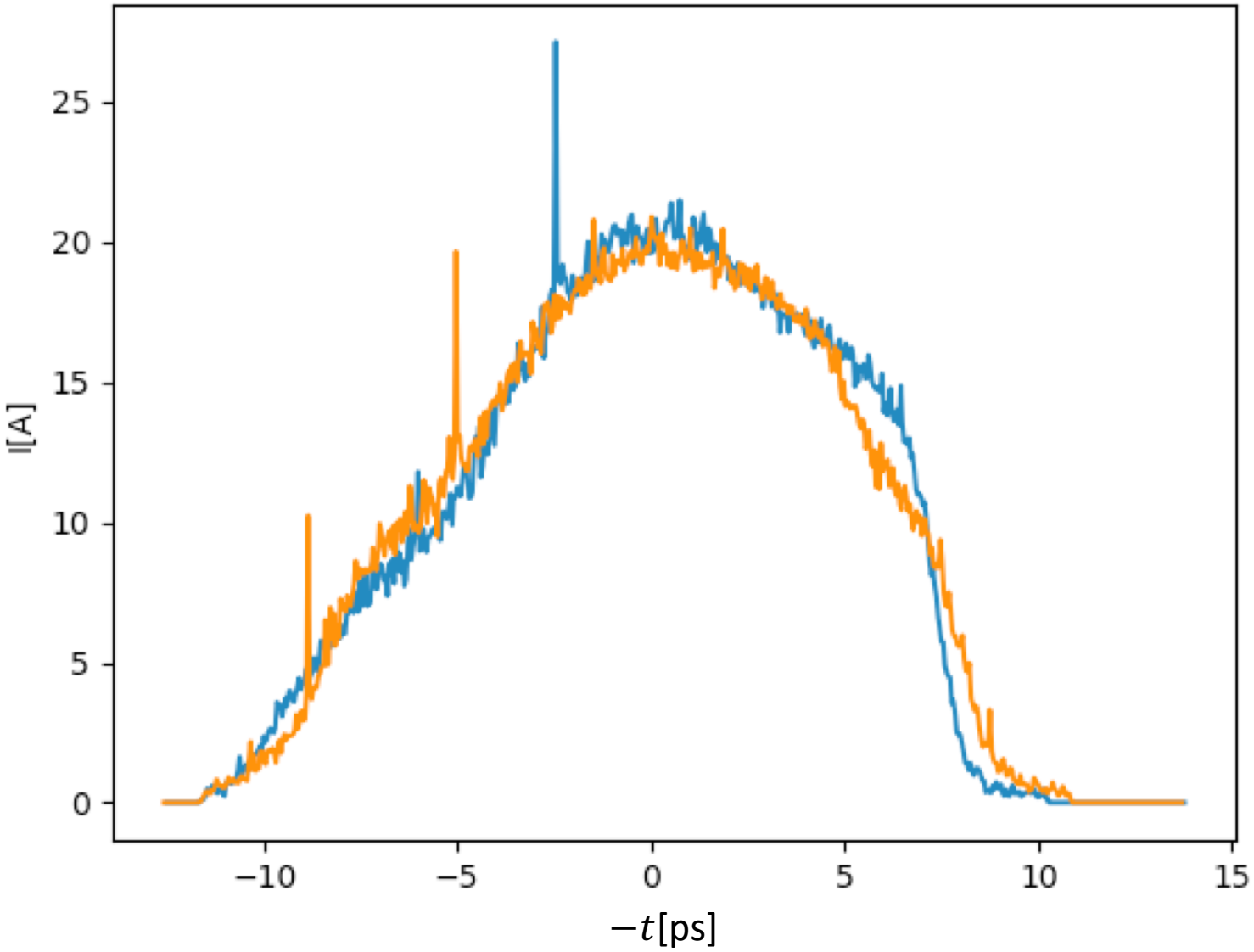
Idea and method

- Use only A1 near the “on-crest” phase and keep the beam energy at TDS approximately the same
- Take TDS pictures for several charges: 100 :250:500:750 pC
- At each charge to take TDS pictures for different phases: -6:-4:-2:0:2:4:6 degrees
- For each scan to find two parameters from analysis :
  - initial energy E_0 (the energy after the gun + a possible systematic error of the energy measurements in LH),
  - phase shift φ_0.
- The analysis is based on the suggestion that the “self-fields” phase space is independent from the RF phase of A1.
- No other fitting parameters or scaling factors have been used. Only the measured quantities and E_0, φ_0 come into the analysis.

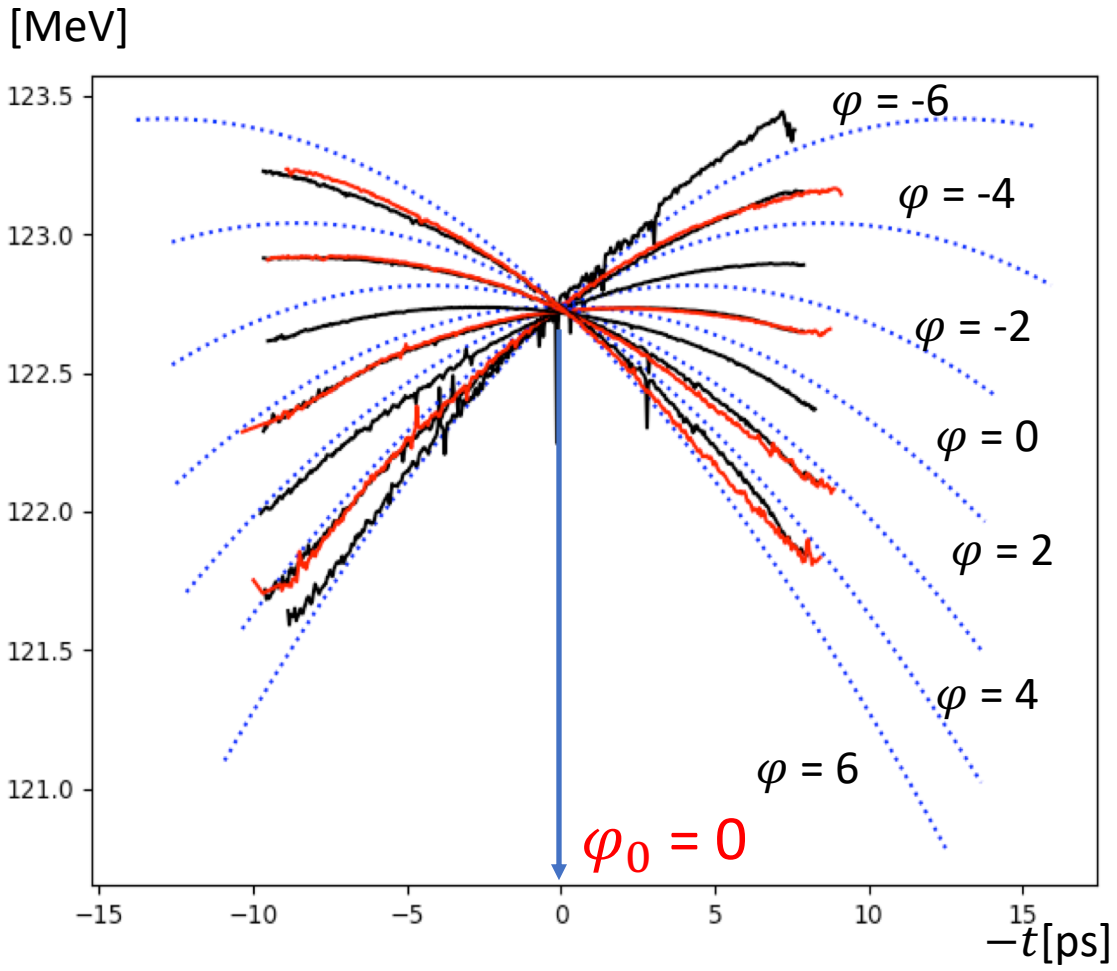


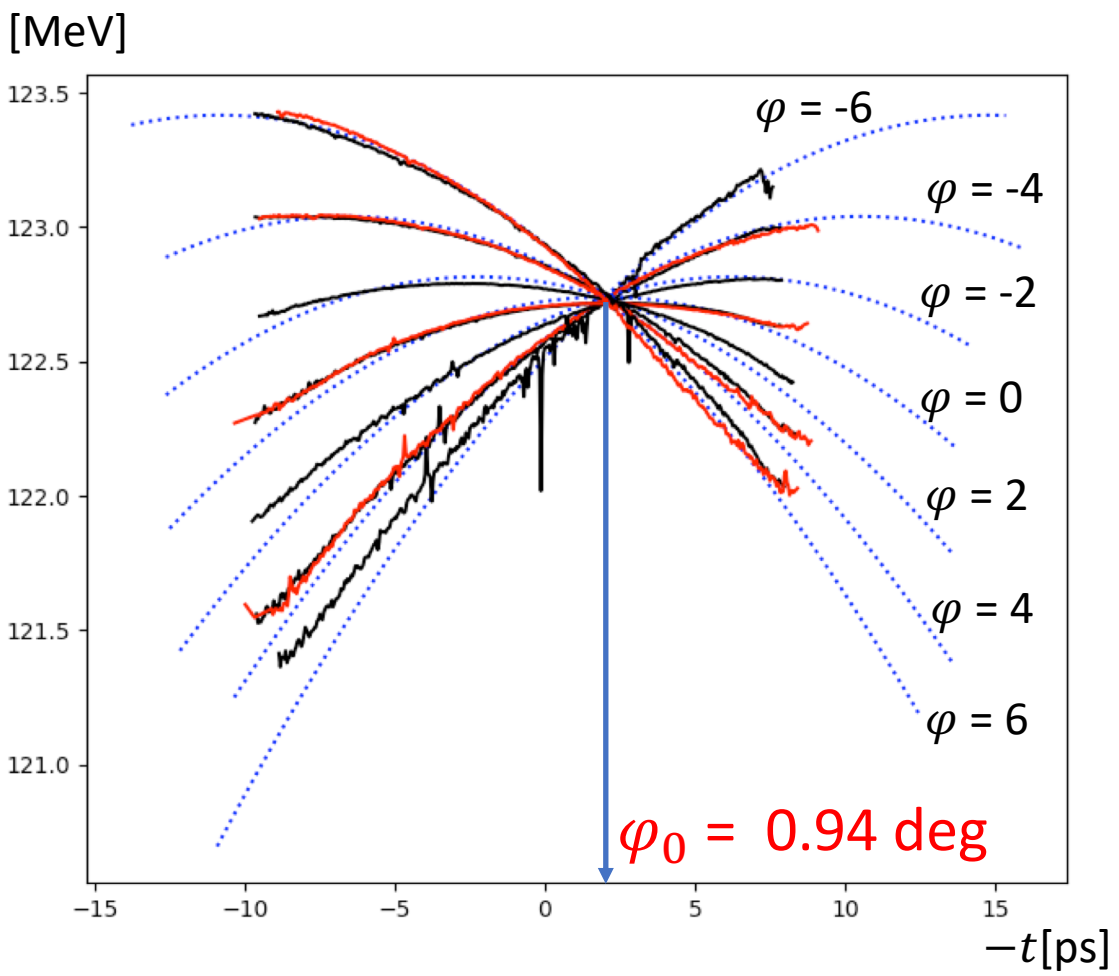
Motivation (29.10.2019).

The current from the first/second zero crossing at TDS



Motivation (29.10.2019).





$V(0) = 122.74$ MV

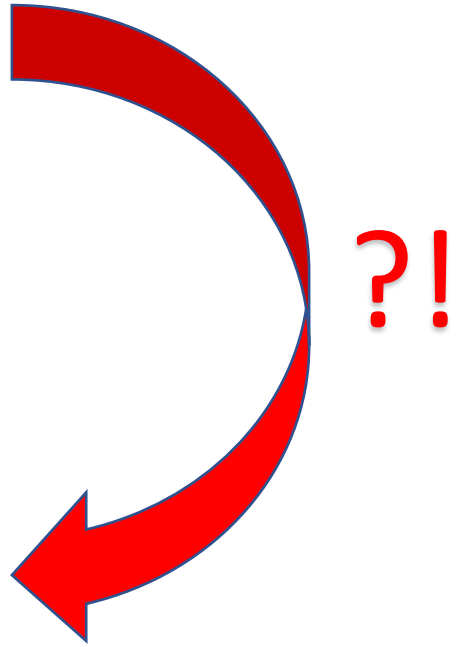
$$V(\varphi) = \frac{V(0)}{\cos(\varphi)}$$

$$y_M(t,\varphi) = \Delta E(t) + y_{RF}(0,\varphi)$$

$$y_{RF}(t,\varphi) = eV(\varphi)cos(-\omega t + \varphi - \varphi_0)$$

Experimental results (14.05.2020).

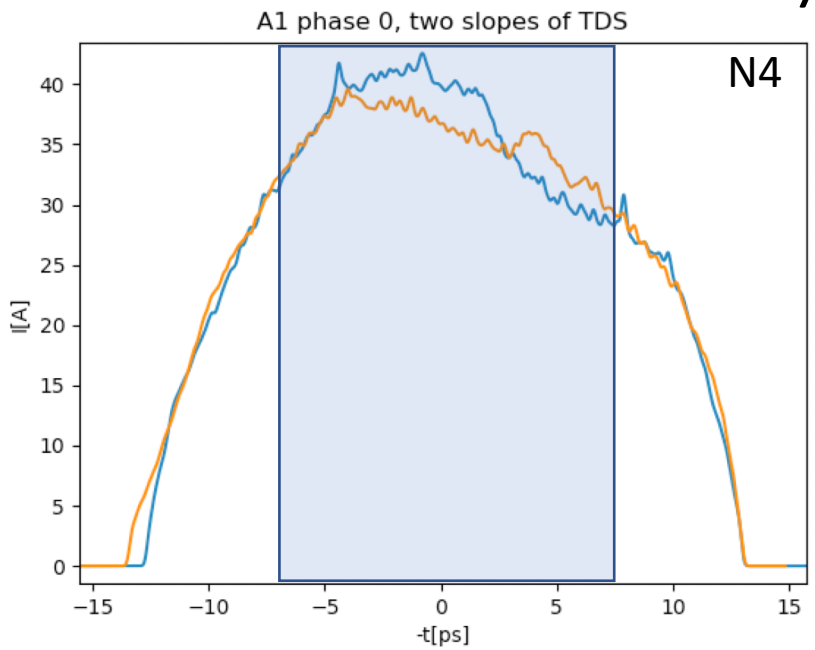
N	Charge, pC	Phase shift according to IntelliPhase, deg	On-crest phase measured by IntelliPhase, deg	On-crest phase position (to ref.), deg
1.	100	**0 (ref)**	**0(ref)**	**0.00**
2.	250	0	-	-
3.	500	0	-	-
4.	750	0	0.61	0.61
5.	750	0.61	0	0.61
6.	500	0.26	0	0.26
7.	250	-0.44	0	-0.44
8.	100	-1.00	0	**-1.00**

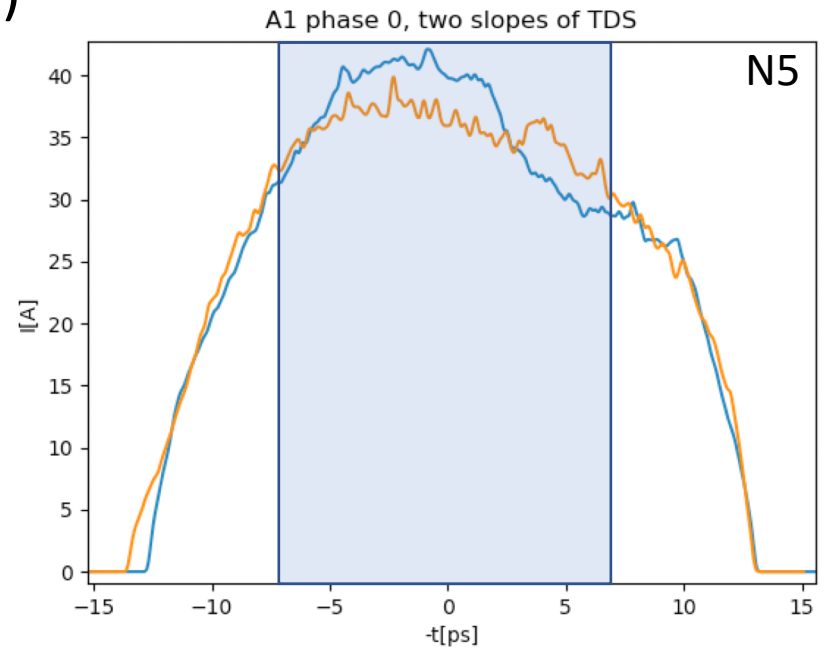


?!

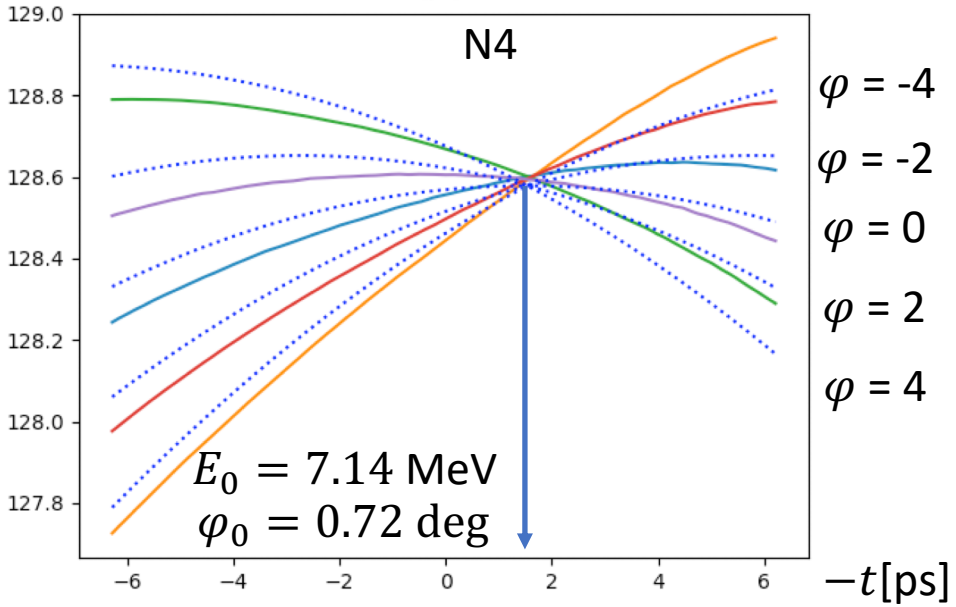
- Why does the on-crest phase position move with the charge?
- Why does the on-crest phase position not return to zero?

750 pC (N4, N5)

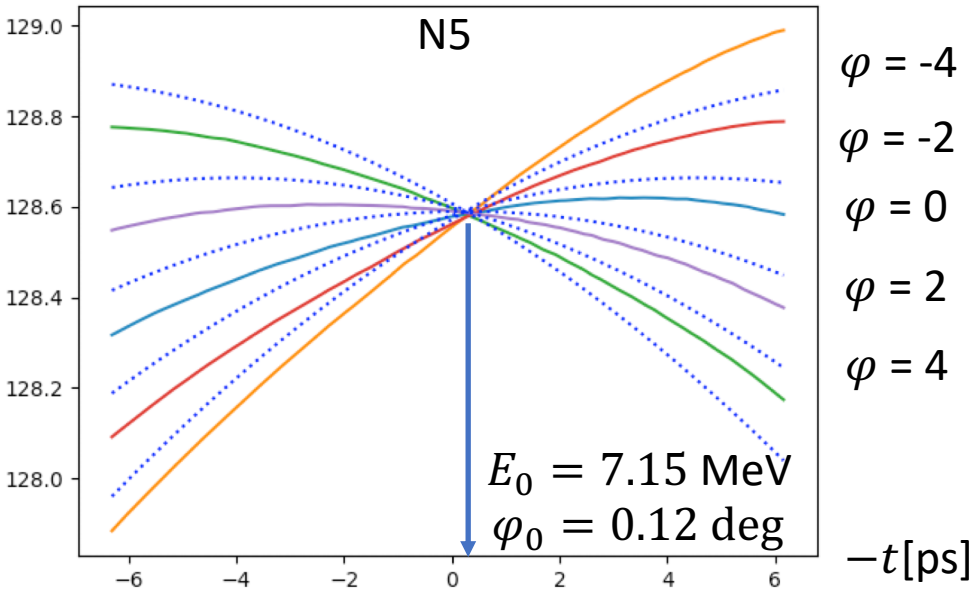




[MeV]



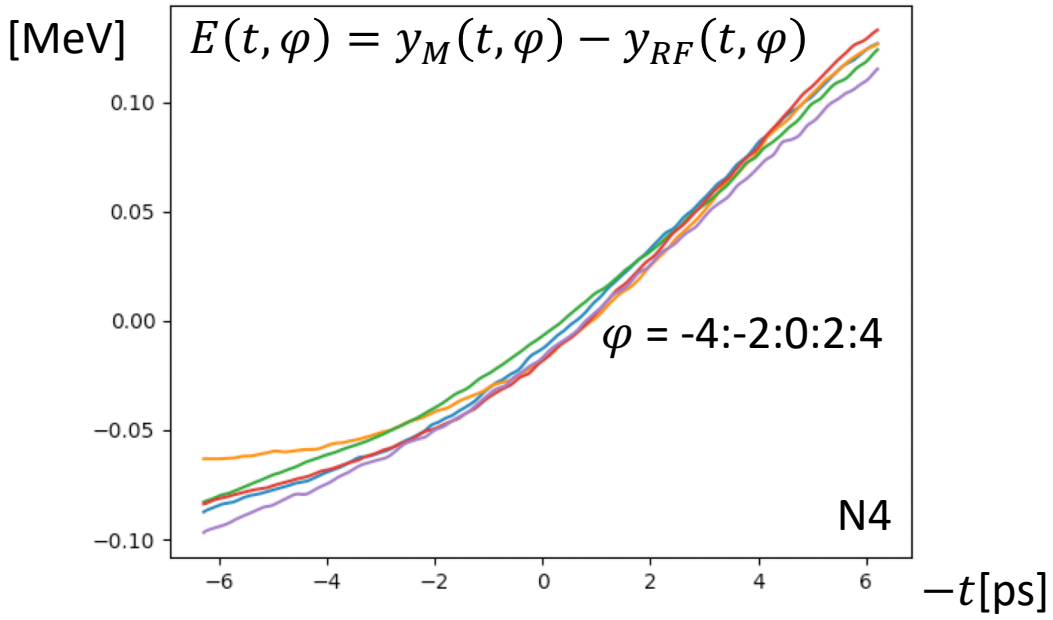
[MeV]

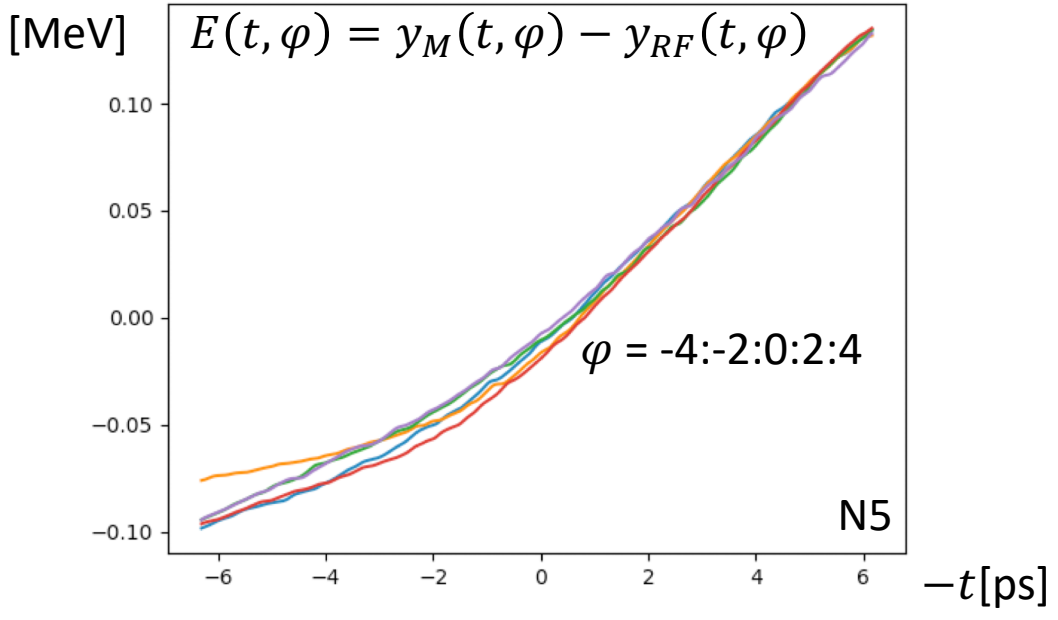


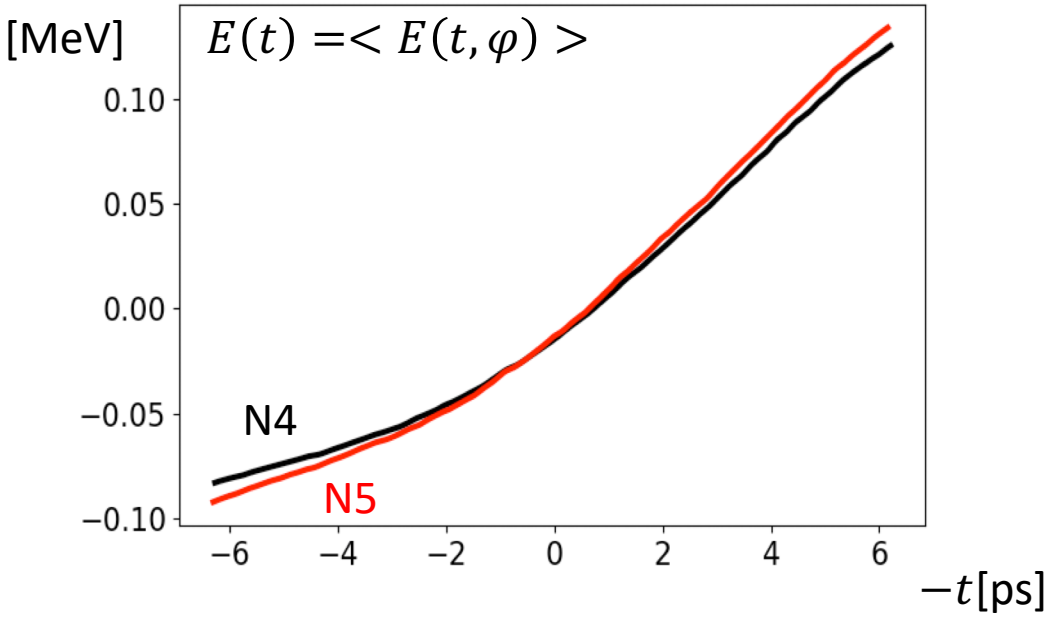
$$y_M(t,\varphi) = \Delta E(t) - <\Delta E(t)> + E_{LH}(\varphi)$$

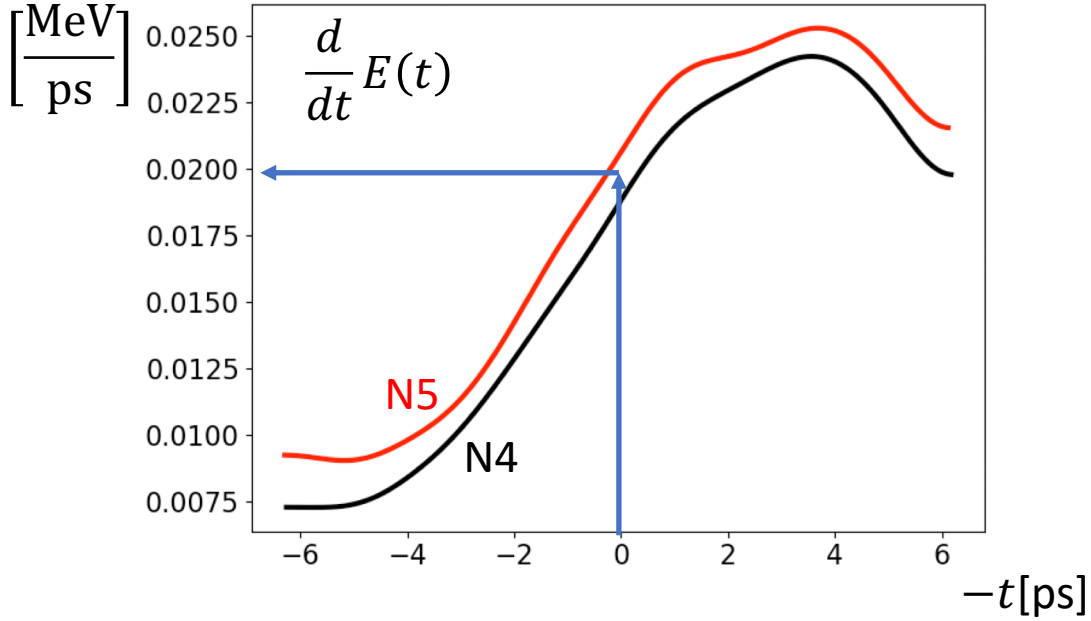
$$y_{RF}(t,\varphi) = eV(\varphi)cos(-\omega t + \varphi - \varphi_0) + E_0$$

750 pC (N4, N5)


[MeV]
$E(t,\varphi) = y_M(t,\varphi) - y_{RF}(t,\varphi)$
φ = -4:-2:0:2:4
N4
$-t$[ps]


[MeV]
$E(t,\varphi) = y_M(t,\varphi) - y_{RF}(t,\varphi)$
φ = -4:-2:0:2:4
N5
$-t$[ps]

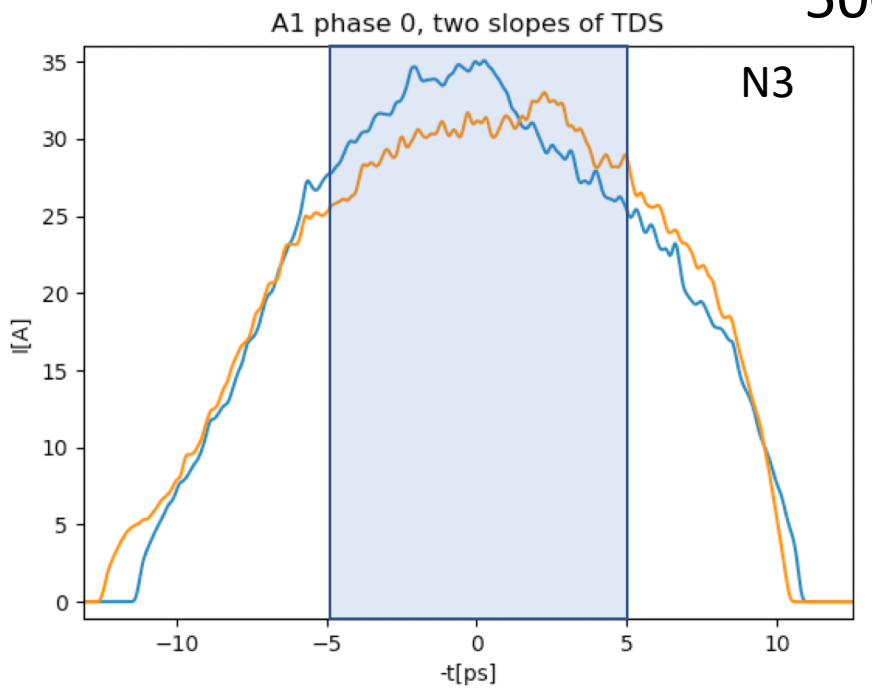

[MeV]
$E(t) =< E(t,\varphi) >$
N4
N5
$-t$[ps]

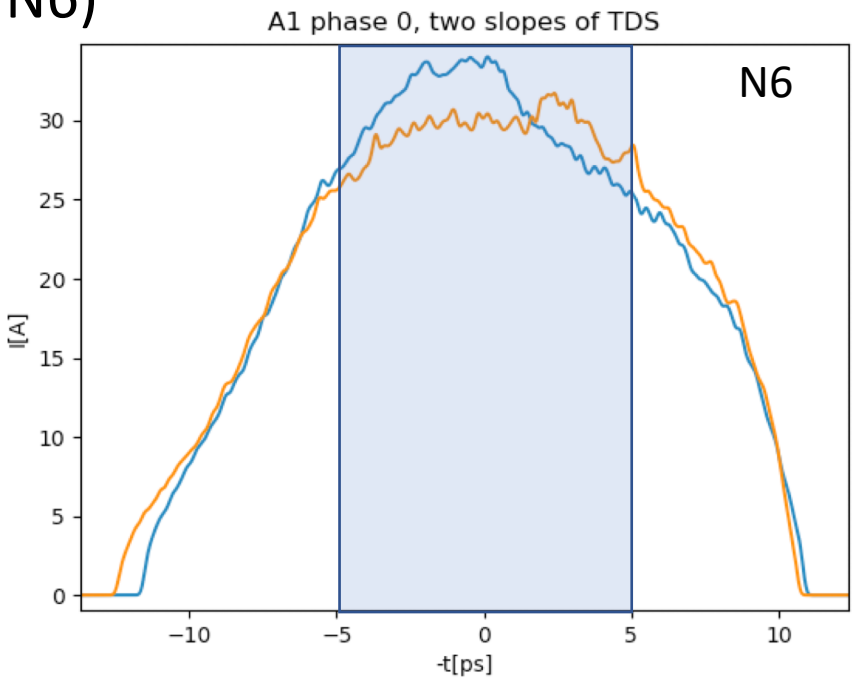

$\left[\frac{\text{MeV}}{\text{ps}}\right]$
$\frac{d}{dt}E(t)$
N5
N4
$-t$[ps]

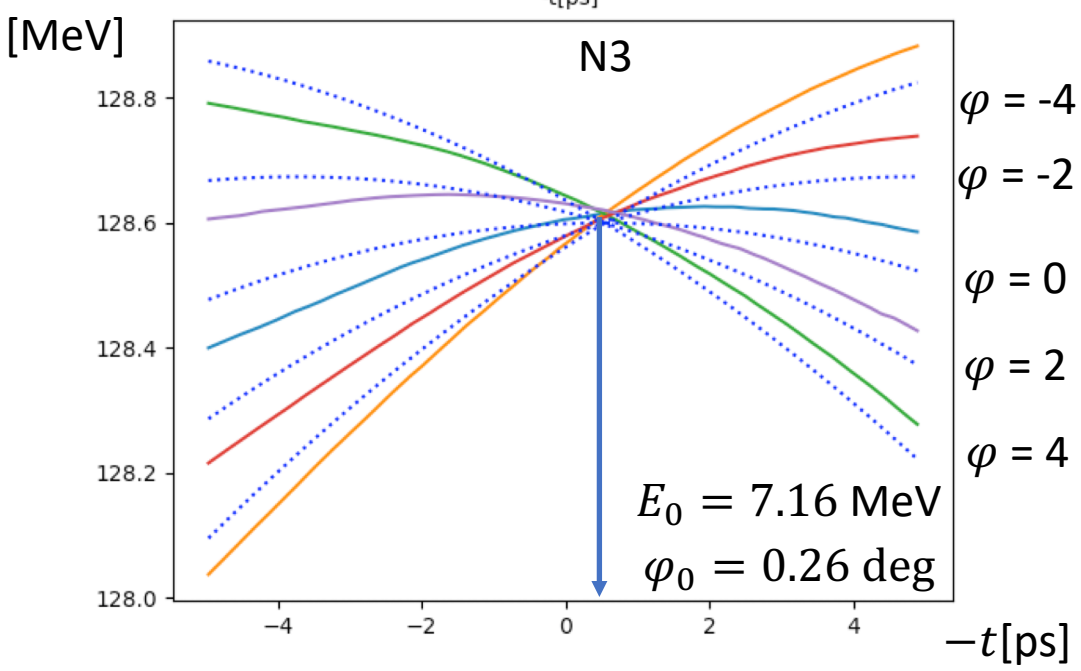
Experimental results (14.05.2020).

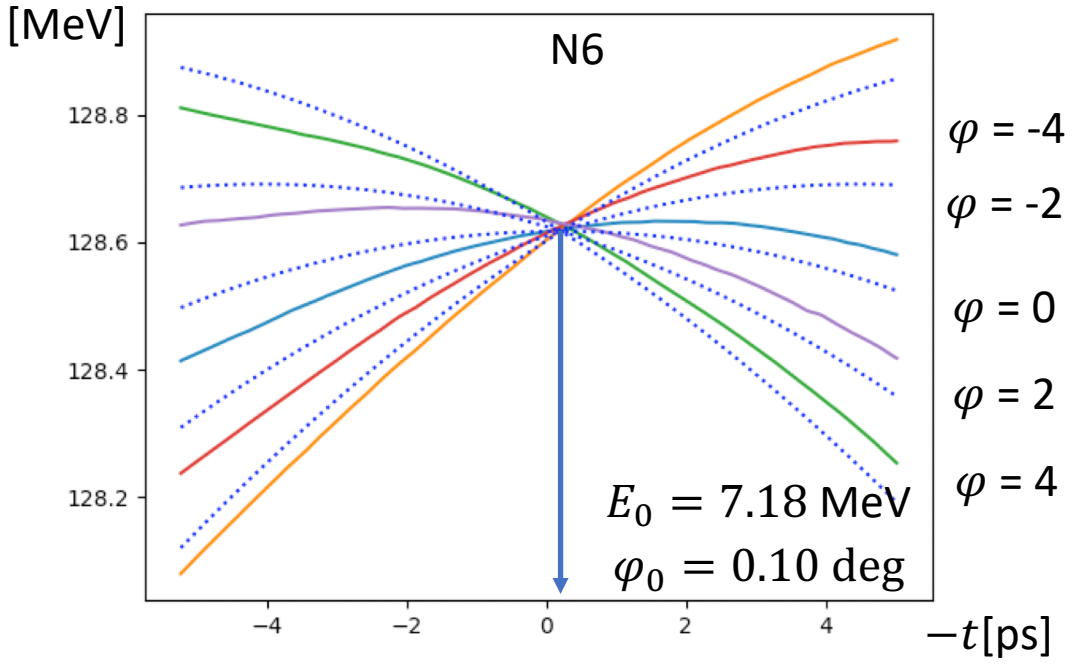
N	Charge, pC	Phase shift according to IntelliPhase, deg	On-crest phase measured by IntelliPhase, deg
1.	100	**0 (ref)**	**0(ref)**
2.	250	0	-
3.	500	0	-
4.	750	0	0.61
5.	750	0.61	0
6.	500	0.26	0
7.	250	-0.44	0
8.	100	-1.00	0

500 pC (N3, N6)

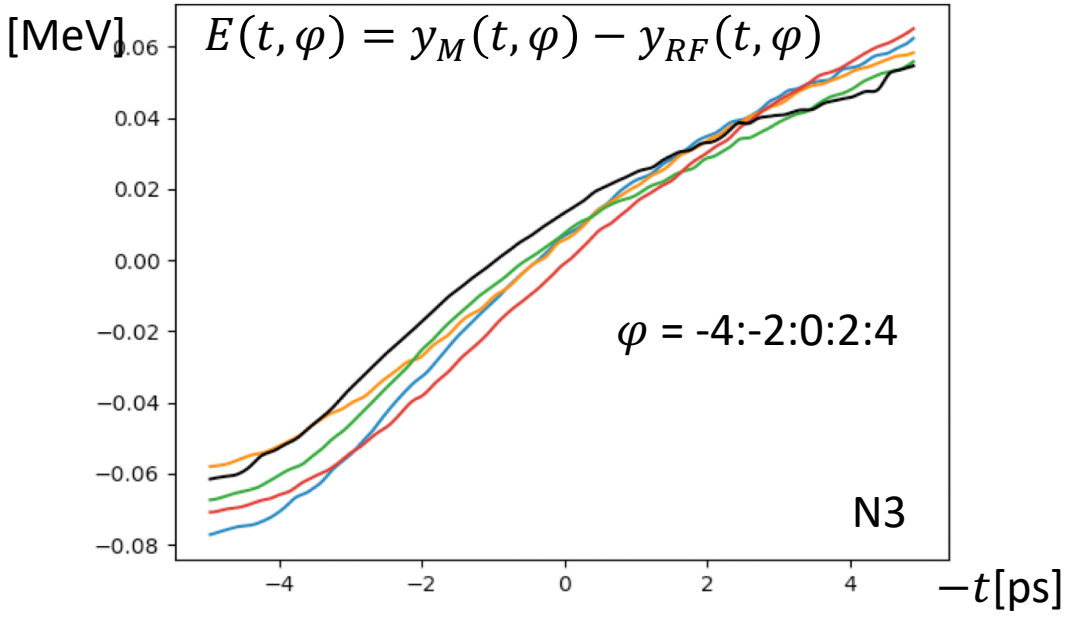

A1 phase 0, two slopes of TDS
N3
I[A]
-t[ps]

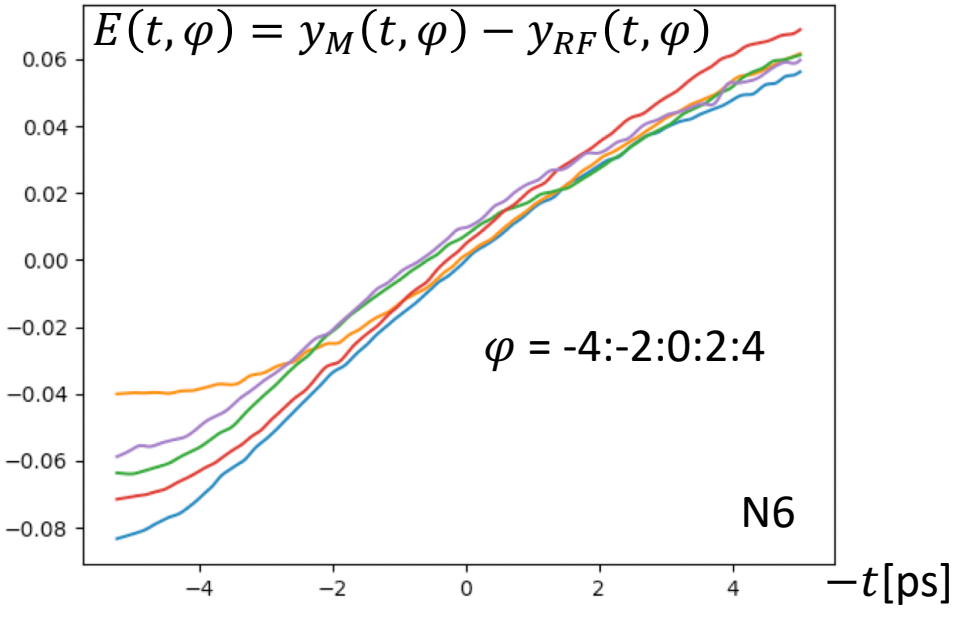

A1 phase 0, two slopes of TDS
N6
I[A]
-t[ps]

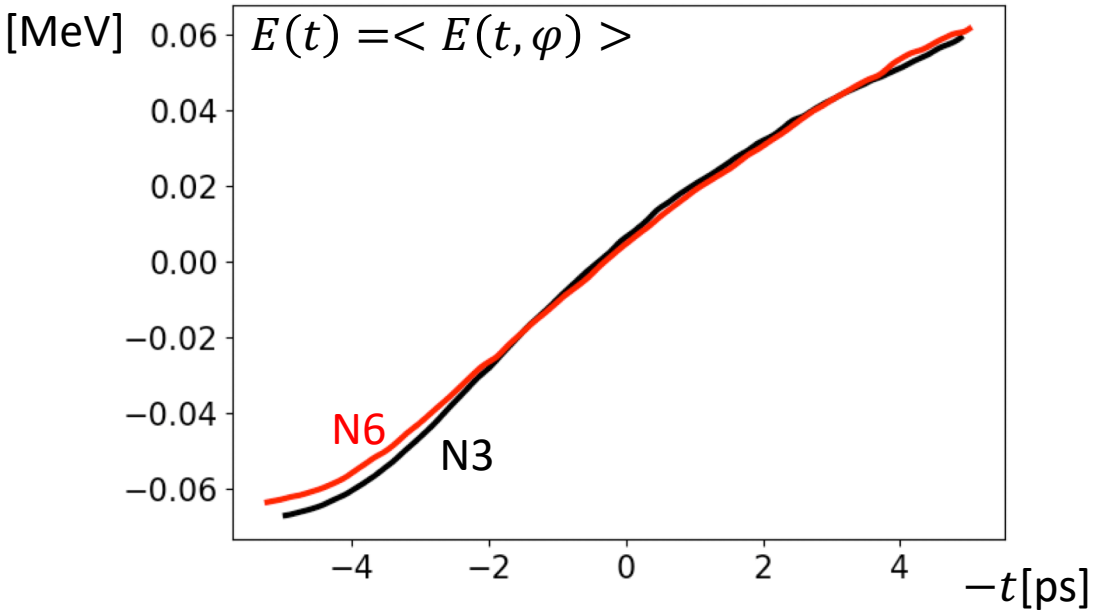

[MeV]
N3
φ = -4
φ = -2
φ = 0
φ = 2
φ = 4
$E_0 = 7.16$ MeV
$\varphi_0 = 0.26$ deg
$-t$[ps]

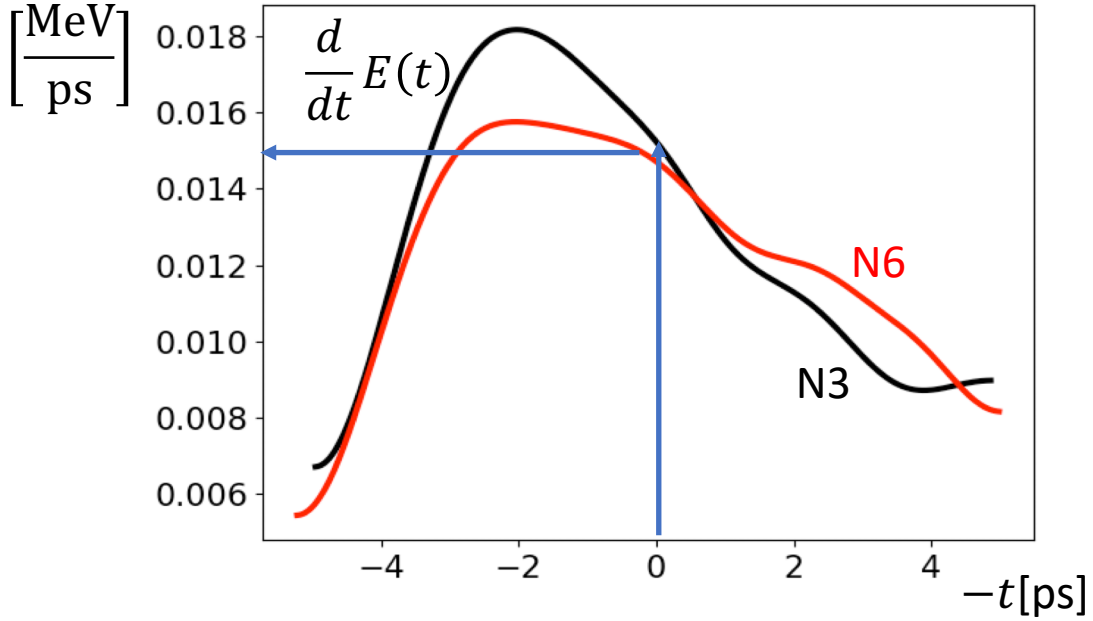

[MeV]
N6
φ = -4
φ = -2
φ = 0
φ = 2
φ = 4
$E_0 = 7.18$ MeV
$\varphi_0 = 0.10$ deg
$-t$[ps]

500 pC (N3, N6)


[MeV]
$E(t,\varphi) = y_M(t,\varphi) - y_{RF}(t,\varphi)$
φ = -4:-2:0:2:4
N3
$-t$[ps]


$E(t,\varphi) = y_M(t,\varphi) - y_{RF}(t,\varphi)$
φ = -4:-2:0:2:4
N6
$-t$[ps]

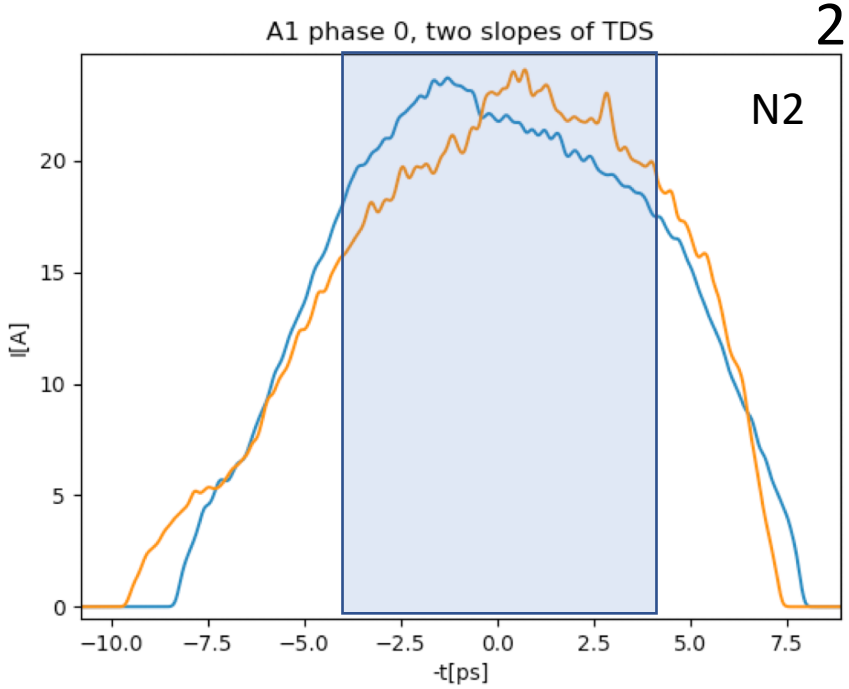

[MeV]
$E(t) =< E(t,\varphi) >$
N6
N3
$-t$[ps]

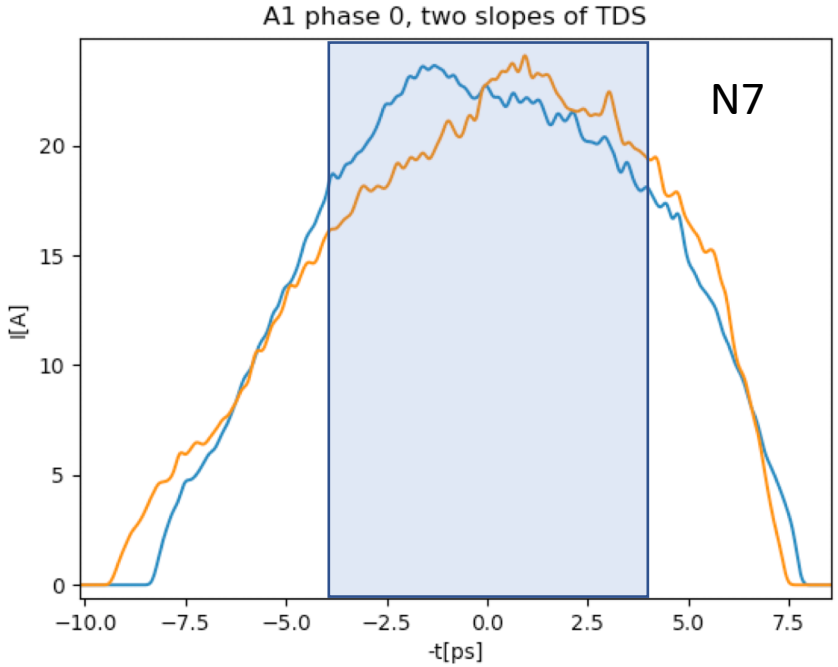

$\left[\frac{\text{MeV}}{\text{ps}}\right]$
$\frac{d}{dt}E(t)$
N6
N3
$-t$[ps]

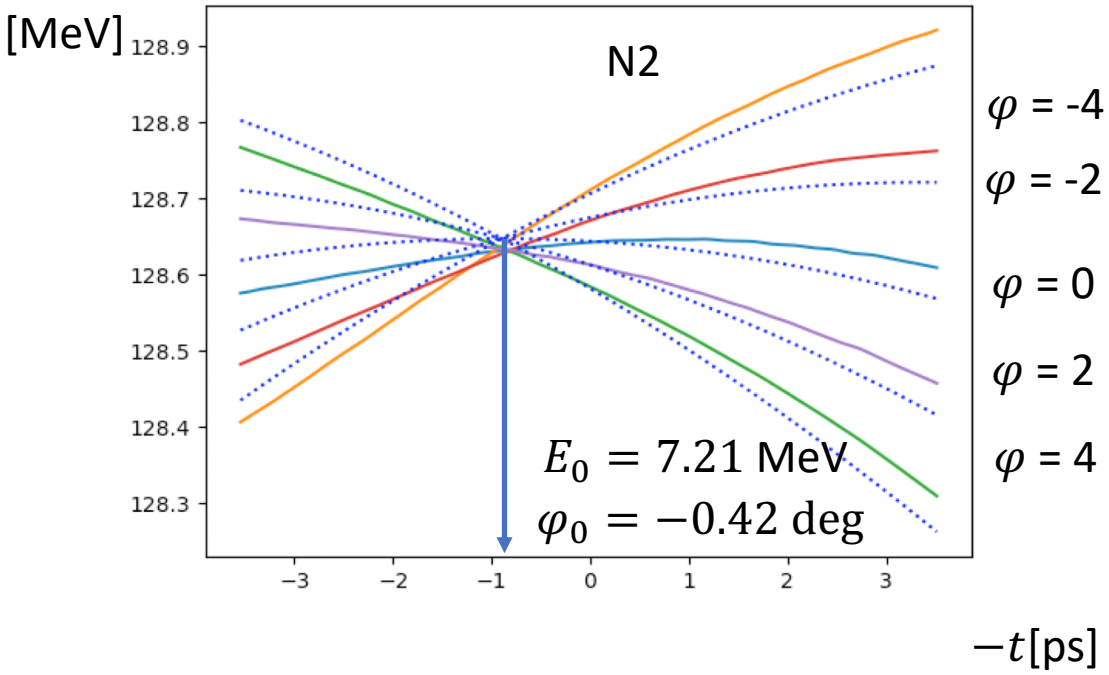
Experimental results (14.05.2020).

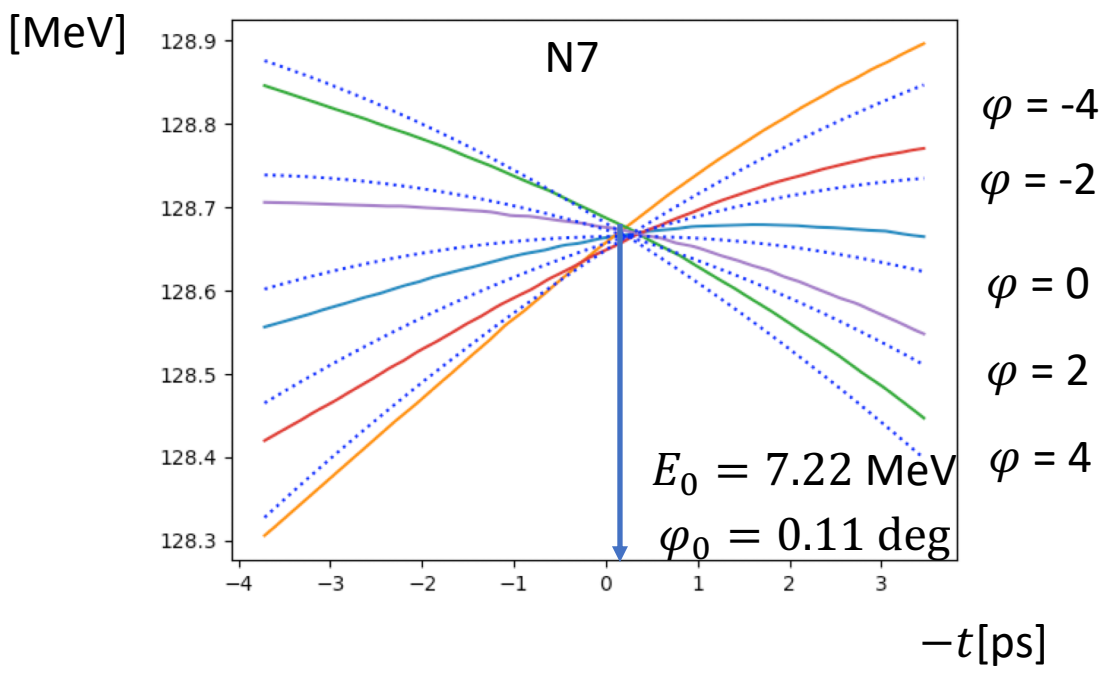
N	Charge, pC	Phase shift according to IntelliPhase, deg	On-crest phase measured by IntelliPhase, deg
1.	100	**0 (ref)**	**0(ref)**
2.	250	0	-
3.	500	0	-
4.	750	0	0.61
5.	750	0.61	0
6.	500	0.26	0
7.	250	-0.44	0
8.	100	-1.00	0

250 pC (N2, N7)

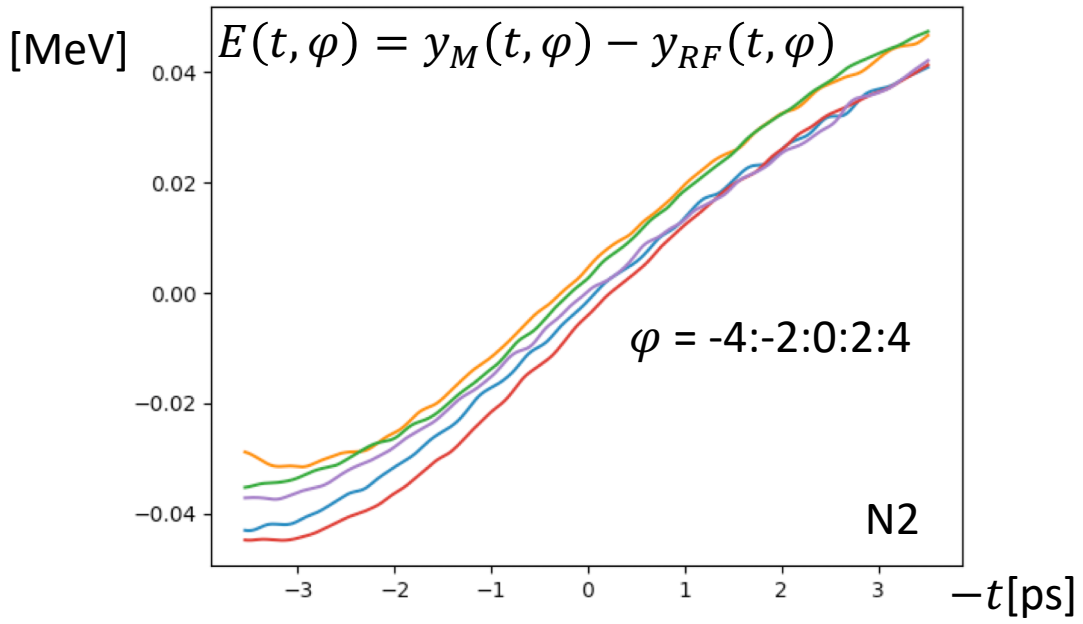

A1 phase 0, two slopes of TDS
N2
I[A]
-t[ps]

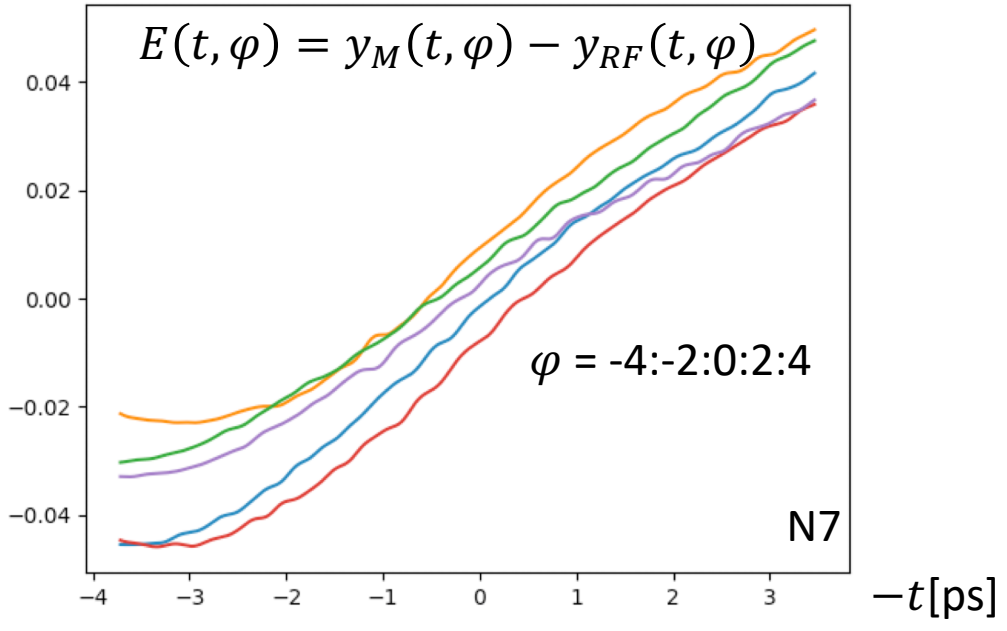

A1 phase 0, two slopes of TDS
N7
I[A]
-t[ps]

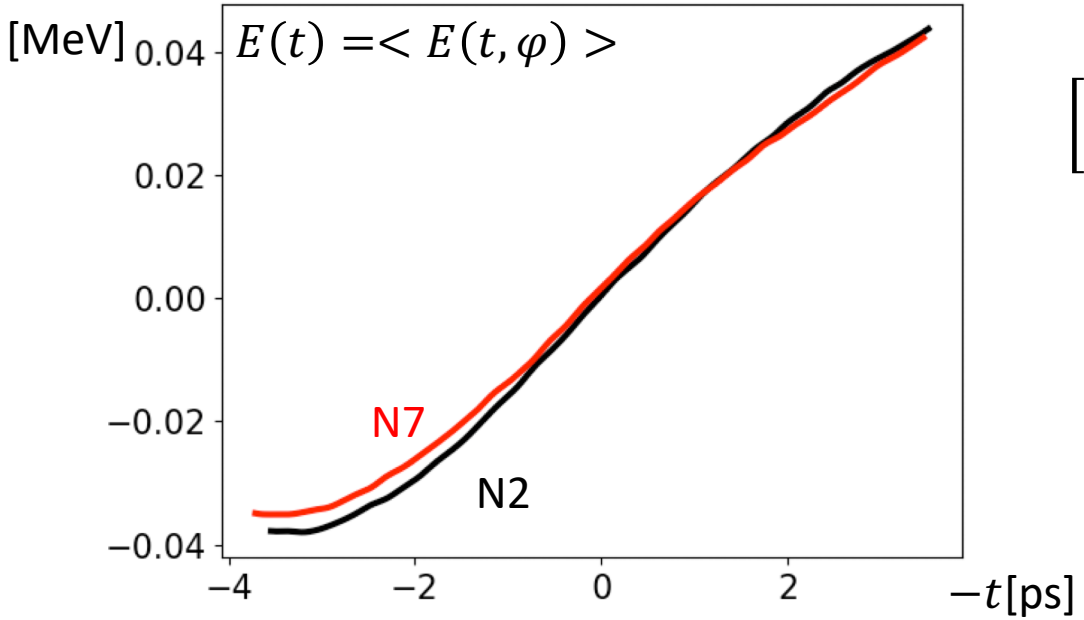

[MeV]
N2
φ = -4
φ = -2
φ = 0
φ = 2
φ = 4
$E_0 = 7.21$ MeV
$\varphi_0 = -0.42$ deg
$-t$[ps]

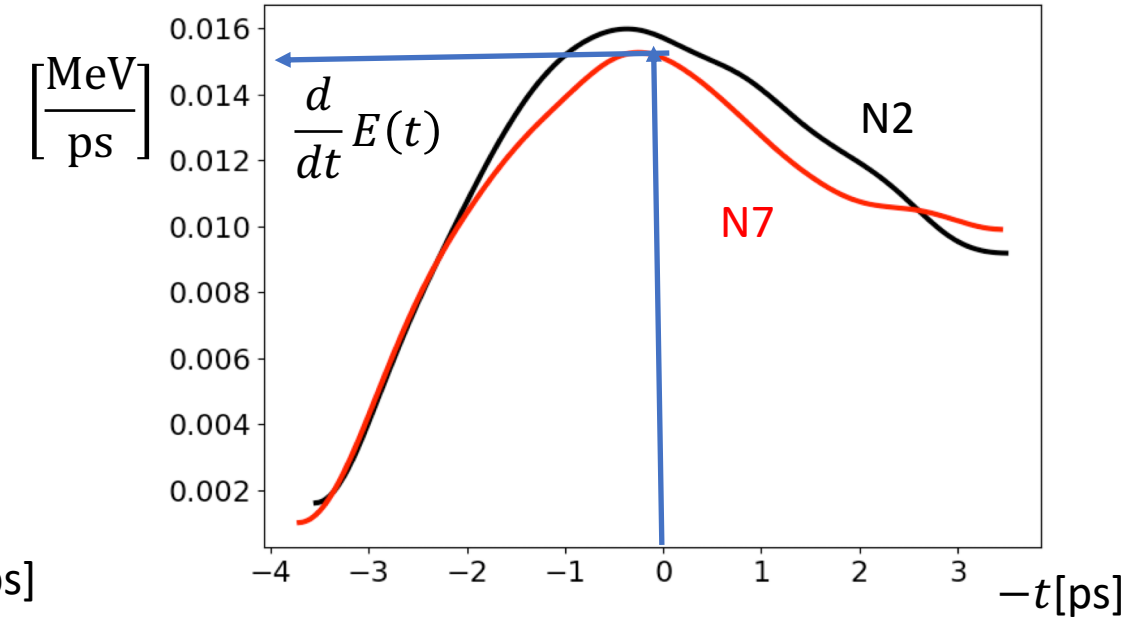

[MeV]
N7
φ = -4
φ = -2
φ = 0
φ = 2
φ = 4
$E_0 = 7.22$ MeV
$\varphi_0 = 0.11$ deg
$-t$[ps]

250 pC (N2, N7)


[MeV]
$E(t,\varphi) = y_M(t,\varphi) - y_{RF}(t,\varphi)$
φ = -4:-2:0:2:4
N2
$-t$[ps]


$E(t,\varphi) = y_M(t,\varphi) - y_{RF}(t,\varphi)$
φ = -4:-2:0:2:4
N7
$-t$[ps]

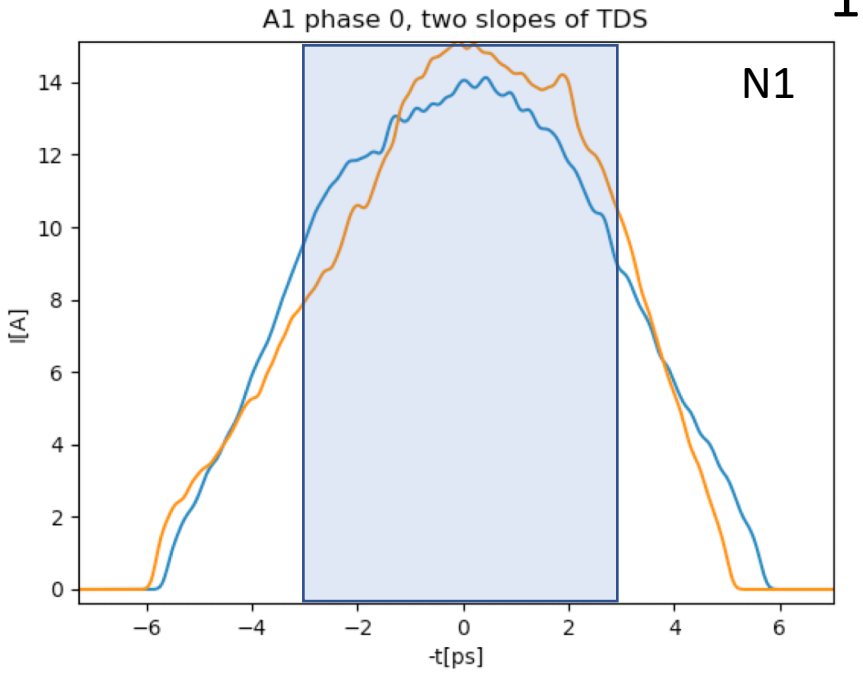

[MeV]
$E(t) =< E(t,\varphi) >$
N7
N2
$-t$[ps]

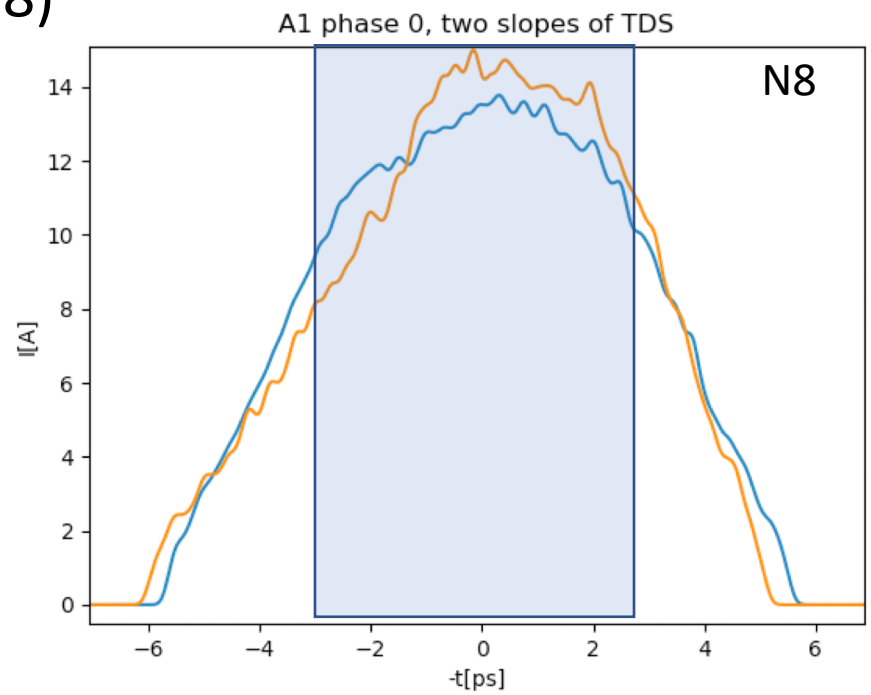

$\left[\frac{\text{MeV}}{\text{ps}}\right]$
$\frac{d}{dt}E(t)$
N2
N7
$-t$[ps]

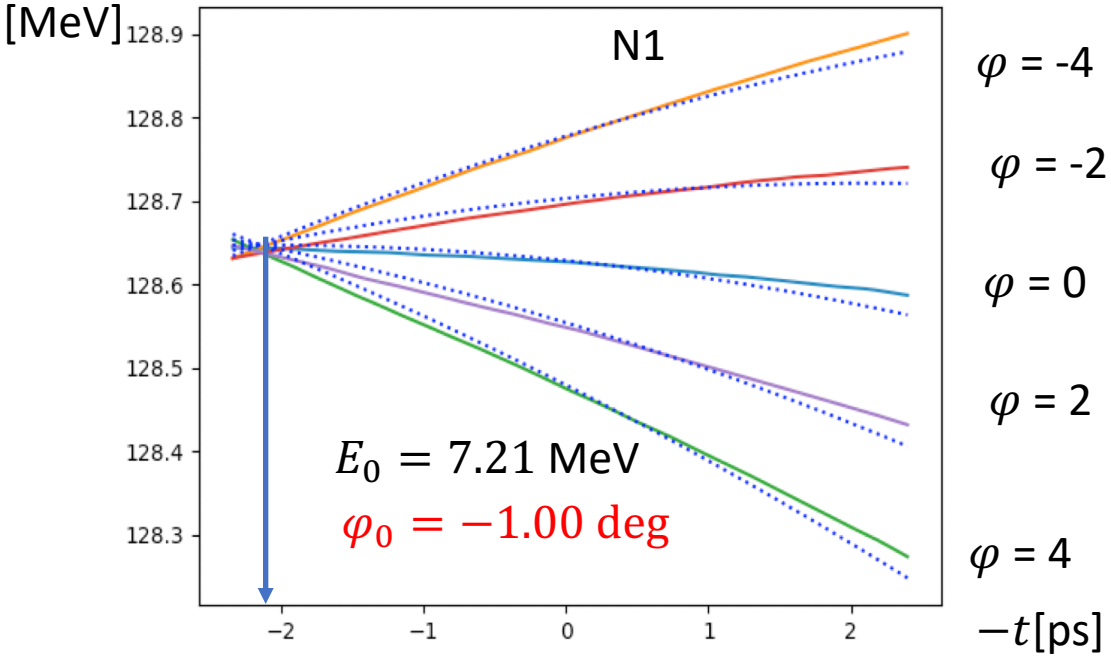
Experimental results (14.05.2020).

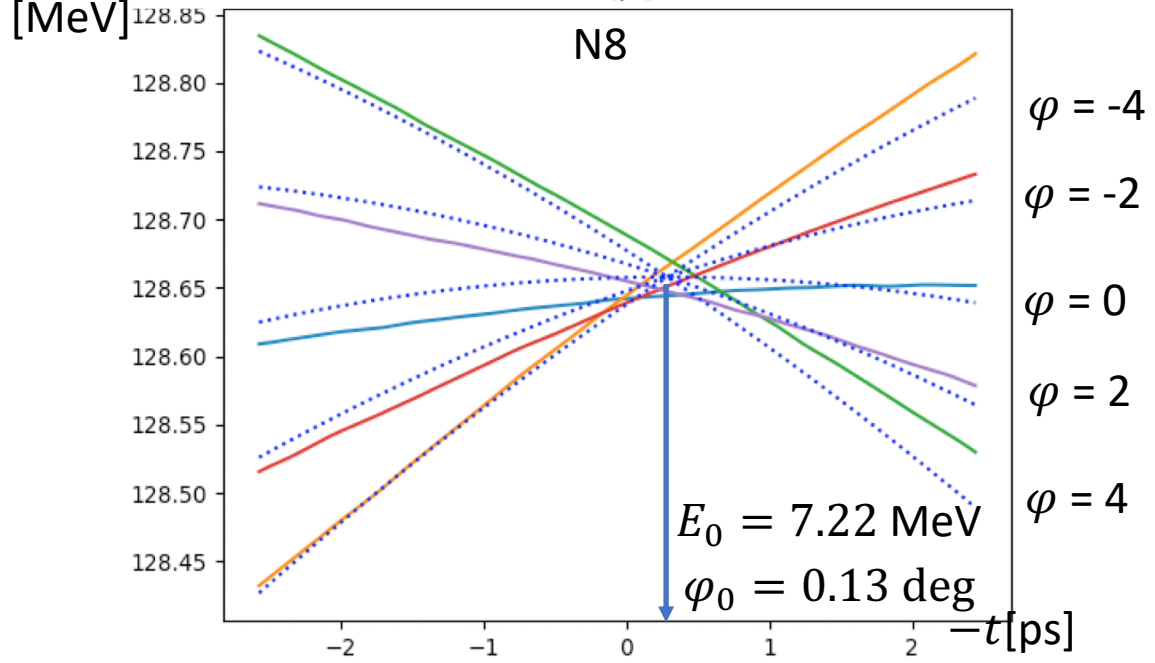
N	Charge, pC	Phase shift according to IntelliPhase, deg	On-crest phase measured by IntelliPhase, deg
1.	100	**0 (ref)**	**0(ref)**
2.	250	0	-
3.	500	0	-
4.	750	0	0.61
5.	750	0.61	0
6.	500	0.26	0
7.	250	-0.44	0
8.	100	-1.00	0

100 pC (N1, N8)

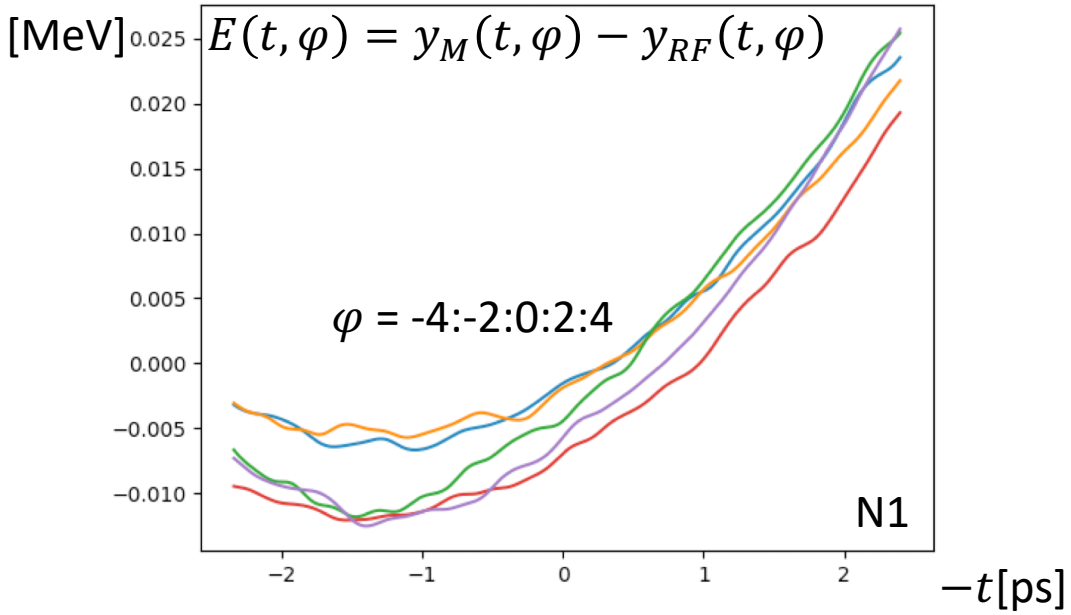

A1 phase 0, two slopes of TDS
N1
I[A]
-t[ps]

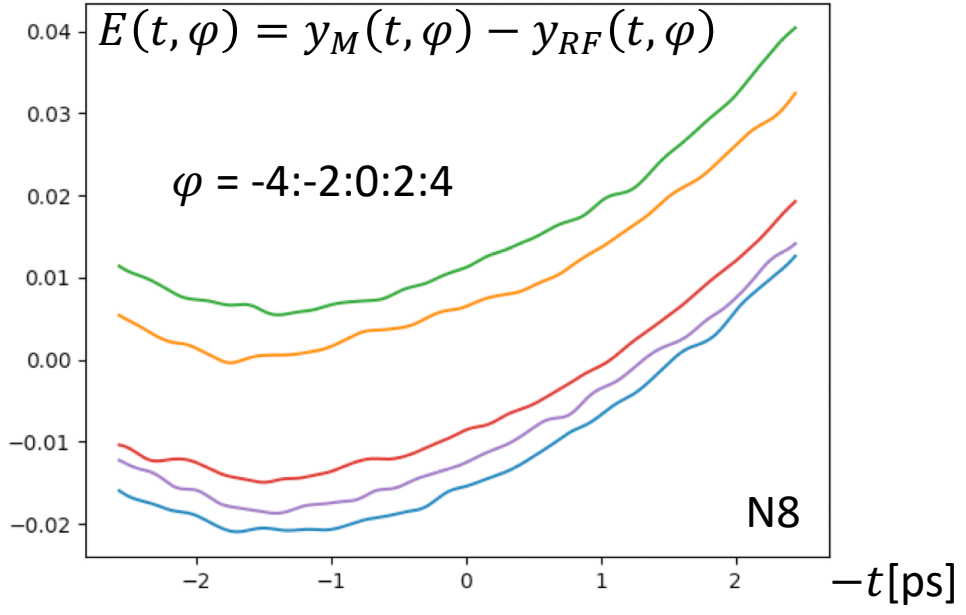

A1 phase 0, two slopes of TDS
N8
I[A]
-t[ps]

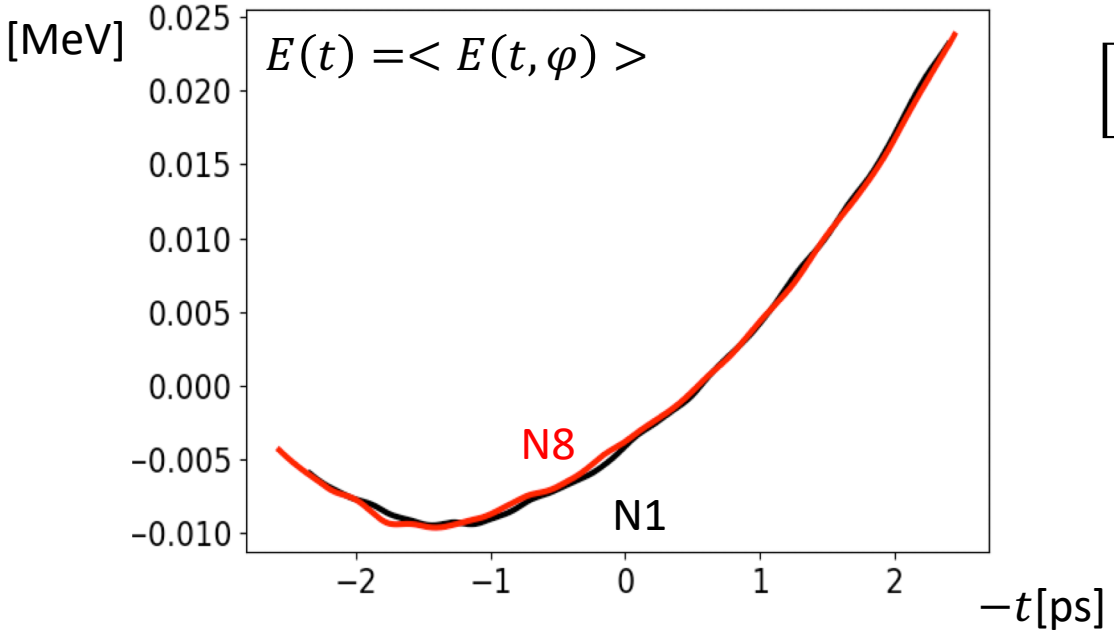

[MeV]
N1
$E_0 = 7.21$ MeV
$\varphi_0 = -1.00$ deg
φ = -4
φ = -2
φ = 0
φ = 2
φ = 4
$-t$[ps]

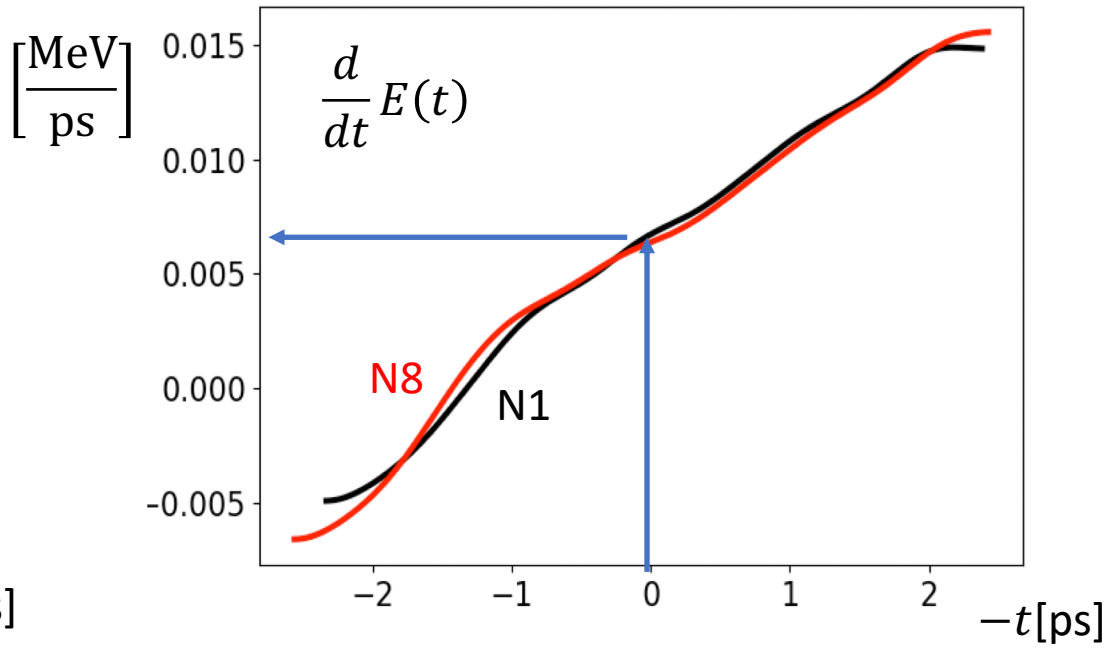

[MeV]
N8
$E_0 = 7.22$ MeV
$\varphi_0 = 0.13$ deg
φ = -4
φ = -2
φ = 0
φ = 2
φ = 4
$-t$[ps]

100 pC (N1, N8)


[MeV]
$E(t,\varphi) = y_M(t,\varphi) - y_{RF}(t,\varphi)$
φ = -4:-2:0:2:4
N1
$-t$[ps]


$E(t,\varphi) = y_M(t,\varphi) - y_{RF}(t,\varphi)$
φ = -4:-2:0:2:4
N8
$-t$[ps]


[MeV]
$E(t) =< E(t,\varphi) >$
N8
N1
$-t$[ps]


$\left[\frac{\text{MeV}}{\text{ps}}\right]$
$\frac{d}{dt}E(t)$
N8
N1
$-t$[ps]

Experimental results (14.05.2020).

N	Charge, pC	Phase shift according to IntelliPhase, deg	Phase measured by IntelliPhase, deg	Phase shift (TDS) φ_0, deg	Phase to the reference (TDS), deg
1.	100	**0 (ref)**	**0(ref)**	-1.00	**-1.00**
2.	250	0	-	-0.42	-0.42
3.	500	0	-	0.26	0.26
4.	750	0	0.61	0.72	0.72
5.	750	0.61	0	0.12	0.73
6.	500	0.26	0	0.10	0.36
7.	250	-0.44	0	0.11	-0.33
8.	100	-1.00	0	0.13	**-0.87**

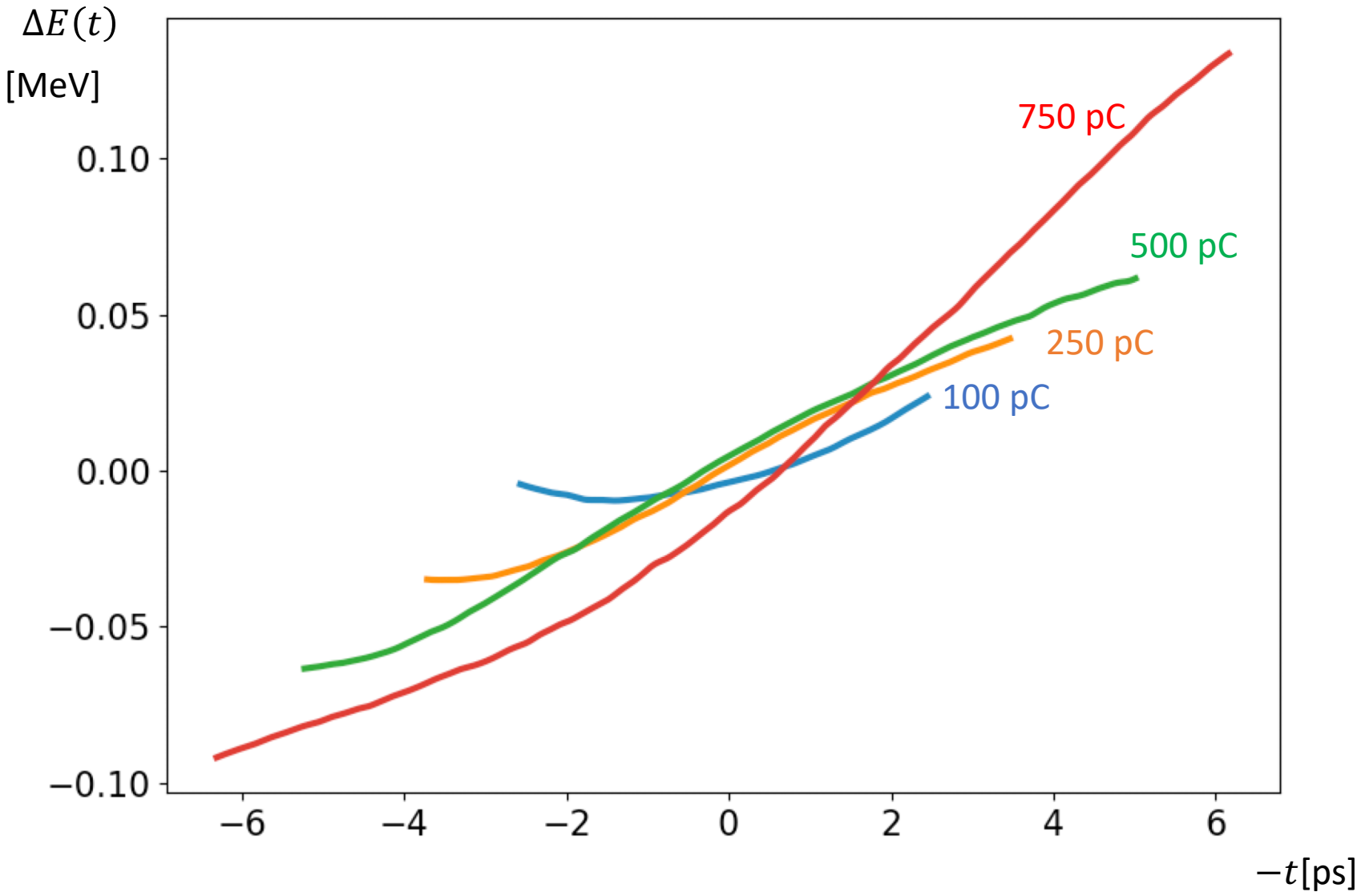
- After initial calibration (N1) a shift of -1 degree has remained for unknown reason
- Other phase calibrations (N4-N8) are accurate with the error less than 0.1 degree
- The on-crest phase shifts by 1.7 degree if charge is changed from 100 pC to 750 pC (can be explained by the bunch lengthening? beam loading?)

Experimental results (14.05.2020).

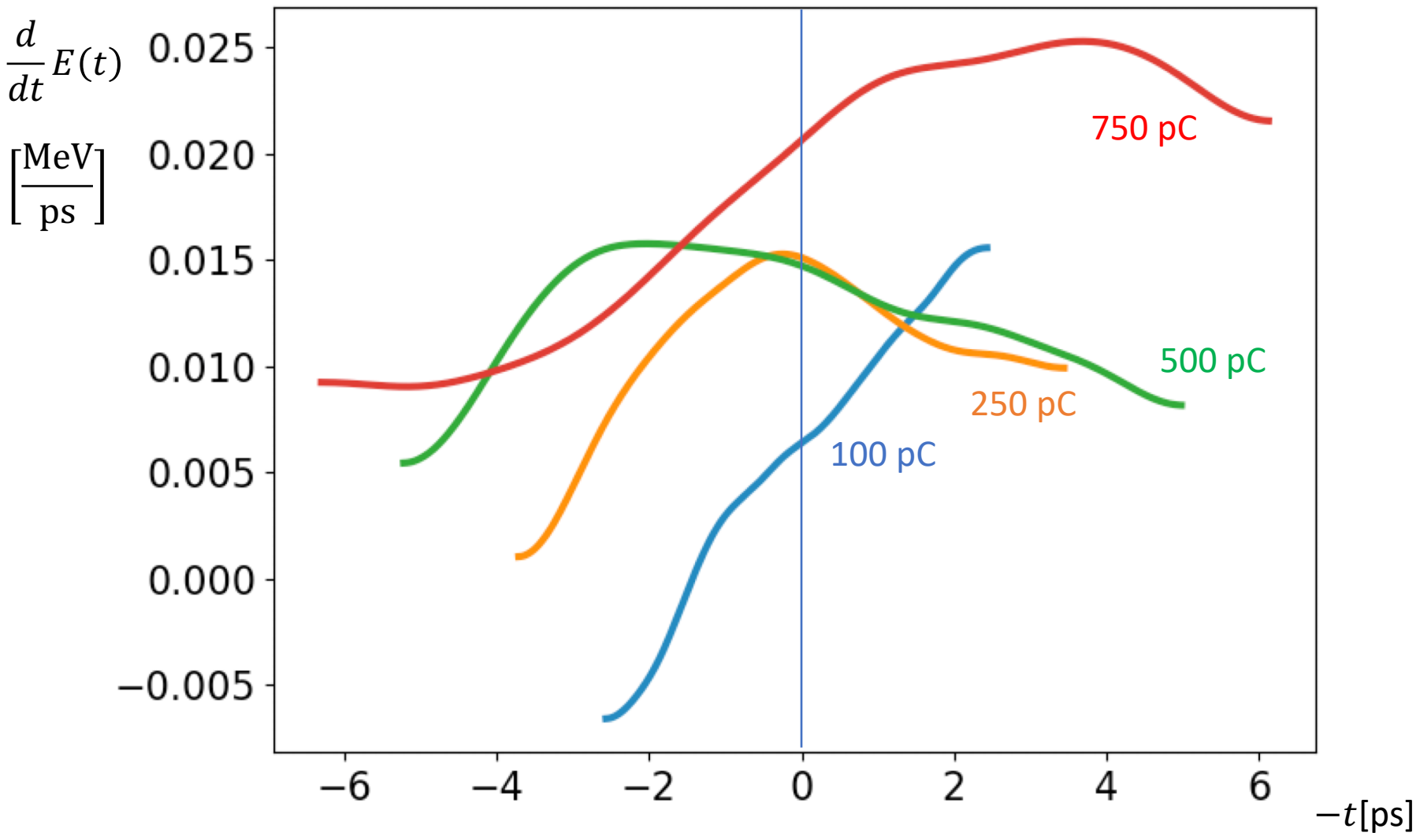
N	Charge, pC	Phase shift according to IntelliPhase, deg	Phase measured by IntelliPhase, deg	Phase shift (TDS) φ_0, deg	Phase to the reference (TDS), deg	Beam energy E_0, MeV	Energy chirp from TDS analysis dE/dt, kV/ps	Bunch length, ps	Peak current, A
1.	100	**0 (ref)**	**0(ref)**	-1.00	**-1.00**	7.21	-7	2.45	14
2.	250	0	-	-0.42	-0.42	7.21	-15	3.70	24
3.	500	0	-	0.26	0.26	7.16	-15	5.20	35
4.	750	0	0.61	0.72	0.72	7.14	-20	6.30	40
5.	750	0.61	0	0.12	0.73	7.15	-20	6.30	40
6.	500	0.26	0	0.10	0.36	7.18	-15	5.20	35
7.	250	-0.44	0	0.11	-0.33	7.22	-15	3.70	24
8.	100	-1.00	0	0.13	**-0.87**	7.22	-7	2.45	14

- After initial calibration (N1) a shift of -1 degree has remained for unknown reason
- Other phase calibrations (N4-N8) are accurate with the error less than 0.1 degree
- The on-crest phase shifts by 1.7 degree if charge is changed from 100 pC to 750 pC (can be explained by the bunch lengthening? beam loading?)

Self-induced phase space



Self-induced energy chirp



Summary

- The measurement of RF phase by energy scan (“IntelliPhase” software) has a systematic error of 0.1 degree,
- We successfully subtracted the RF curvature and have found the “self fields” phase space (due to the self-fields only),
- The energy chirp increases with the charge,
- The used method of the measurements and the analysis produces consistent results,
- The approach suggested in this talk can be used as a more accurate one in measurement of the RF phase,
- A comparison with beam dynamics simulations is highly desired (could require several iterations of the measurements).