Longitudinal Mitigations of Transverse Space Charge Effects

Simon Albright

Acknowledgements: M. E. Angoletta, H. Bartosik, G. P. Di Giovanni, A. Findlay, S. Hancock, A. Huschauer, B. Mikulec, A. Oeftiger, M. Paoluzzi , E. Shaposhnikova, et al

Contents

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- Established longitudinal space charge mitigation
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- PSB – Maximum brightness proton beams
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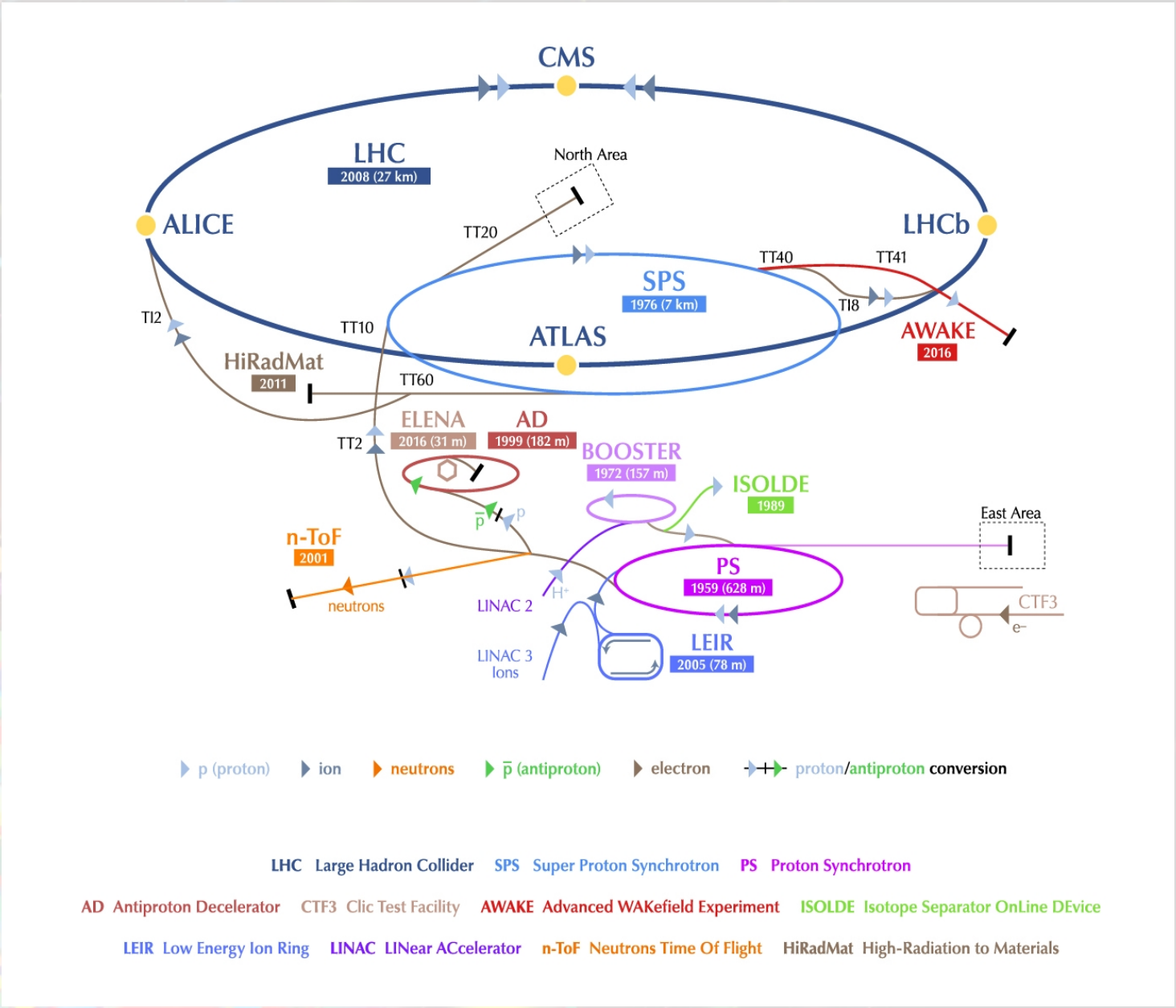
- Conclusion


CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
ELENA
2016 (31 m)
AD
1999 (182 m)
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BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
neutrons
LINAC 2
LINAC 3
Ions
LEIR
2005 (78 m)
CTF3
e−
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ion
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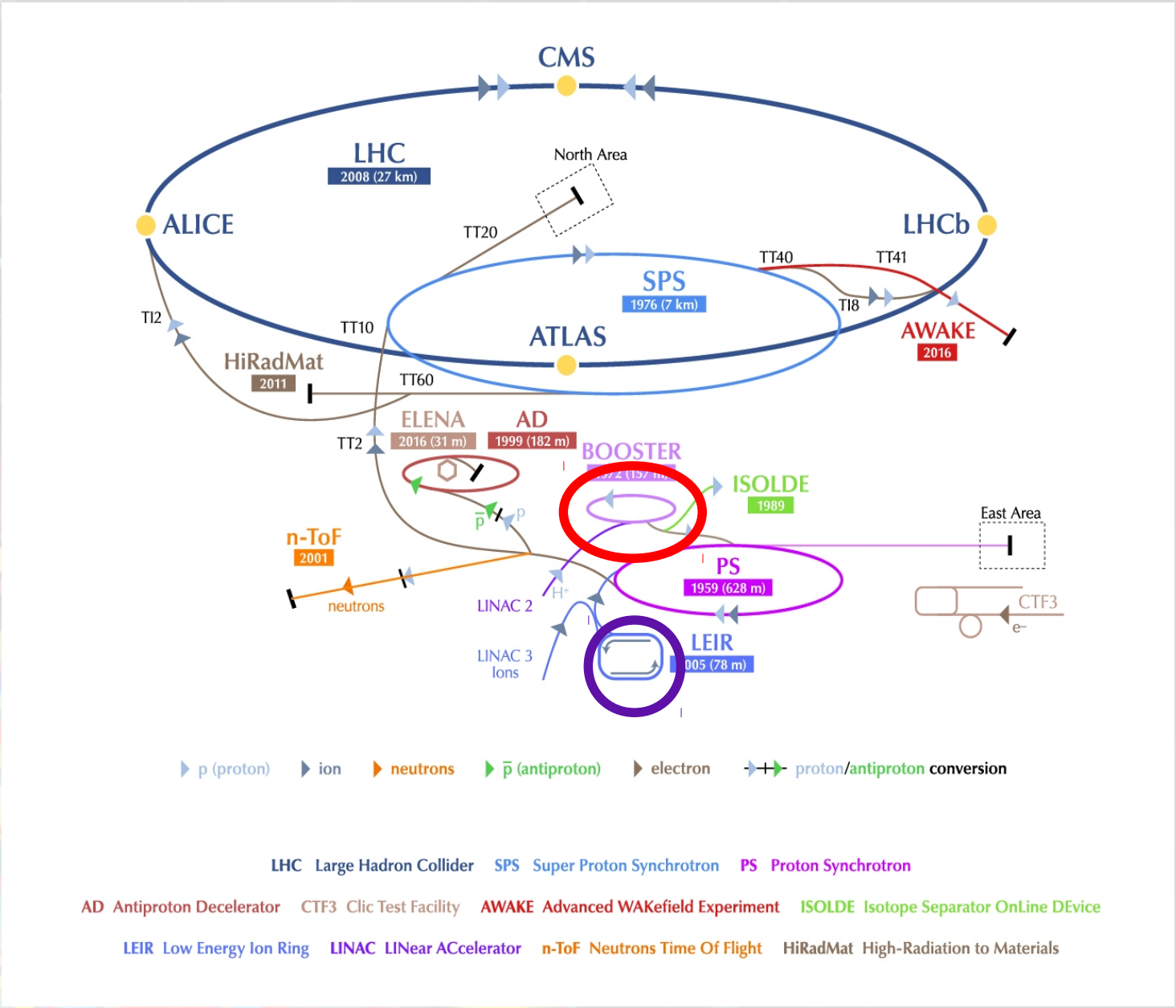
LINAC LINear ACcelerator
n-ToF Neutrons Time Of Flight
HiRadMat High-Radiation to Materials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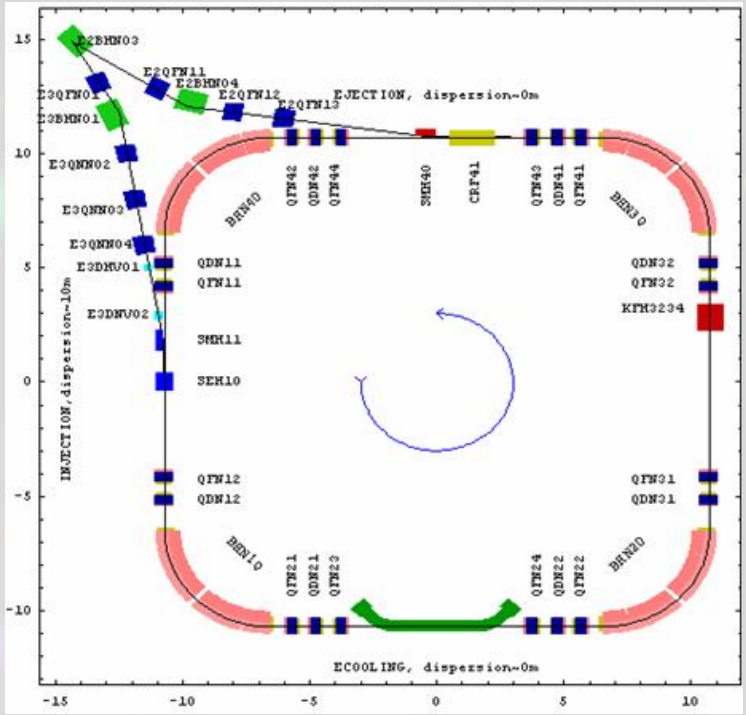
LEIR – Low Energy Ion Ring

- Small machine – average radius = 12.5 m
- 7 multi-turn injections space by 200 ms
- e-cooling during long flat bottom
- Iso-adiabatic RF capture prior to ramp
- RF operated with h=2 + h=4 for high intensity beams
- Broadband Finemet™ RF operated with h=2 + h=4 for high intensity beams



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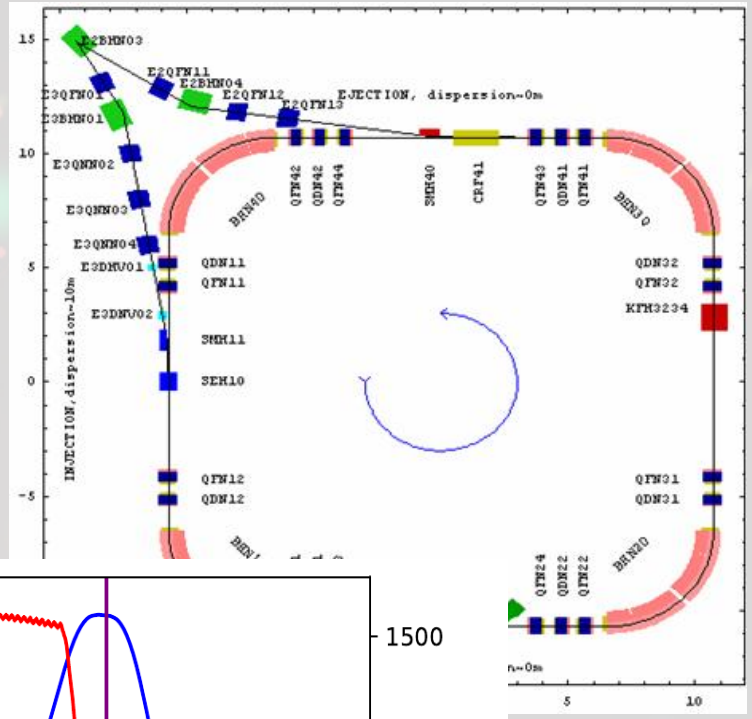
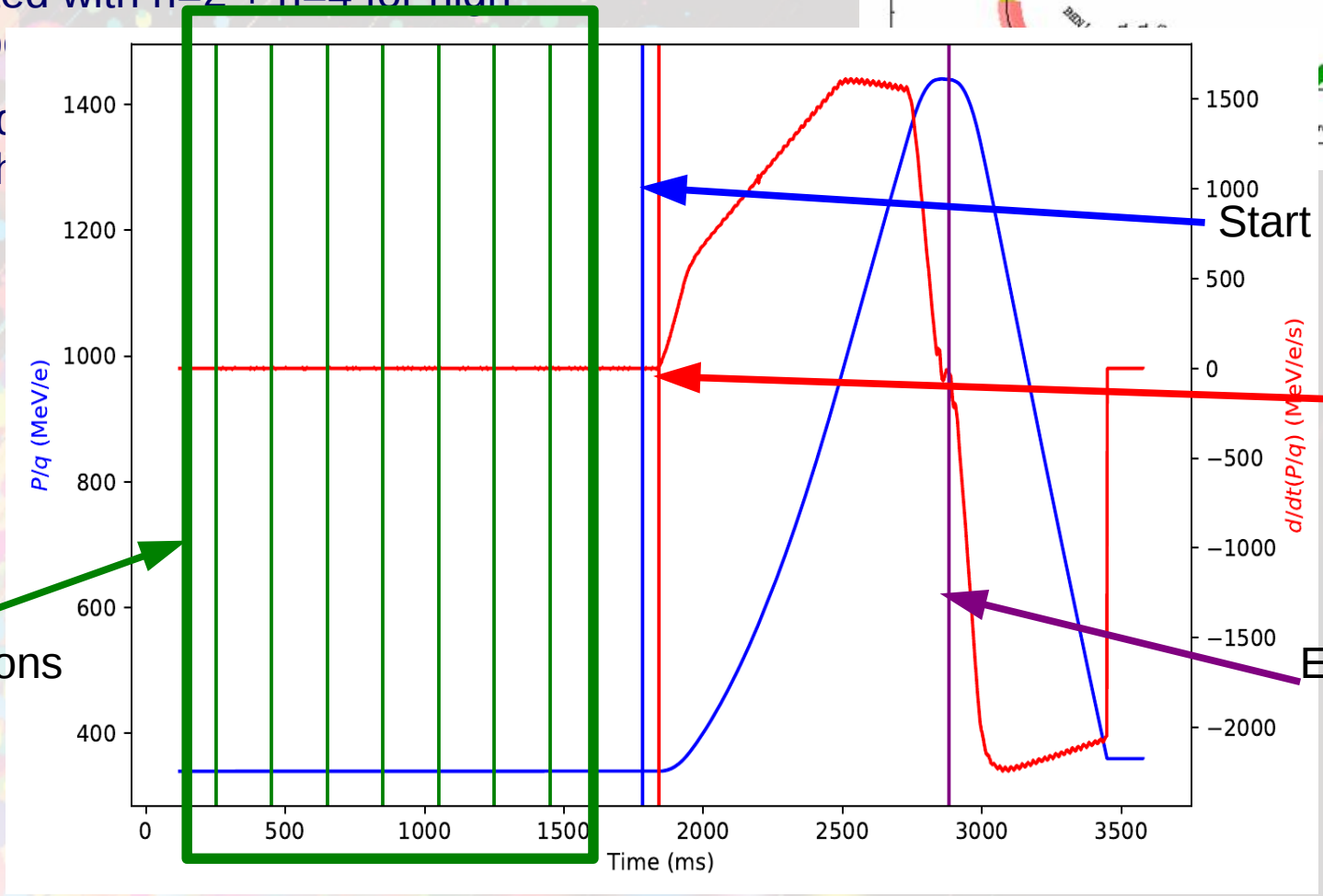
- Broadband + h=4 for h





Start RF capture

Start ramp

Multi-turn injections

Extraction

LEIR – Low Energy Ion Ring

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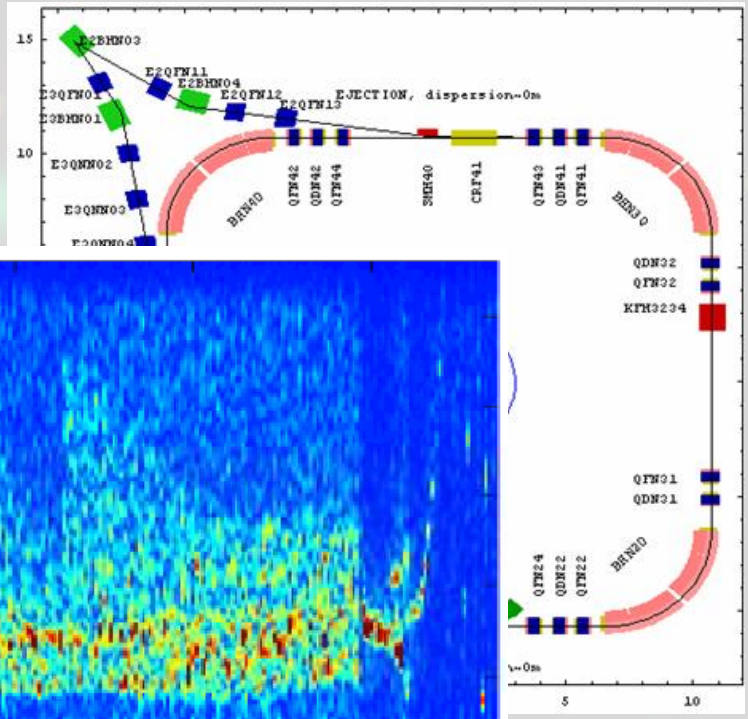
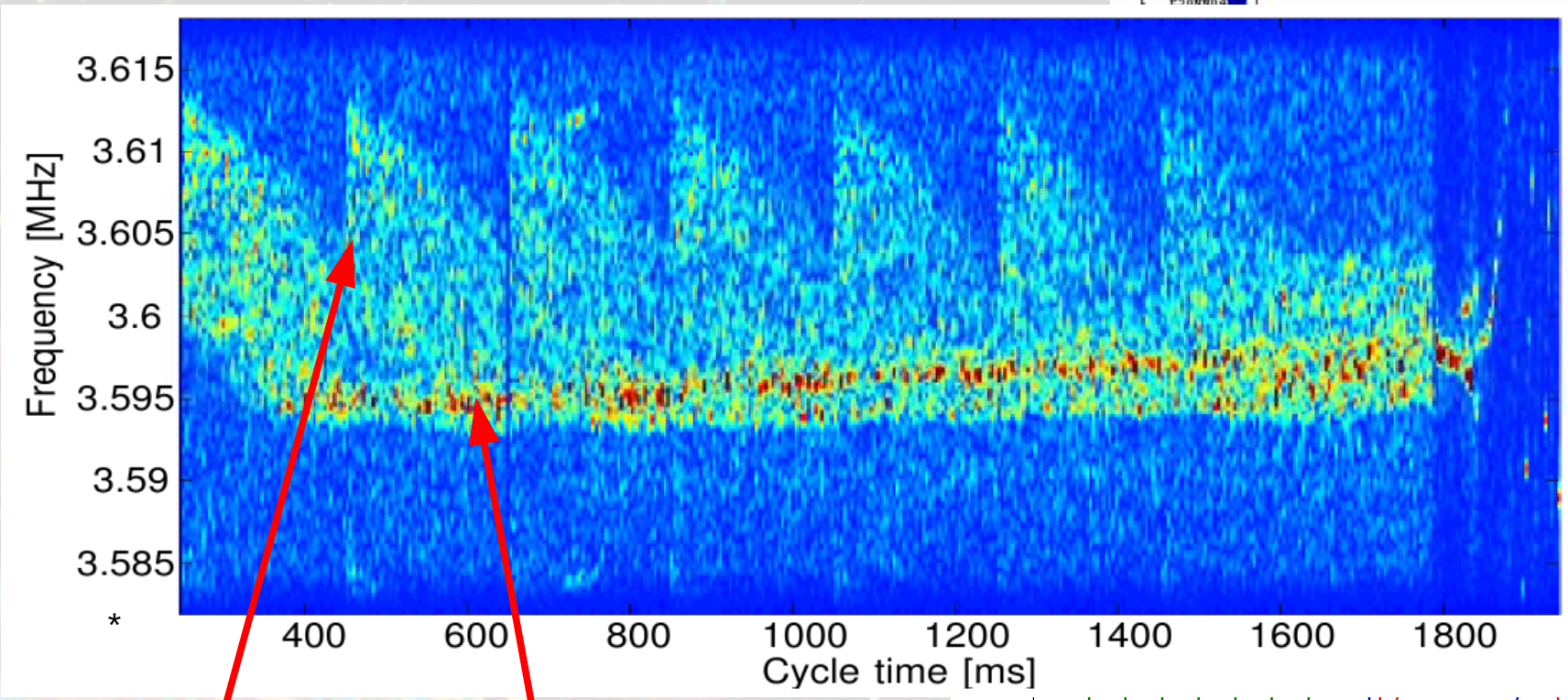
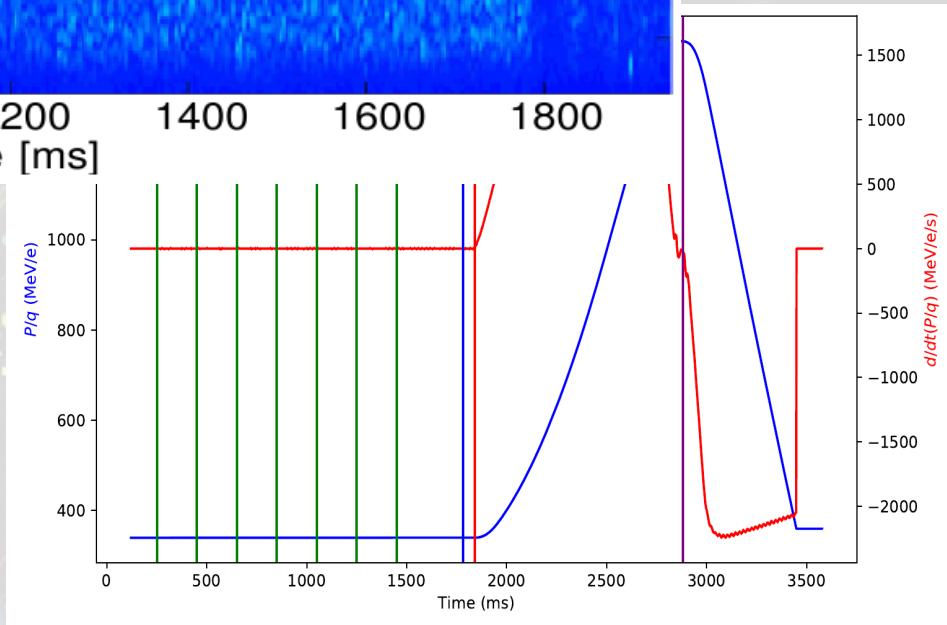




2nd Injection

Cooled stack



* A. Huschauer, Preparing LEIR for the HL-LHC Era, BE-Seminar, 02/06/17

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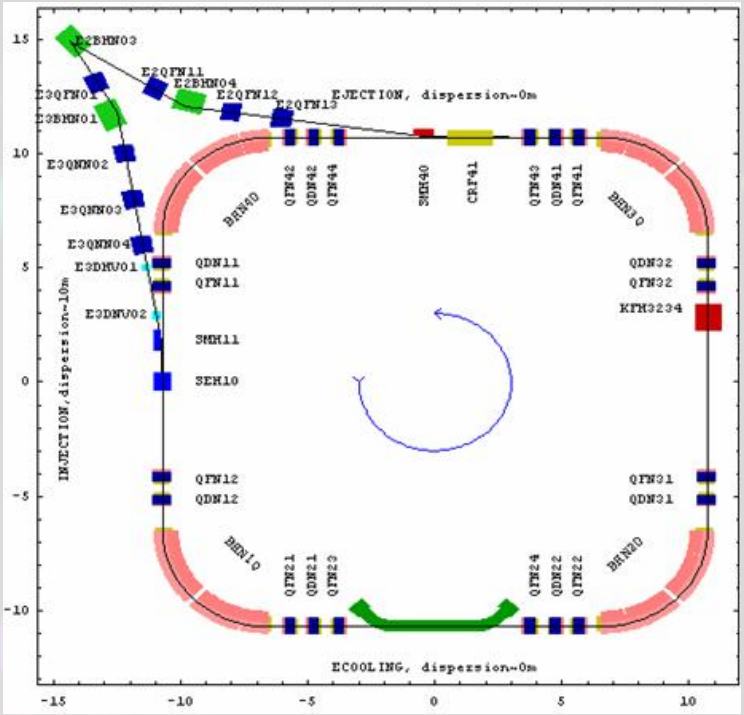

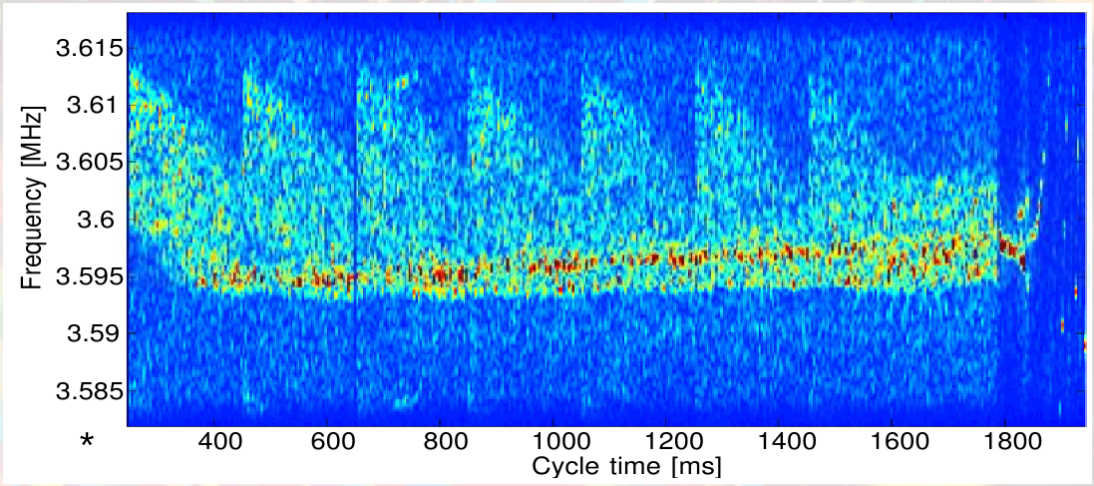

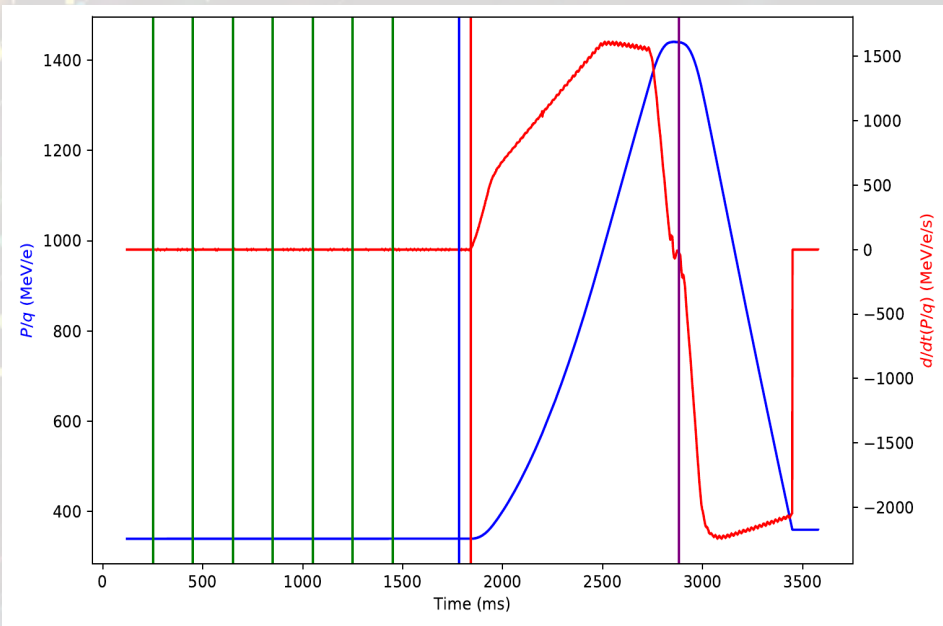

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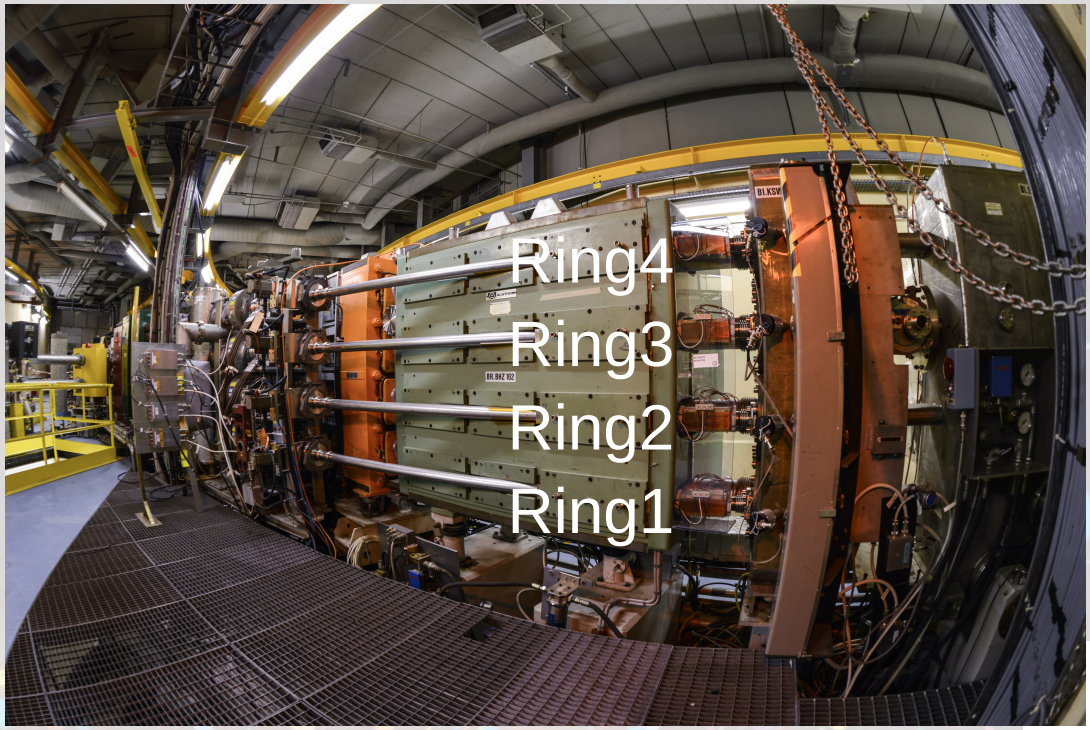
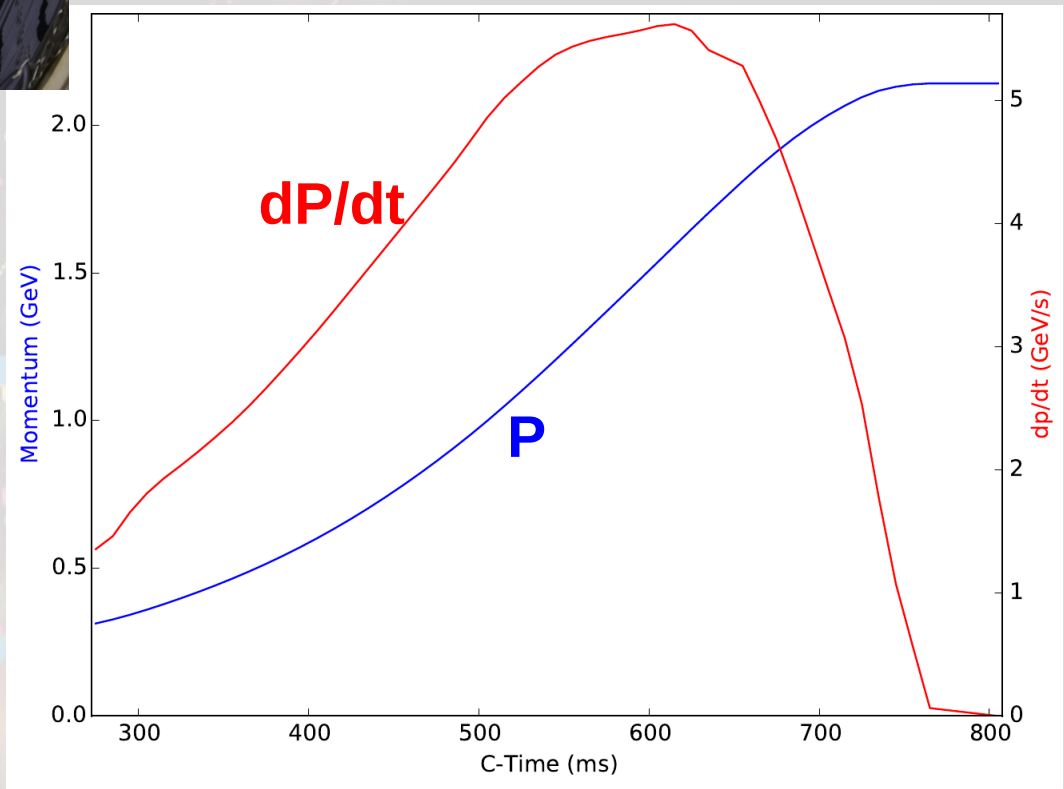
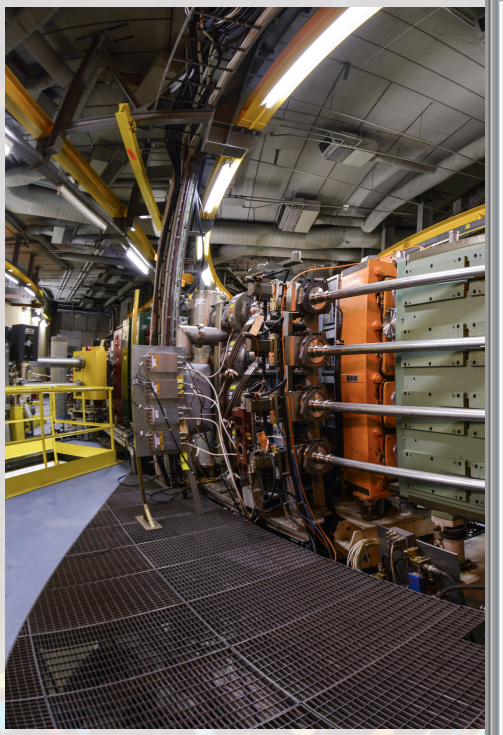
PSB – Proton Synchrotron Booster



- 4 **almost** identical rings
- Common magnetic cycle
- Independent RF systems
- Tunable ferrite RF systems at h=1, h=2, h<=16
- Multi-turn injection at non-zero dB/dt
- Broadband Finemet™ test cavity in Ring 4



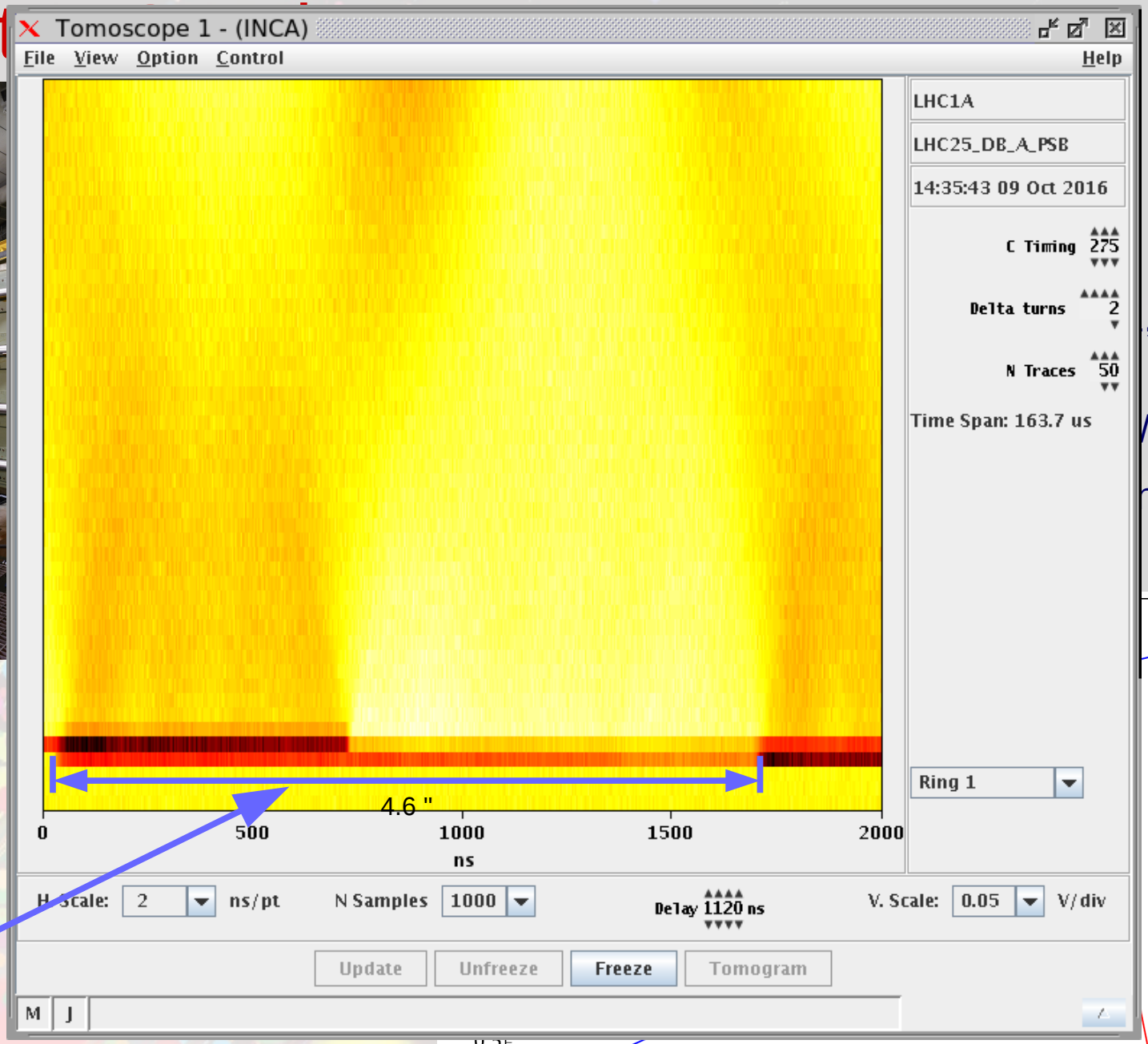
PSB – Prot



, h=2,

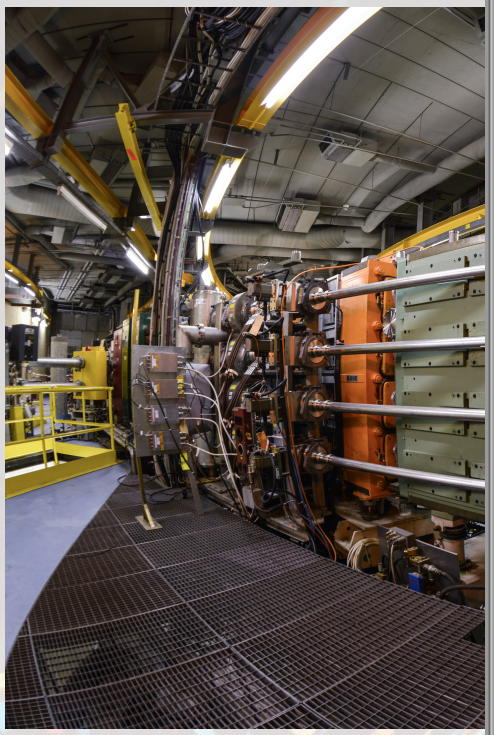
/dt

n Ring 4



1 injected turn

PSB – Prot



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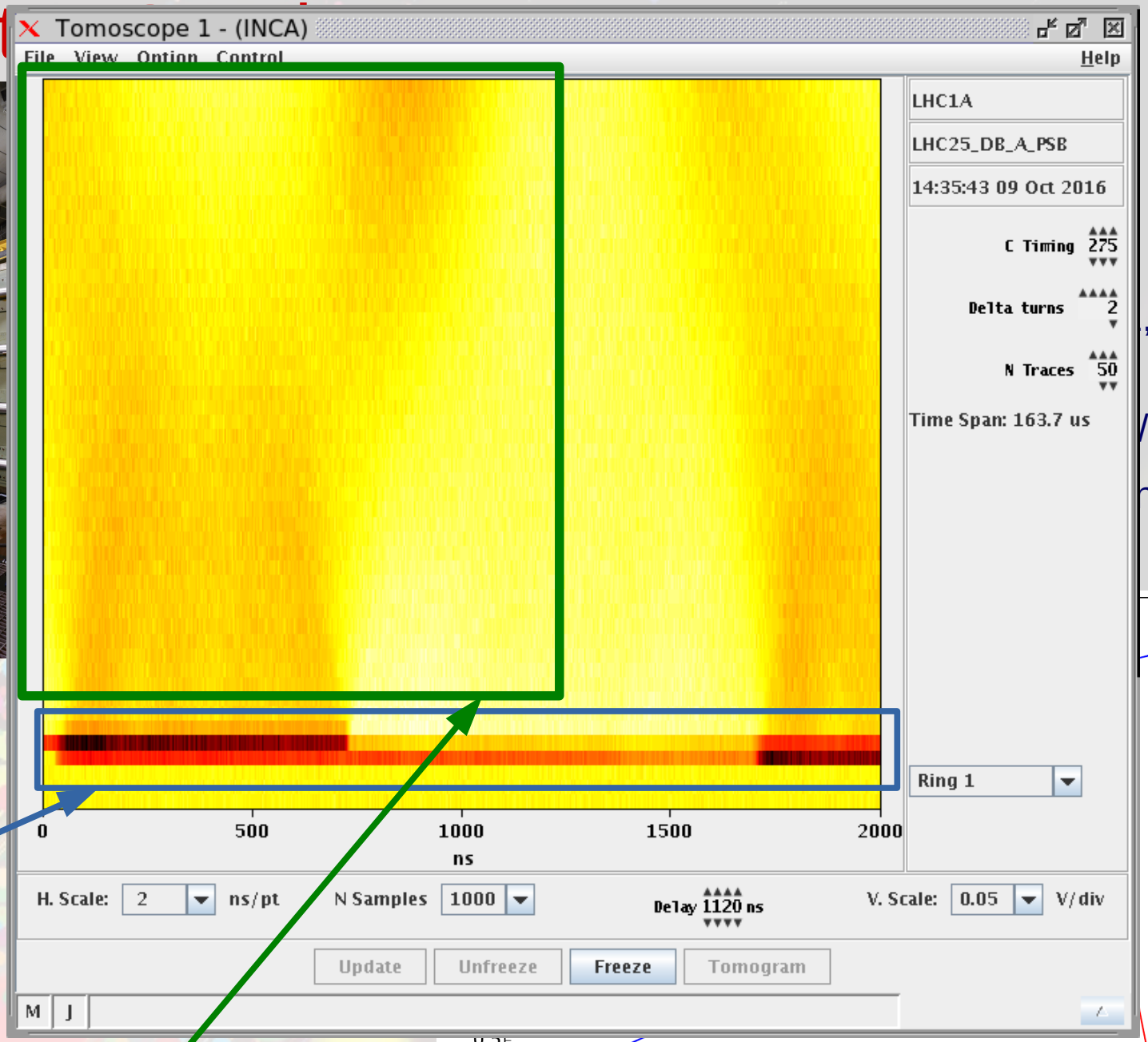
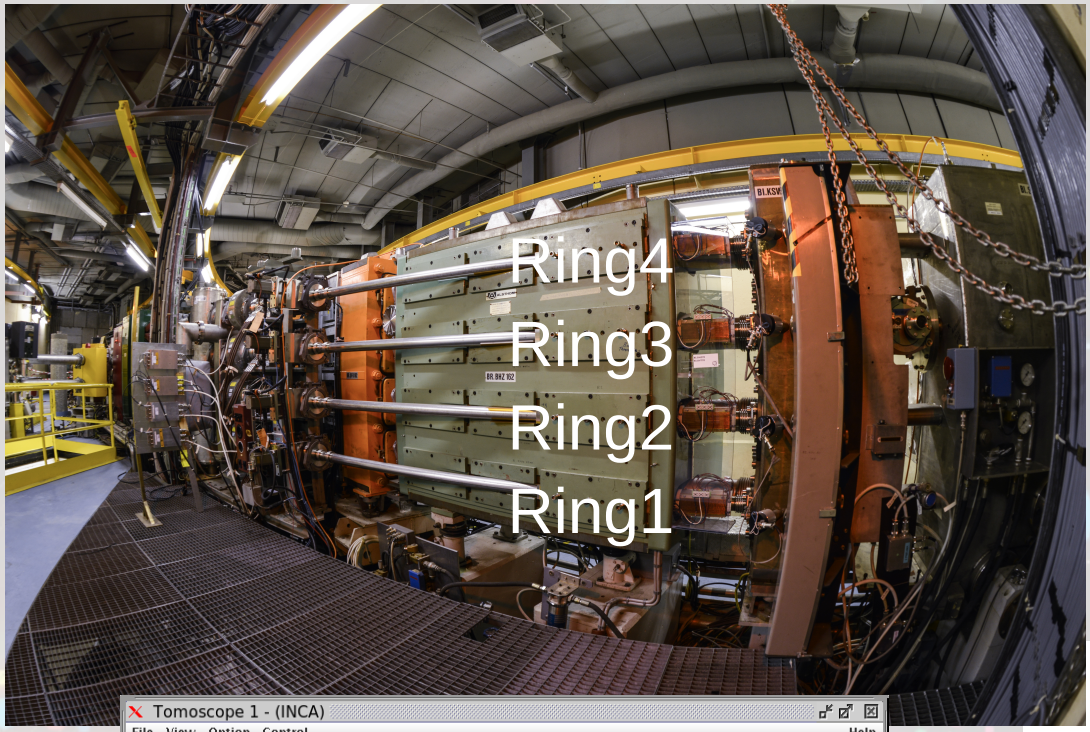


Multi-turn injection

Capture into h1+h2 bucket

PSB – Proton Synchrotron Booster



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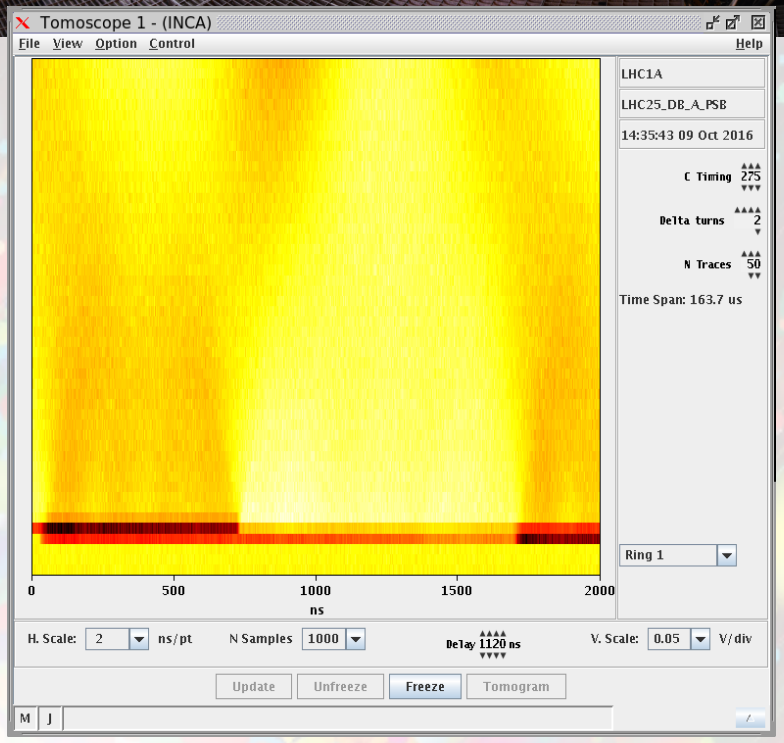

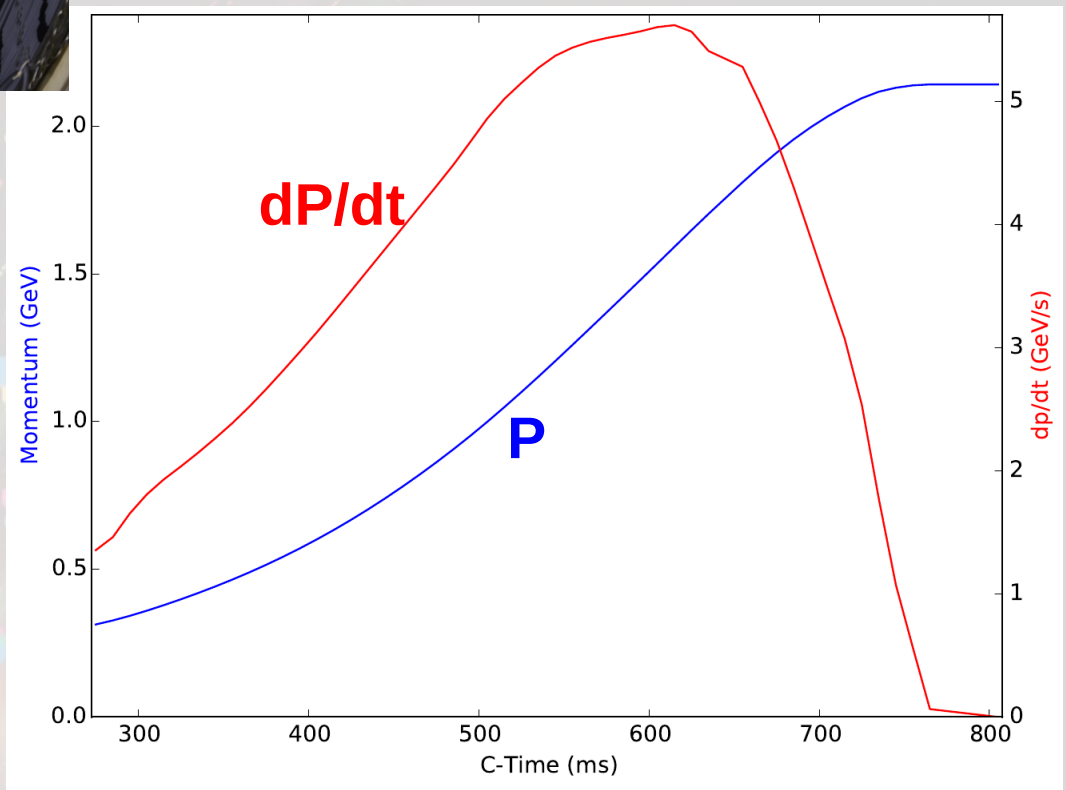

Space Charge Mitigation

$$\Delta Q_{x,y} = -\frac{q\lambda}{8\pi^2\varepsilon_0 m_p c^2 \beta^2 \gamma^3} \oint \frac{\beta_{x,y}(s)}{\sigma_{x,y}(s)\left(\sigma_x(s)+\sigma_y(s)\right)}$$

$$\sigma_x(s) = \sqrt{\frac{\beta_x(s)\varepsilon_x}{\beta\gamma} + D_x^2(s)\delta_{rms}^2}$$

$$\sigma_y(s) = \sqrt{\frac{\beta_y(s)\varepsilon_y}{\beta\gamma}}$$

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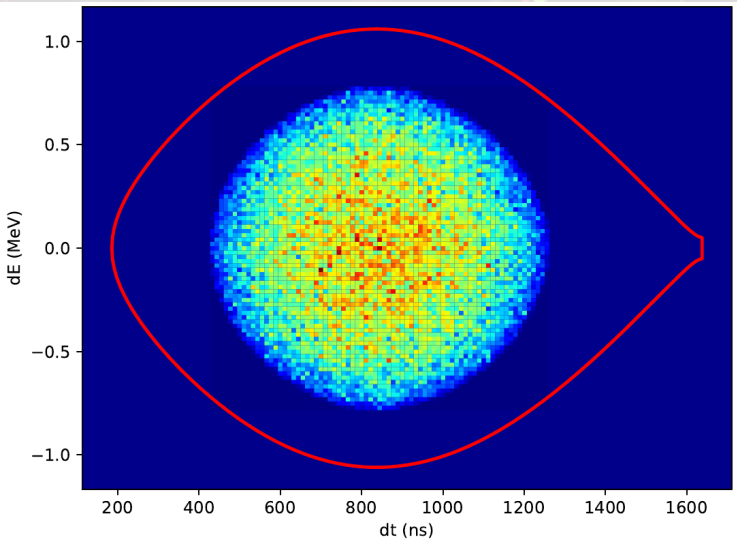
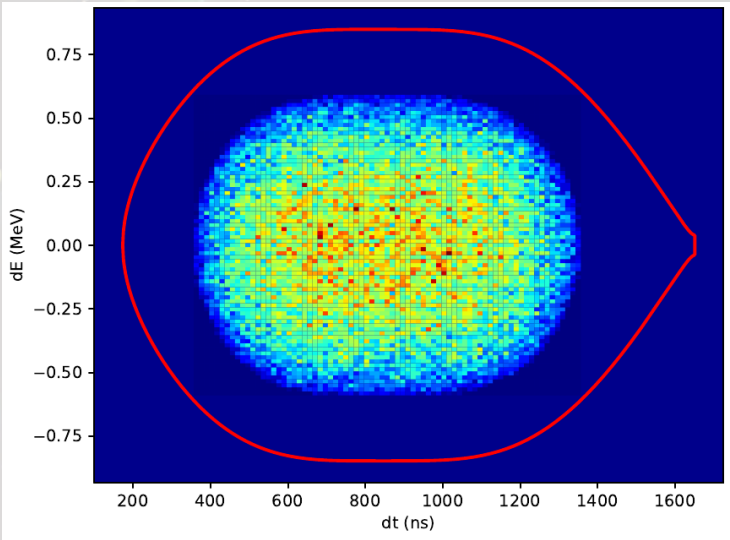
$$\Delta Q_{x,y} = f\left(\lambda, \delta_{RMS}\right)$$

Space Charge Mitigation

Single harmonic



Double harmonic (Bunch Lengthening Mode)



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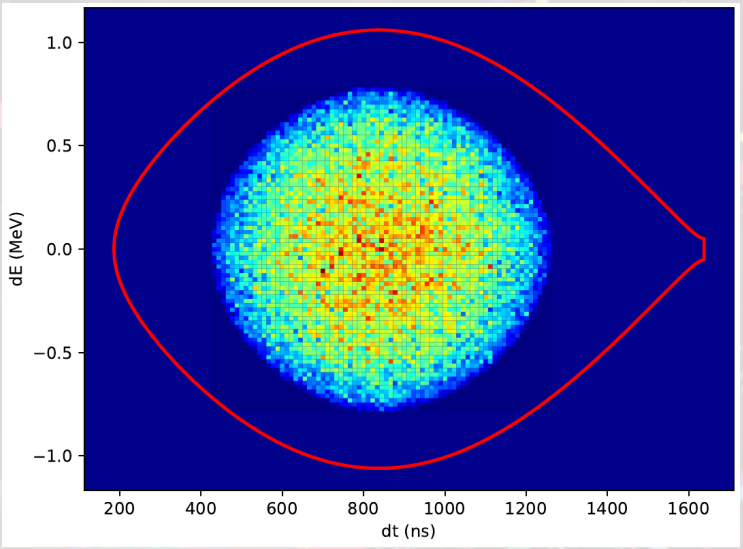

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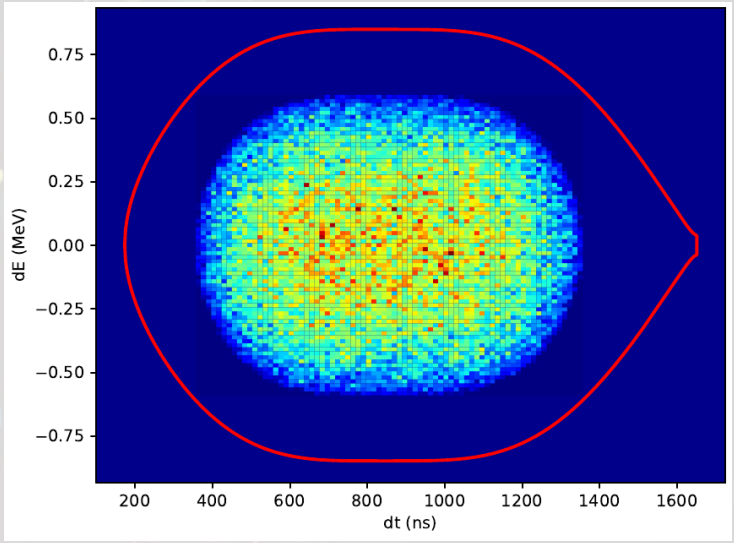
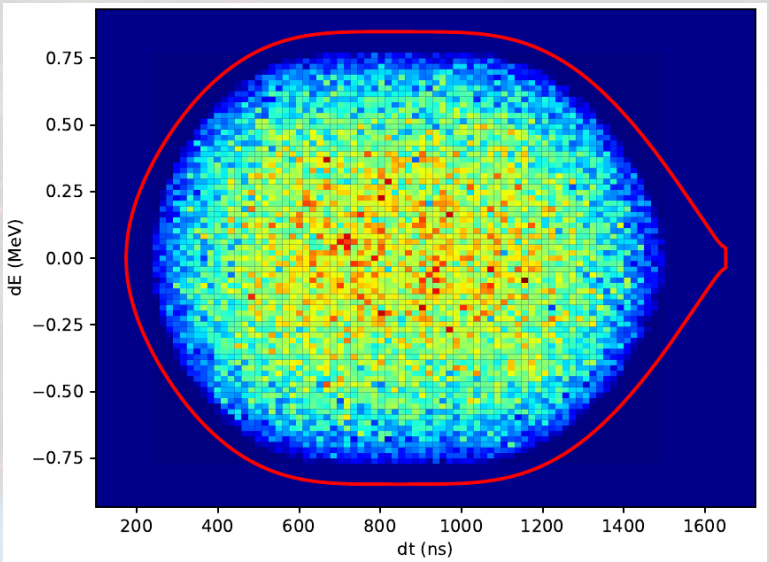


Double harmonic (BLM) + long. emittance blow-up



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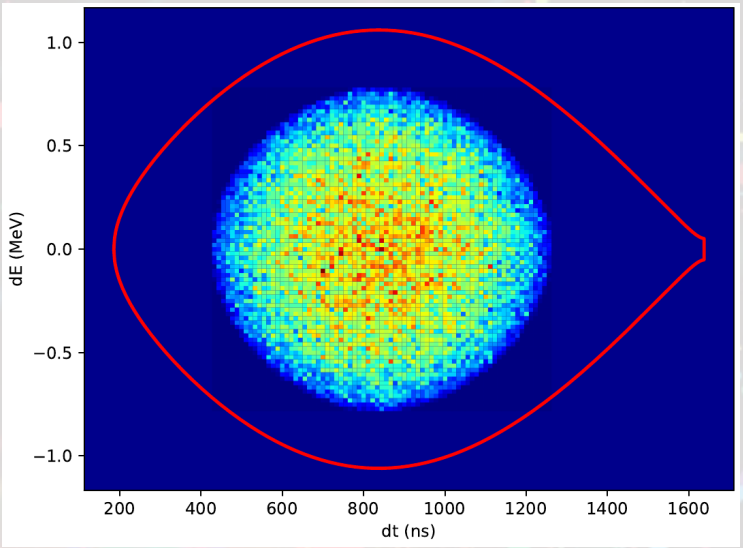
Single harmonic



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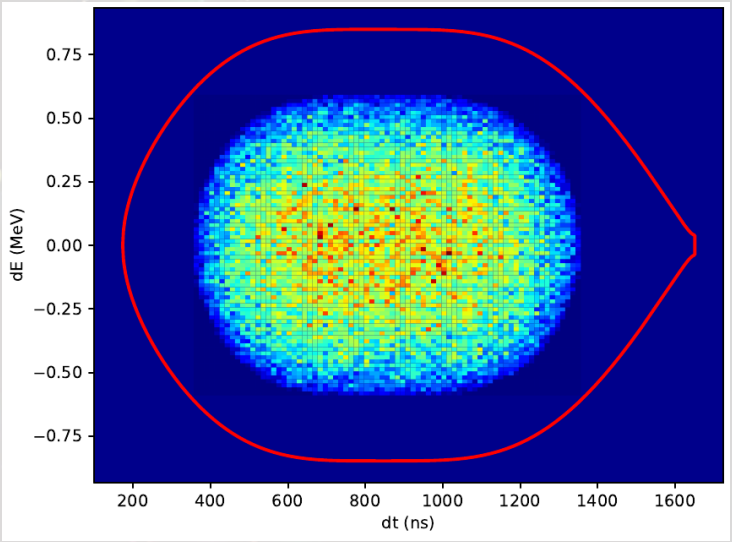

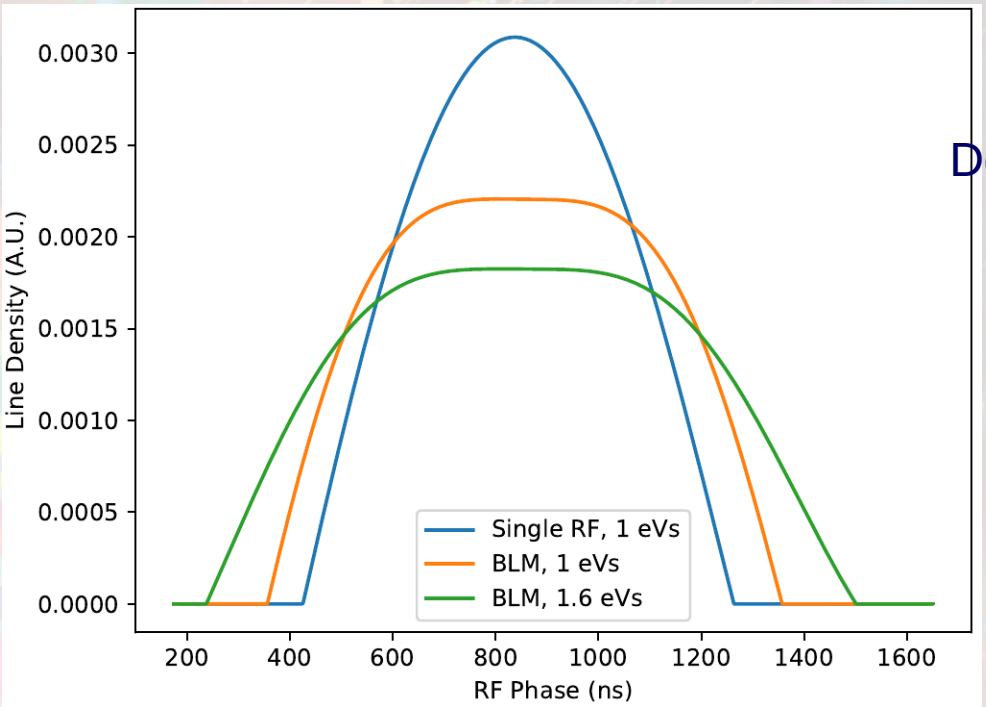

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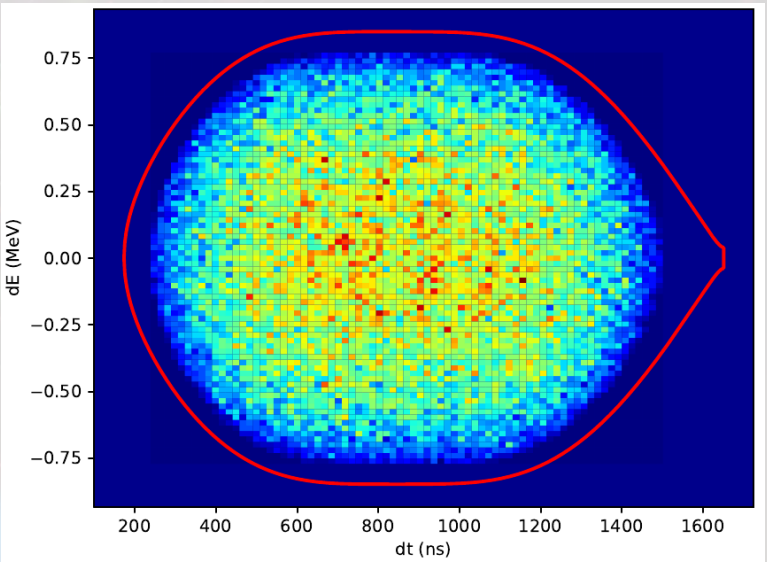

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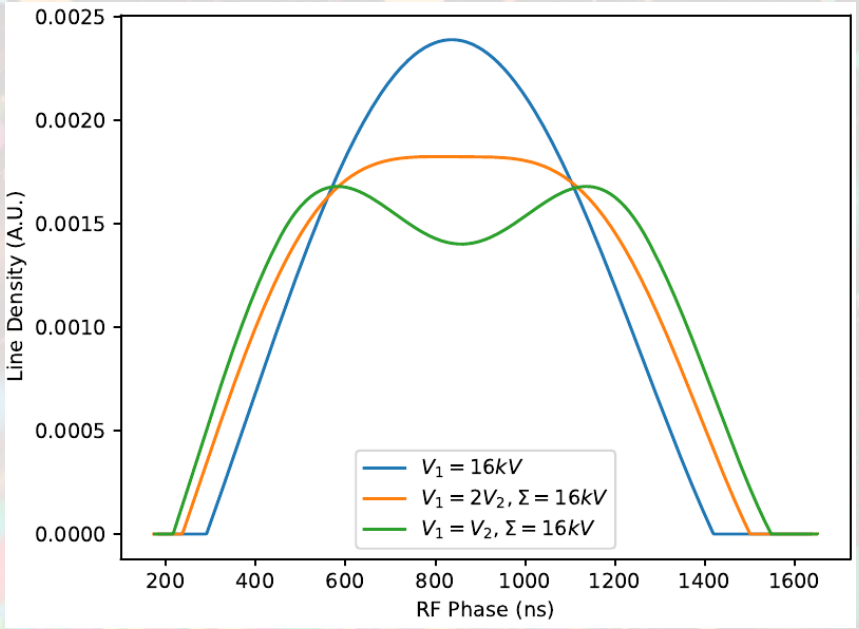
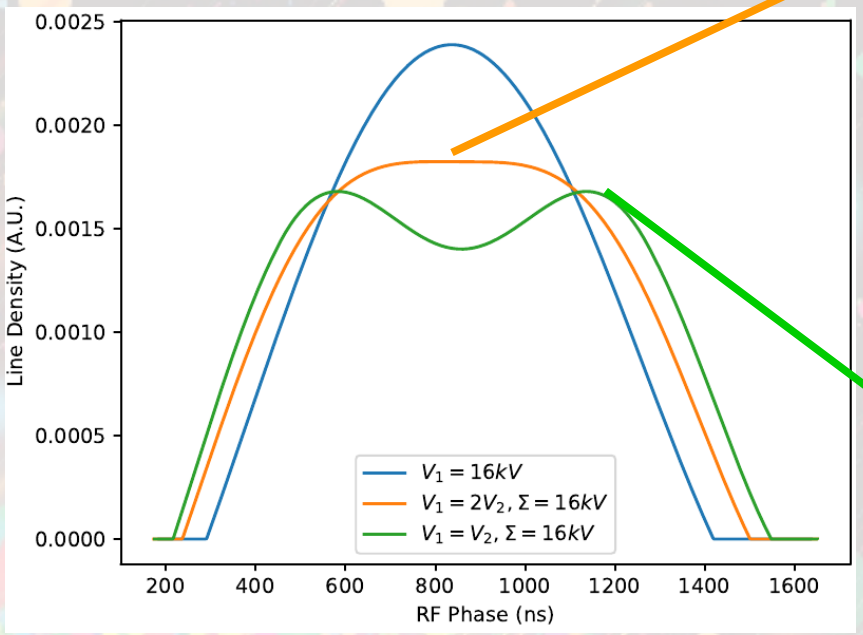
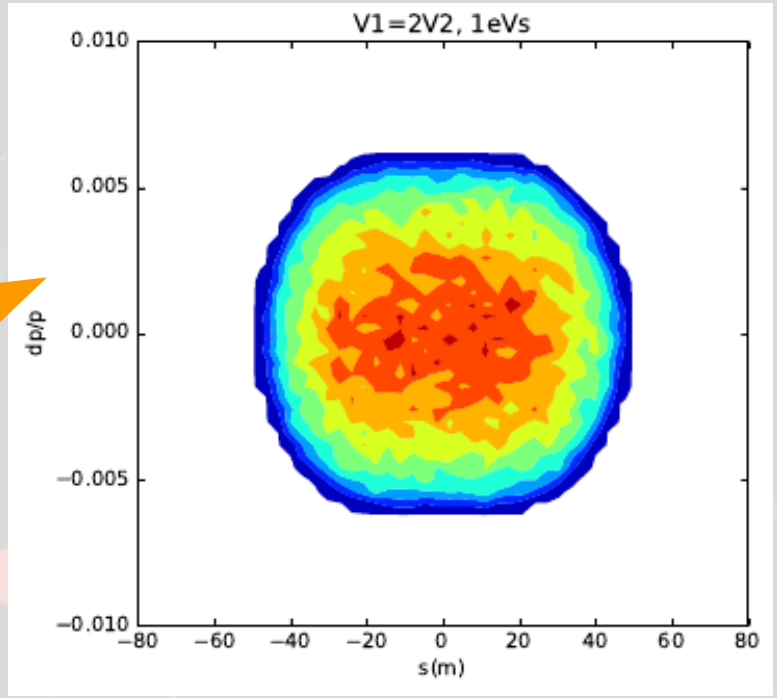


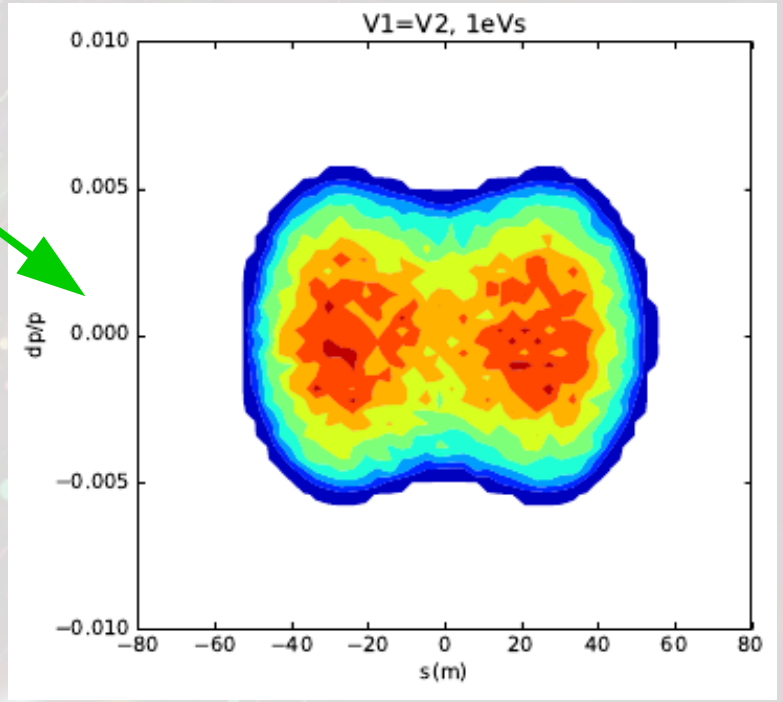
Example: PS Booster

- 2 RF narrow band tunable ferrite cavities
- h=1 for acceleration (max. 8 kV)
- h=2 for bunch shaping (max. 8 kV)
- During LS2 ferrites will be replaced with broadband Finemet™ cavities
- Finemet™ will enable arbitrary voltage distribution increasing flexibility

Space Charge Mitigation

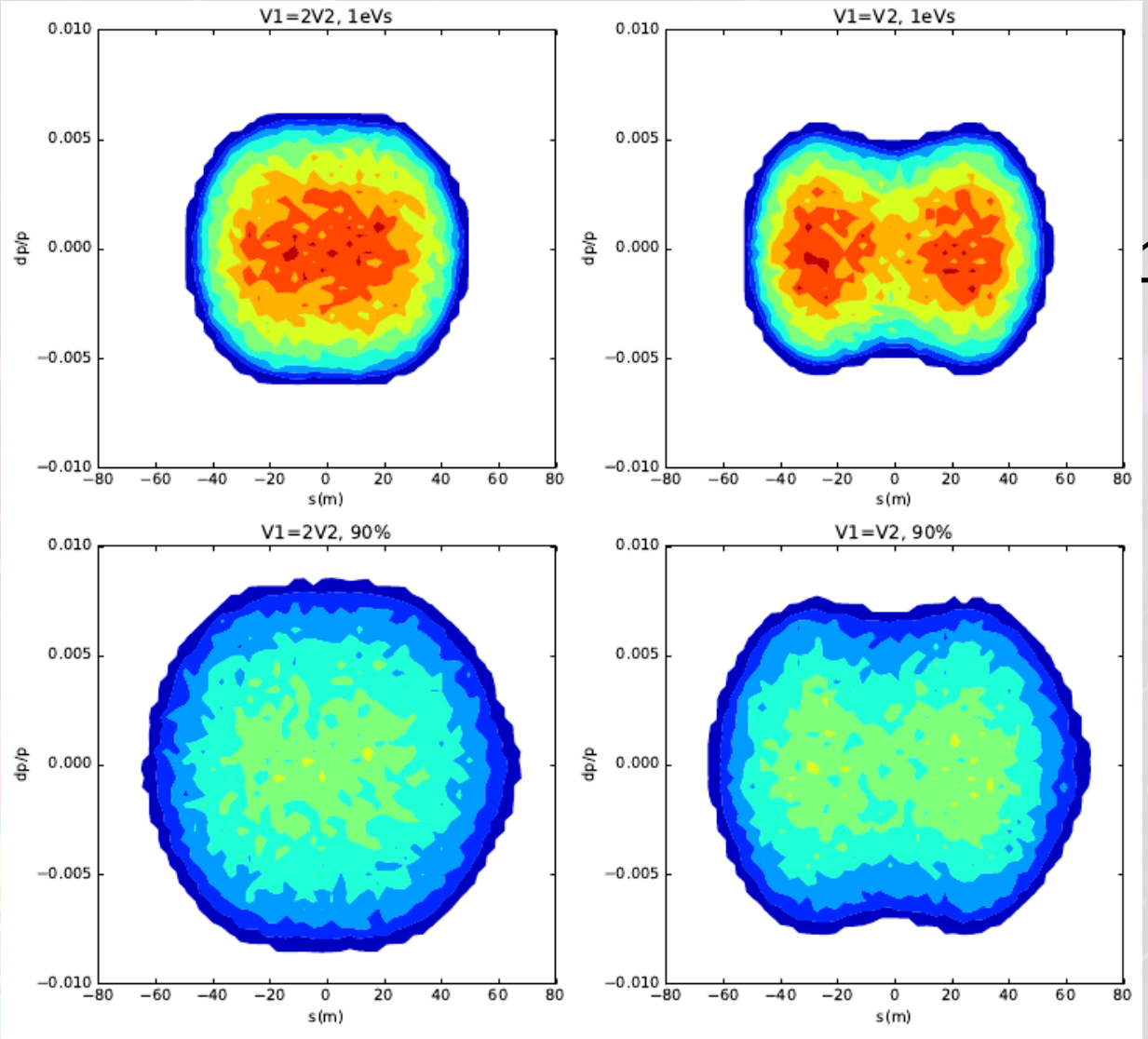






Space Charge Mitigation

$V_1 = 2V_2$ $V_1 = V_2$

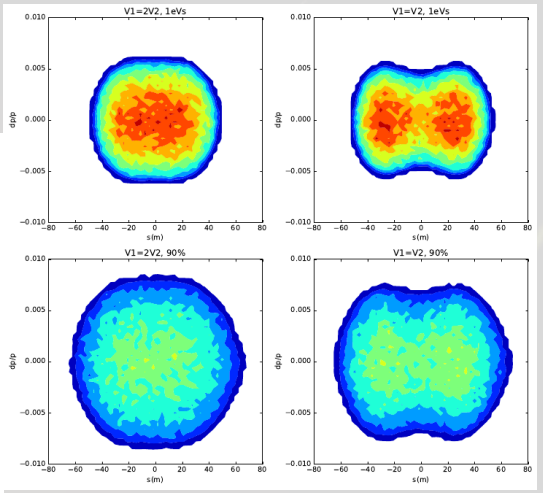


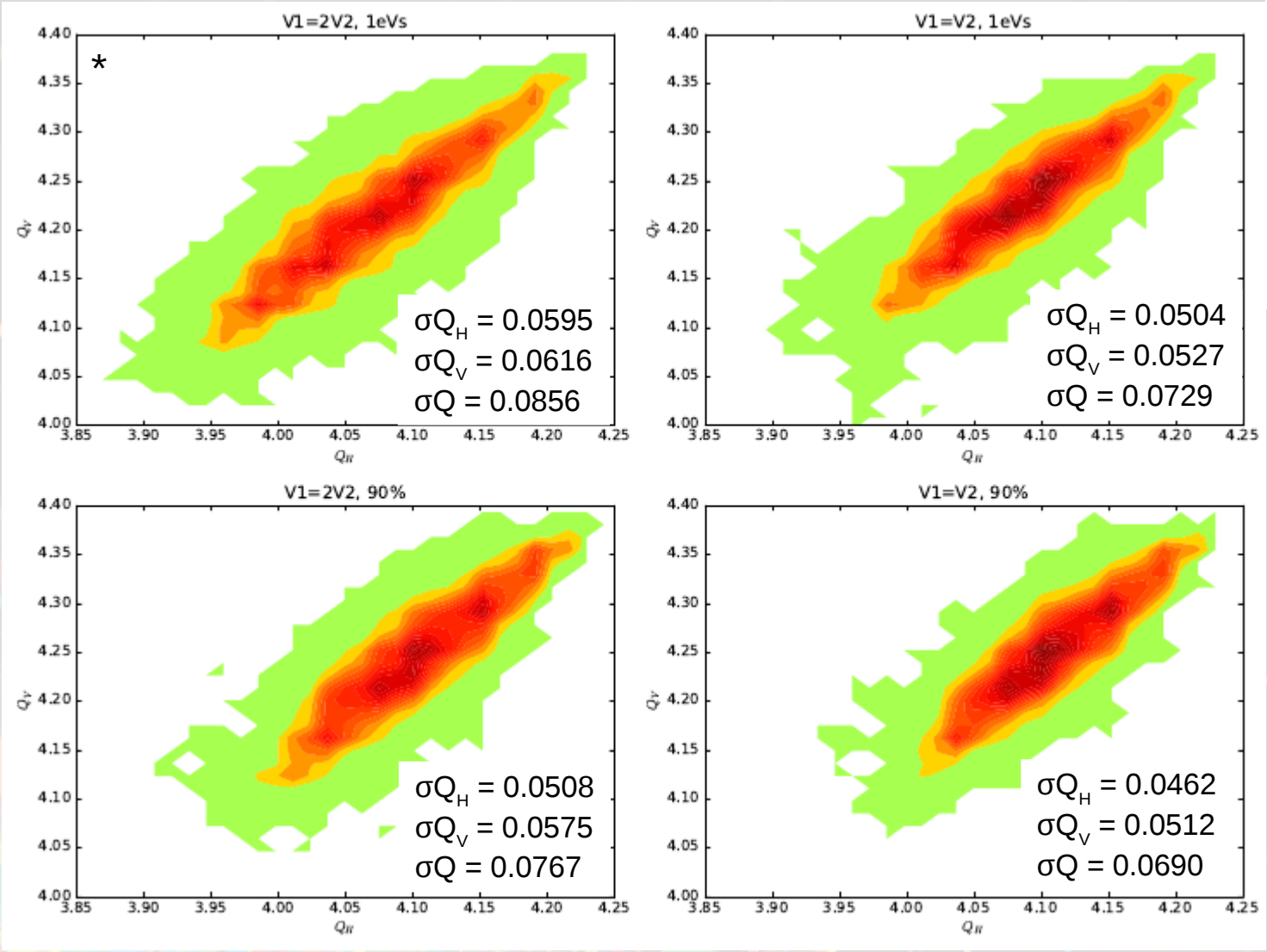
1 eVs long. emittance

long. emittance = 90% bucket area

$V_1=2V_2$ A_B ~ 1.9 eVs $V_1=V_2$ A_B ~ 1.8 eVs

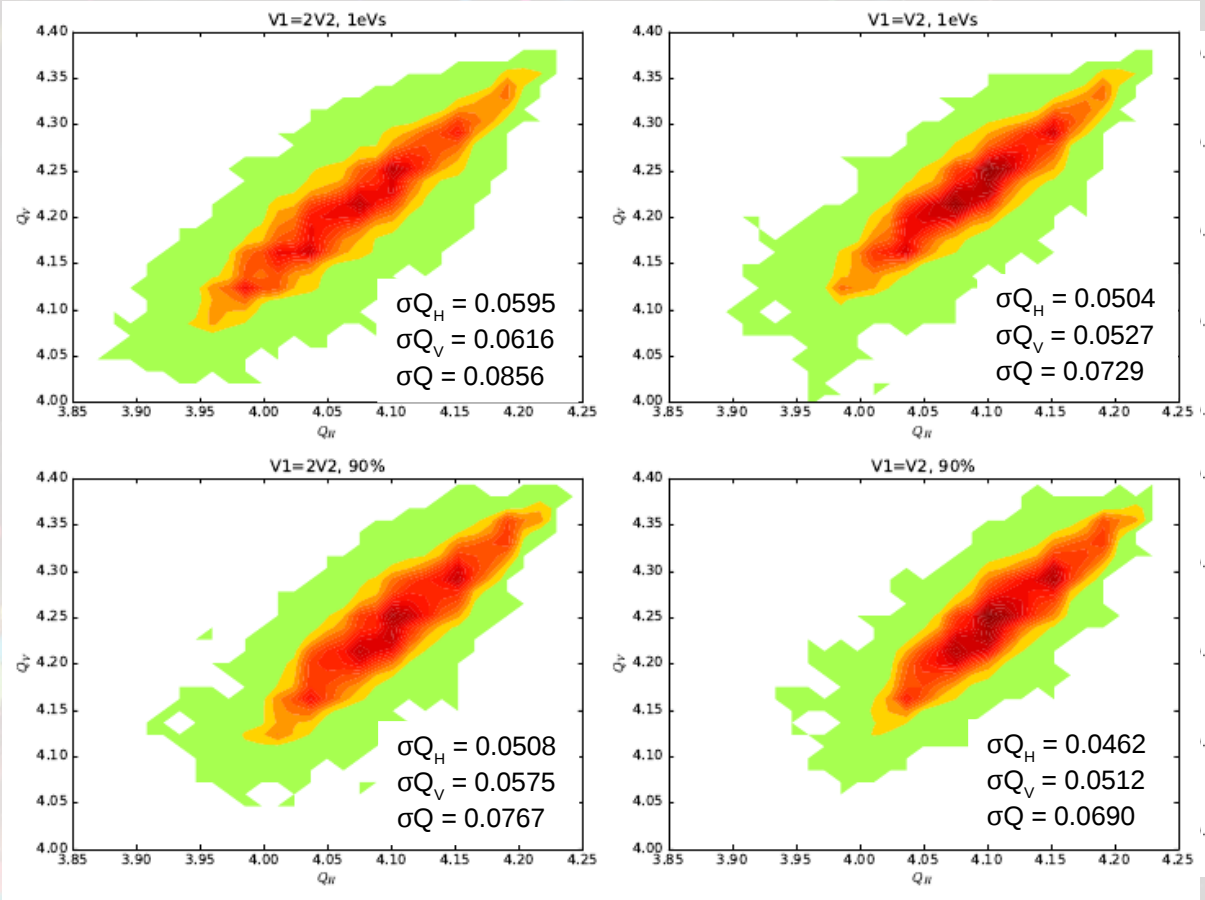
Space Charge Mitigation

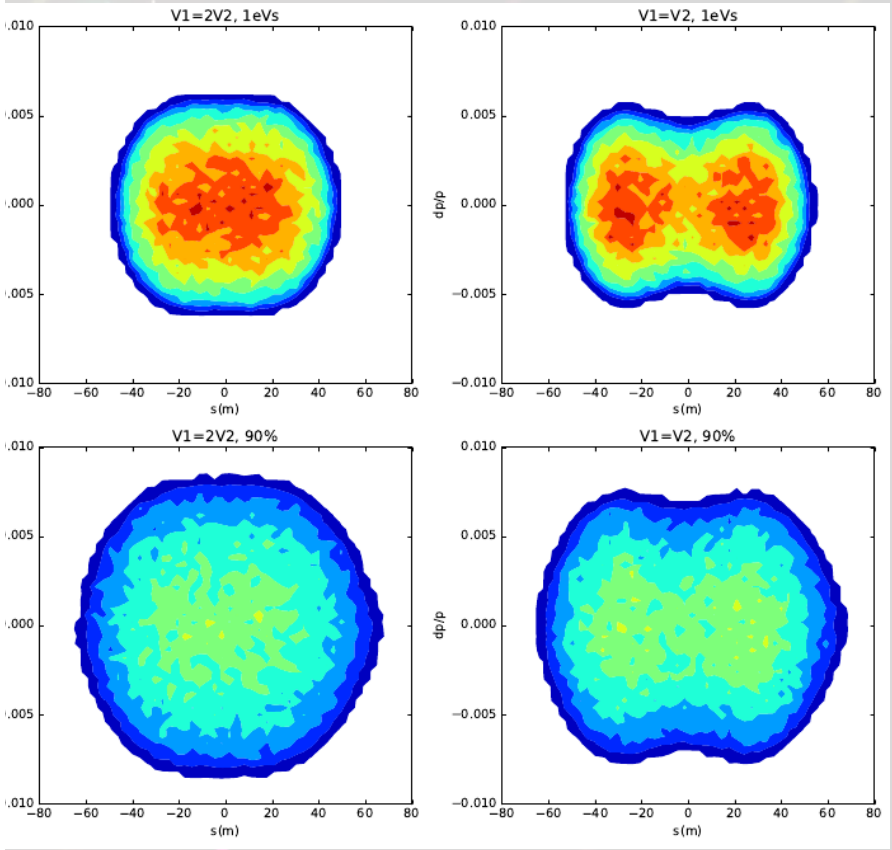




* Thanks to A. Oeftiger for tune spread simulations

Space Charge Mitigation





- Simulation confirms what we already know, big long bunches reduce space charge
- Changing voltage ratios can be as effective as longitudinal emittance blow-up from 1 →1.7 eVs

Application

LEIR:

- High 6D density coasting beams
- Adiabatic RF capture on flat bottom
- Consider maximum extracted intensity
- Transmission limited by transverse space charge effects*

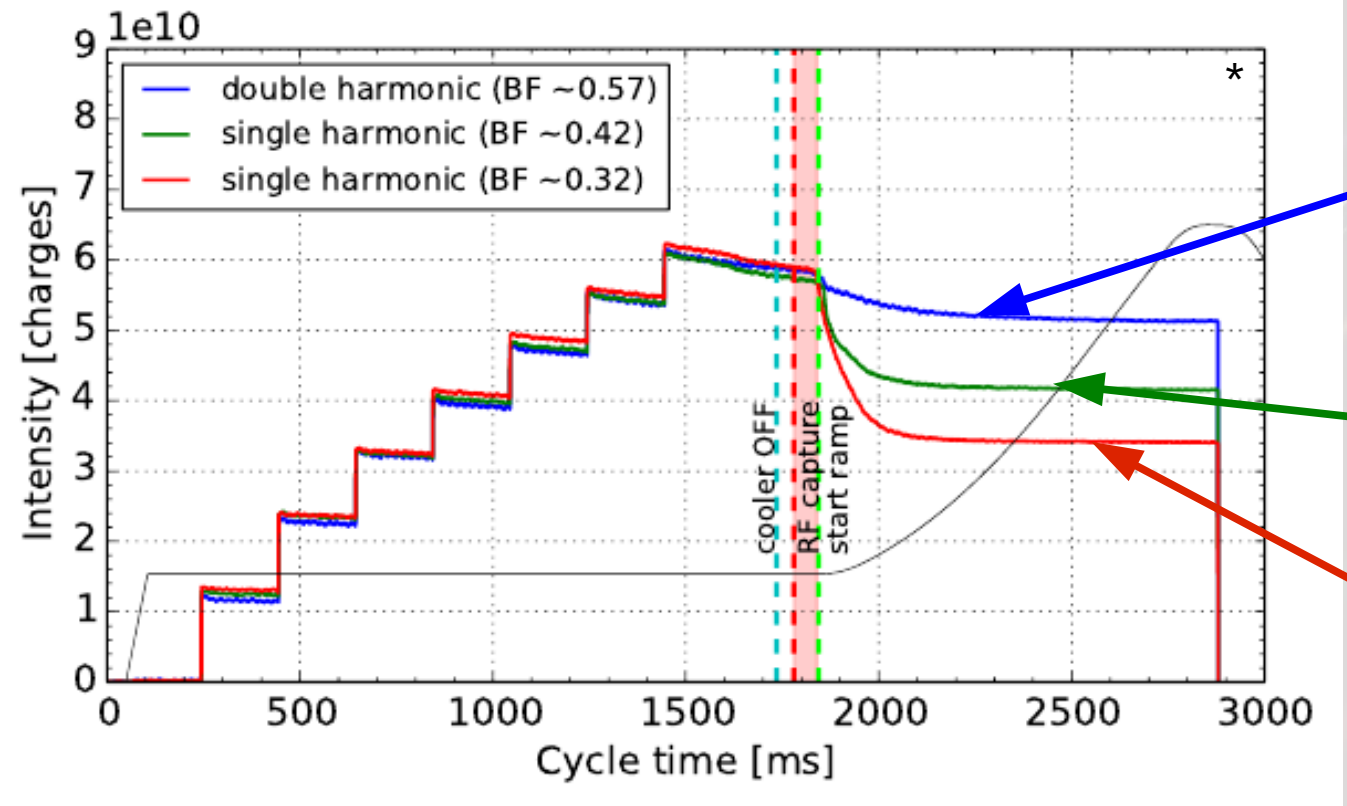
PSB:

- Multi-turn injection on ramp
- RF capture during injection
- Consider maximum brightness
- Transmission and brightness both affected by space charge[+]

*HB2016 – TUAM5X01, H.Bartosik et al
IPAC2017 – THPAB049, A. Huschauer et al

[+]LHC Injectors Upgrade TDR – Vol. 1: Protons

Application - LEIR



High long. emittance, double harmonic

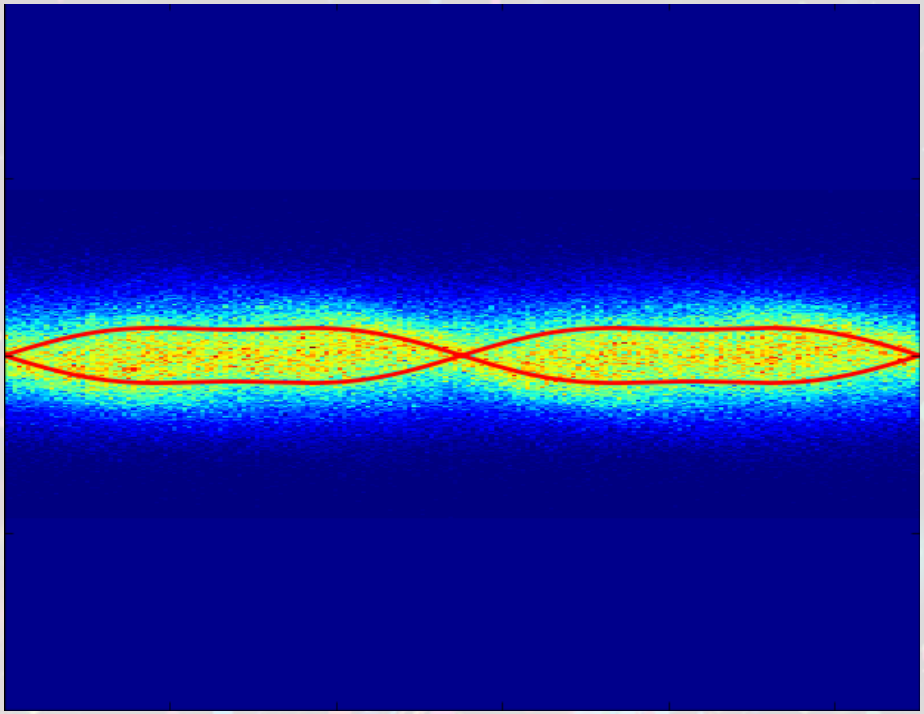
High long. emittance, single harmonic

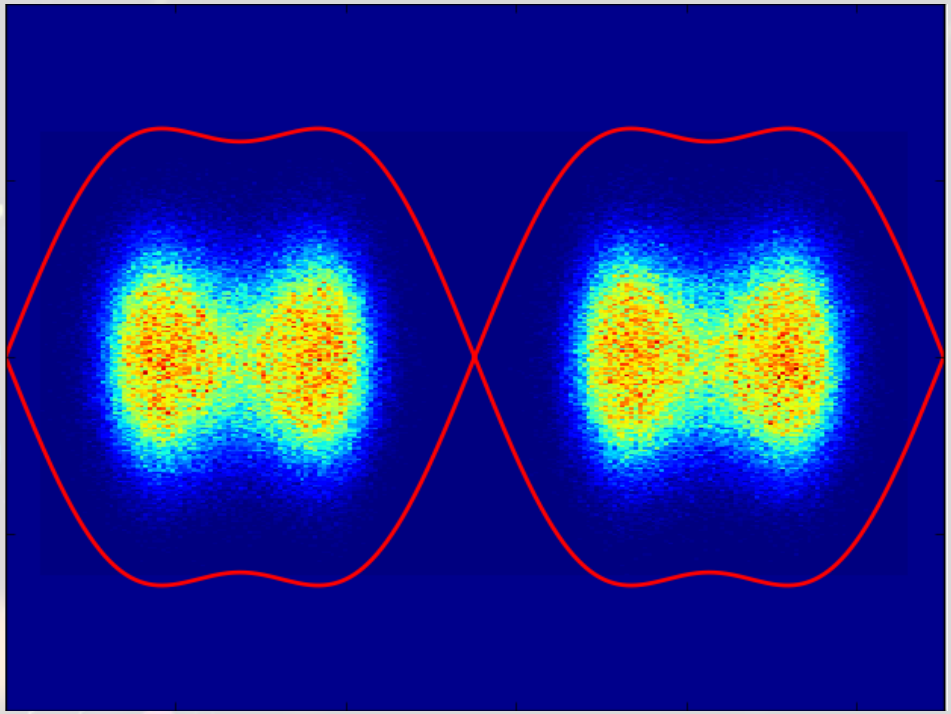
Low long. emittance, single harmonic

- Losses start during or immediately after RF capture
- No time for dedicated blow-up, 10s of ms required
- Maximise bunching factor during capture process to reduce losses

*HB2016 – TUAM5X01, H.Bartosik et al

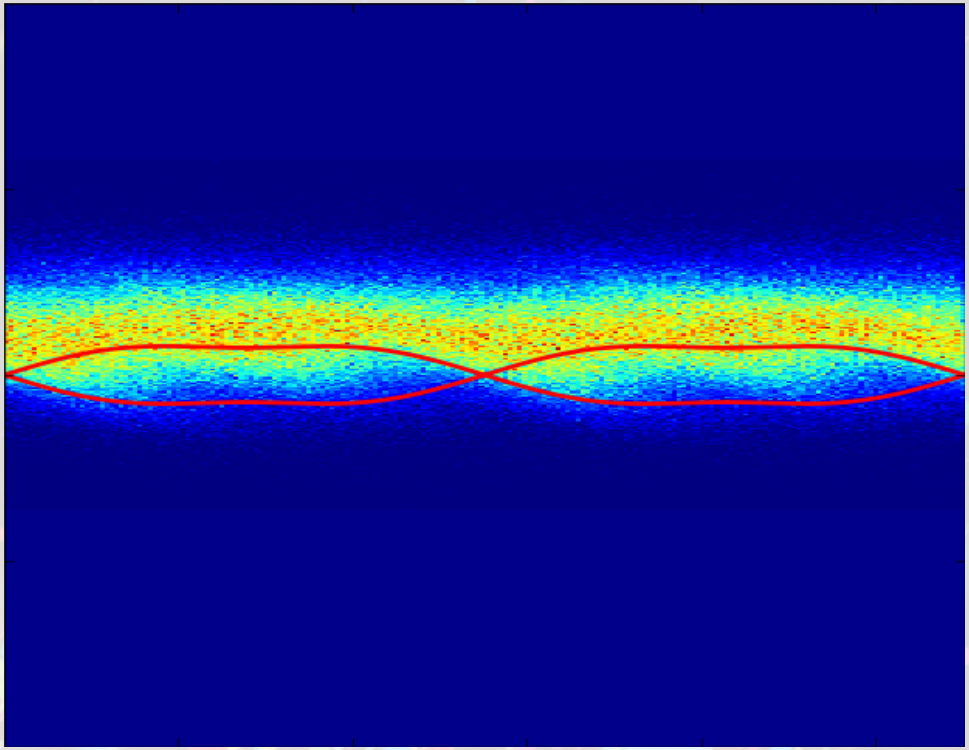
Application - LEIR

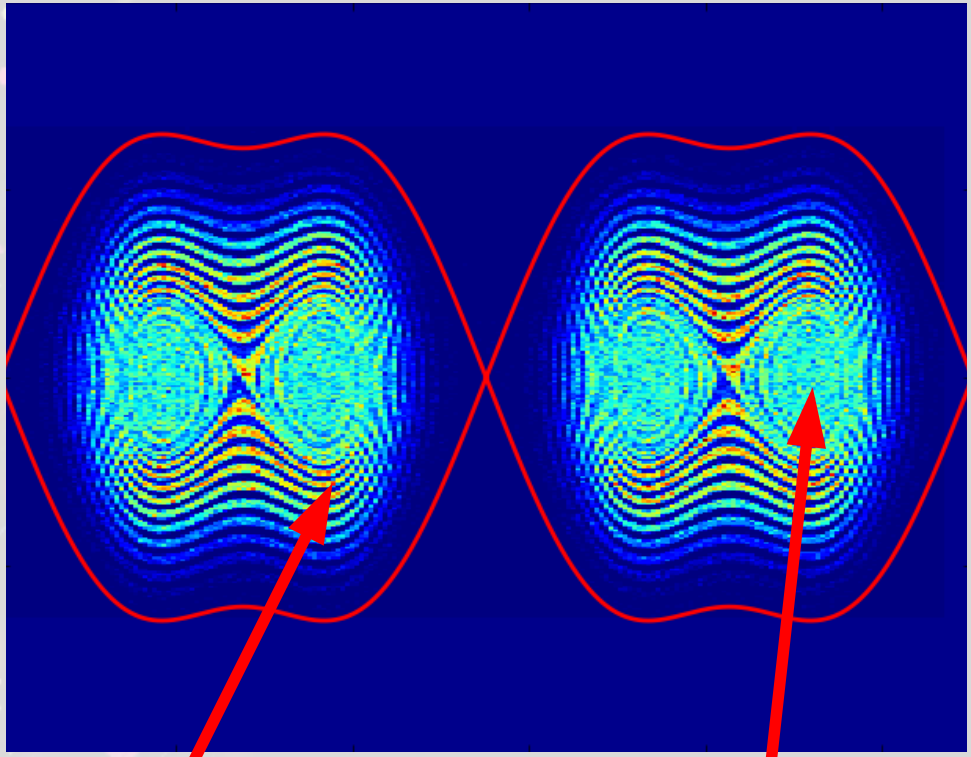




- Adiabatic capture on flat bottom
- $F_{RF} = F_{beam}$, bucket forms on bunch leading to smallest possible longitudinal emittance

Application - LEIR



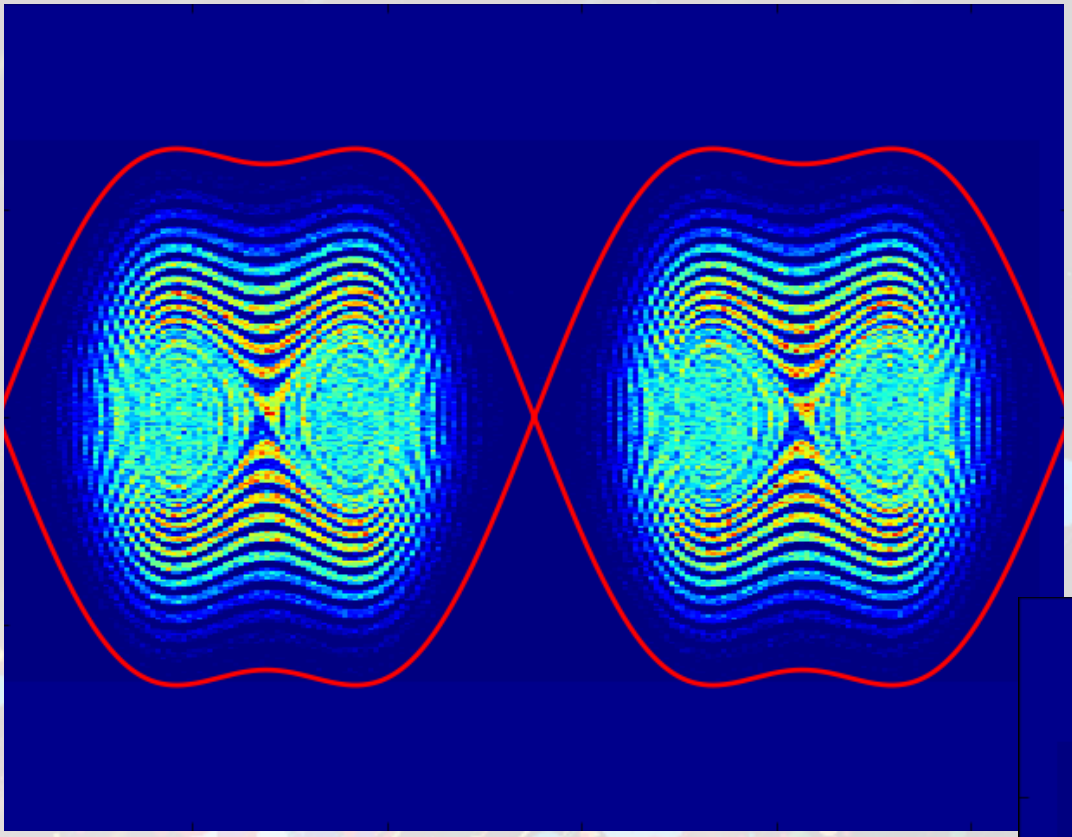


high density outside

low density core

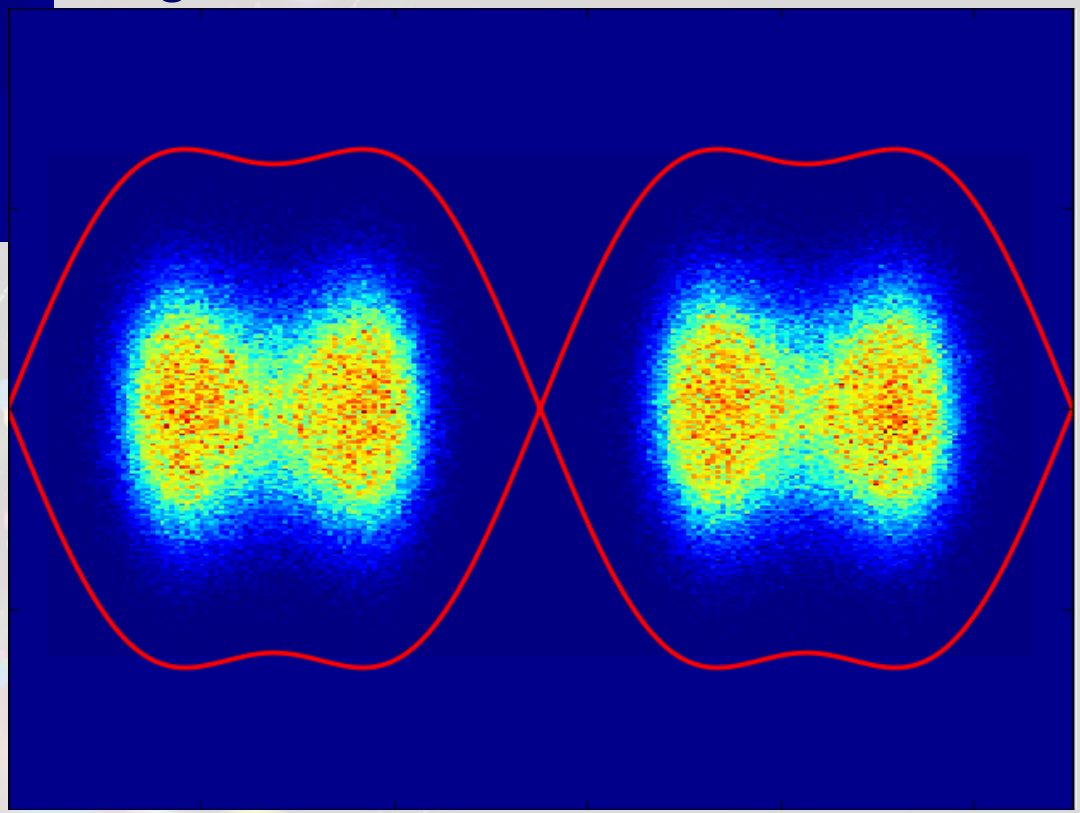
- F_{RF} =/= F_{beam}, captured emittance increased and core density decreased
- Increased bunching factor → reduced space charge effect

Application - LEIR

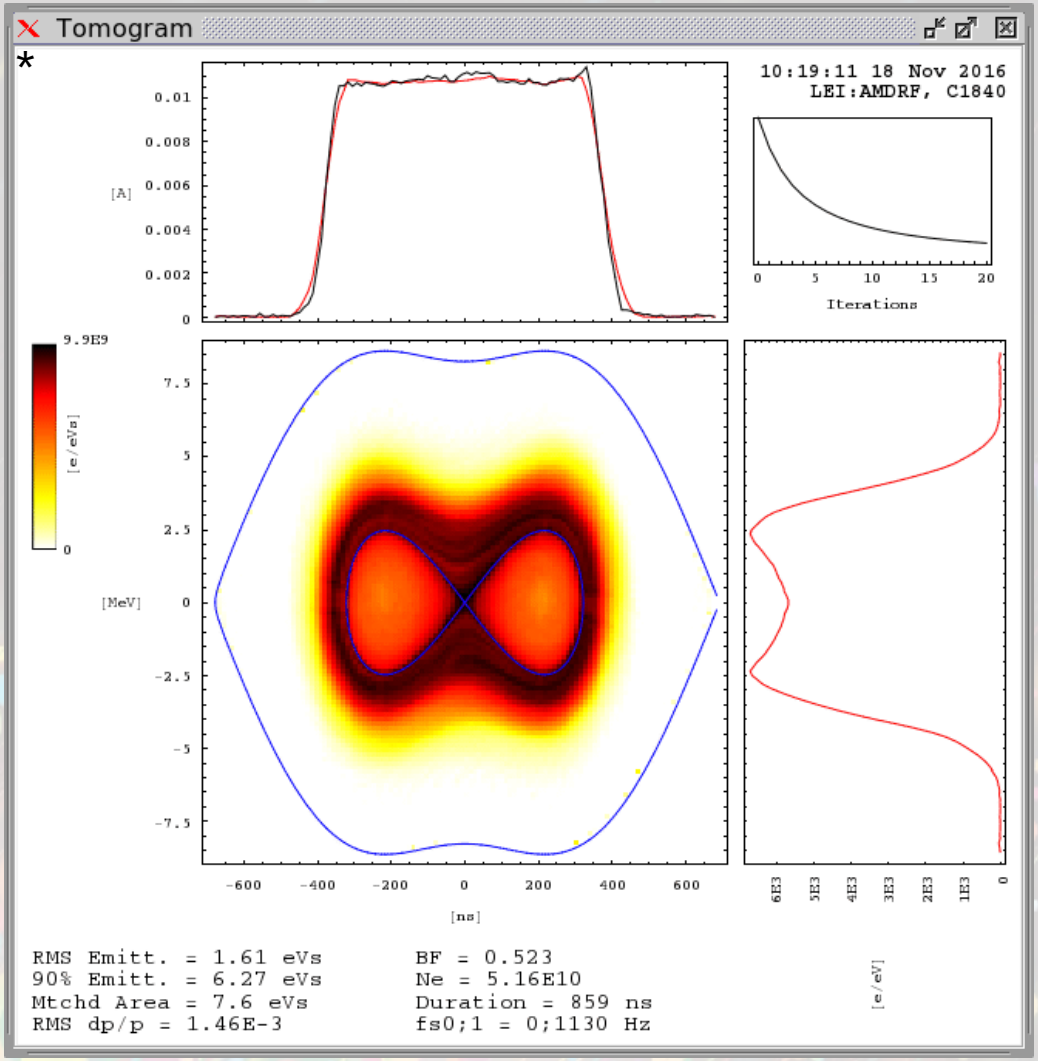


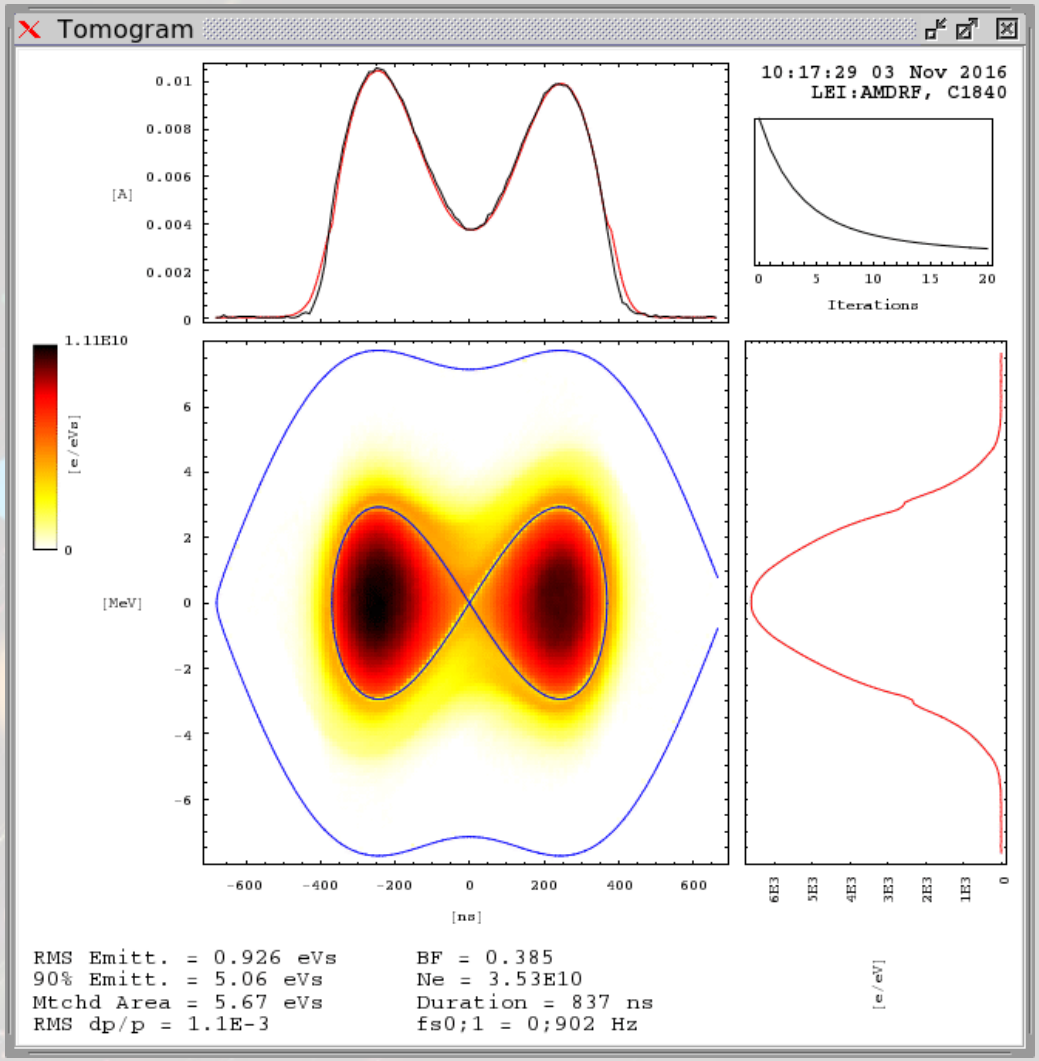
Low density, high bunching factor, low losses

High density, low bunching factor, high losses



Application - LEIR





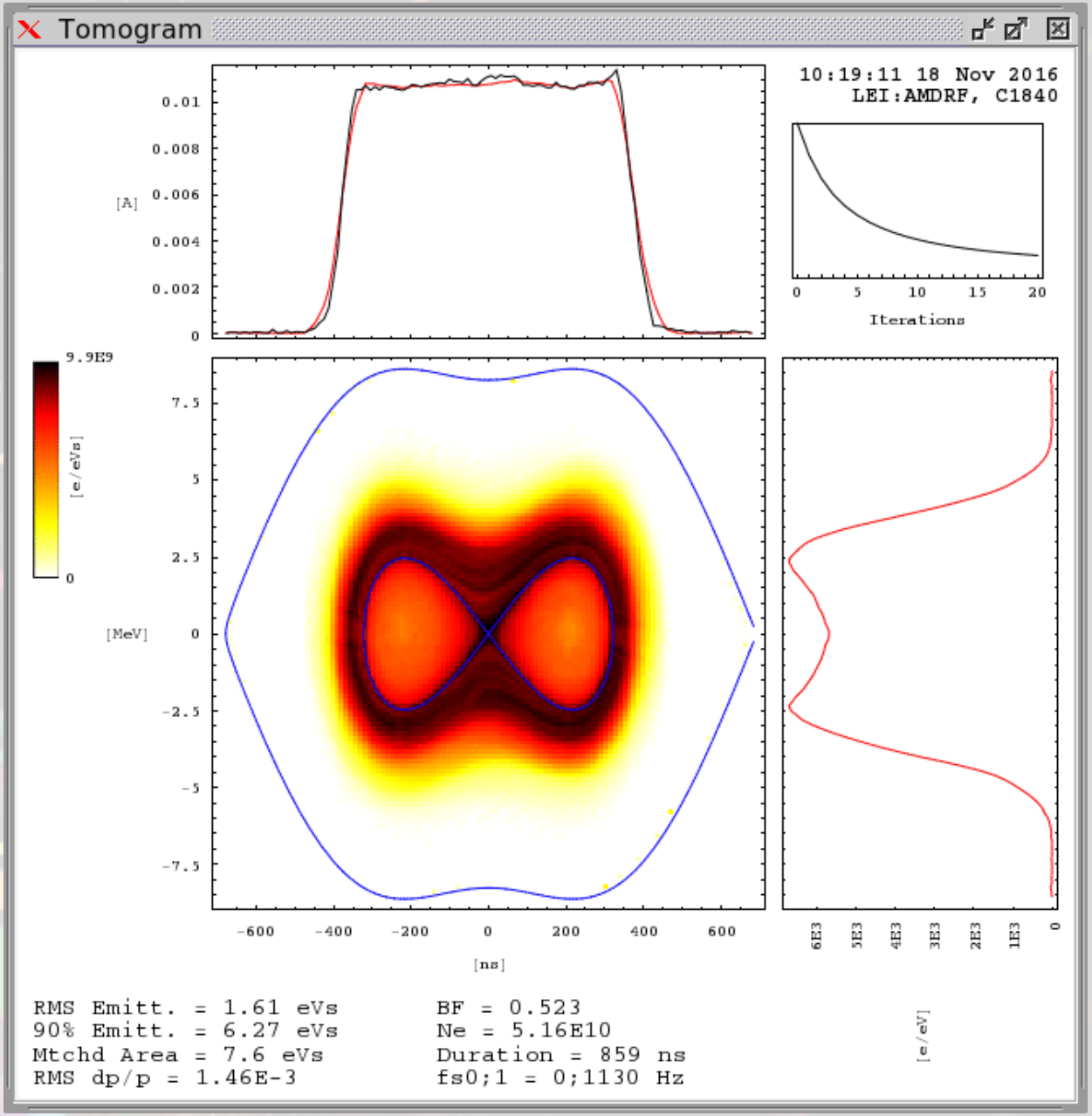
Bunching Factor: 0.523
RMS dp/p: 1.46E-3
Matched Area: 7.6 eVs

Bunching Factor: 0.385
RMS dp/p: 1.1E-3
Matched Area: 5.67 eVs

* Steven Hancock

Application - LEIR

- Hollow bunches very good for space charge*
- Improved transmission in LEIR
- Captured distribution very sensitive to difference between F_{RF} and F_{beam}

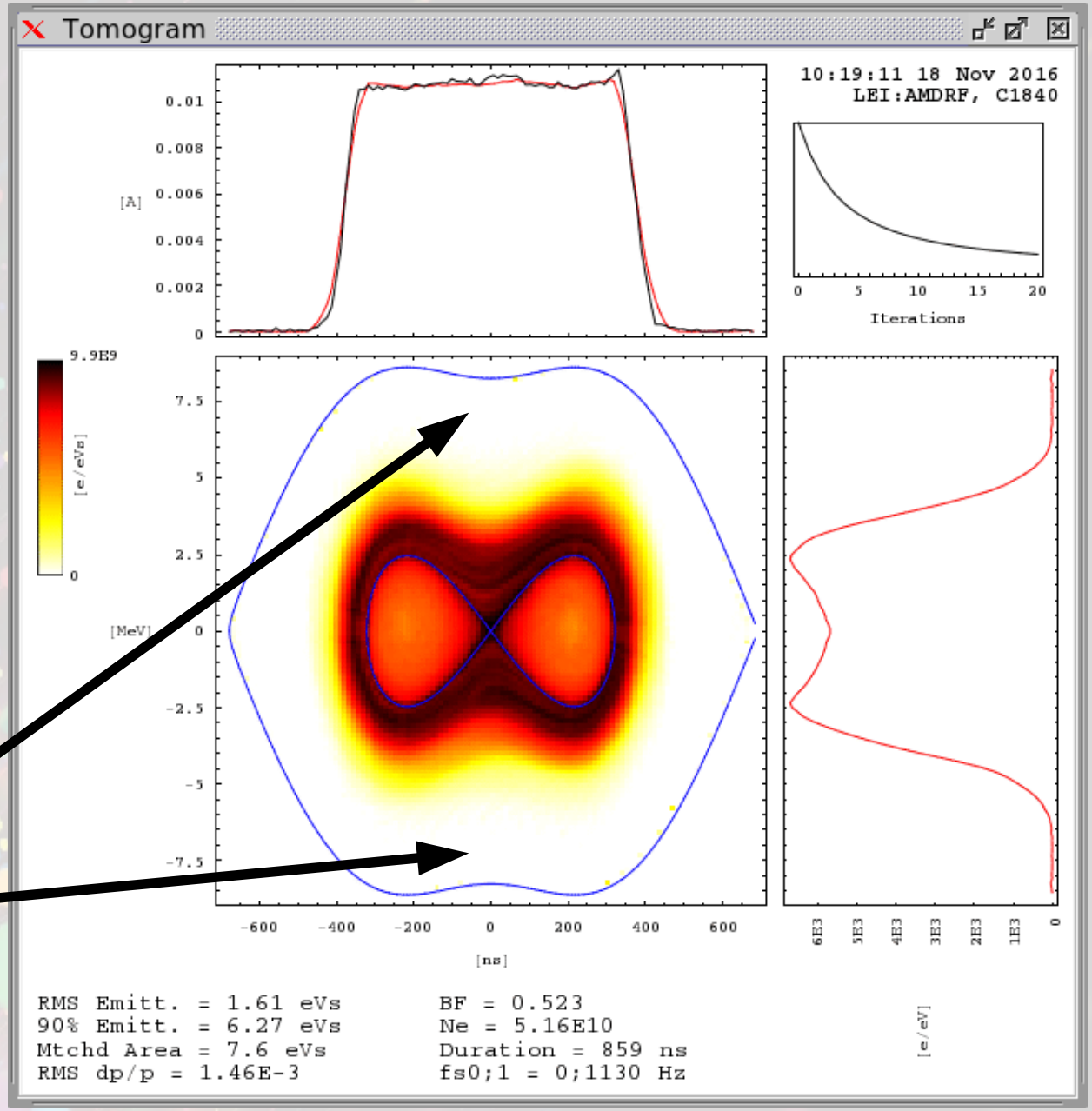


*For more details see: Adrian Oeftiger, “Hollow bunches for space charge mitigation”

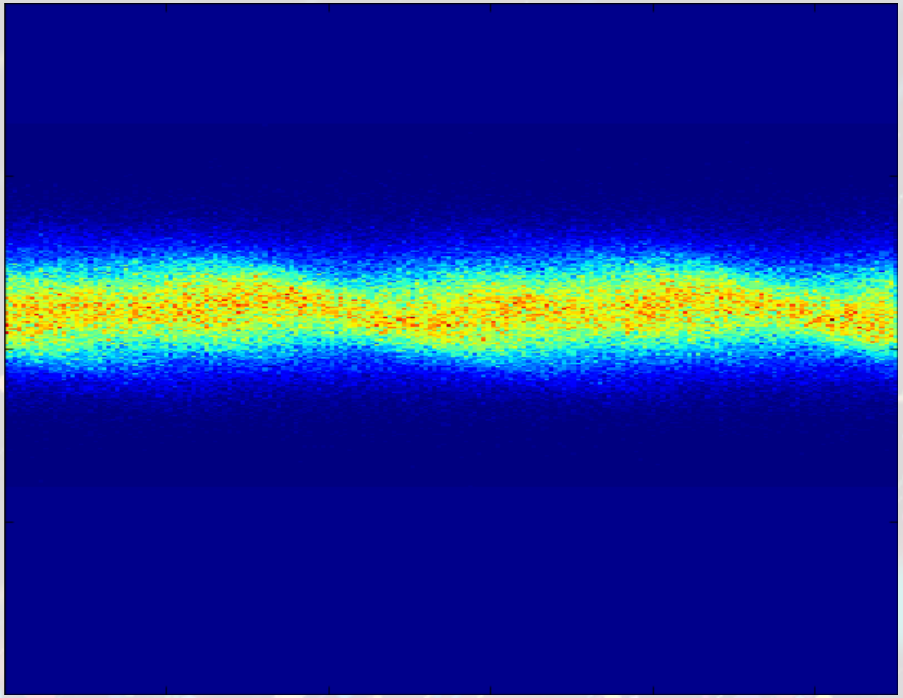
Application - LEIR

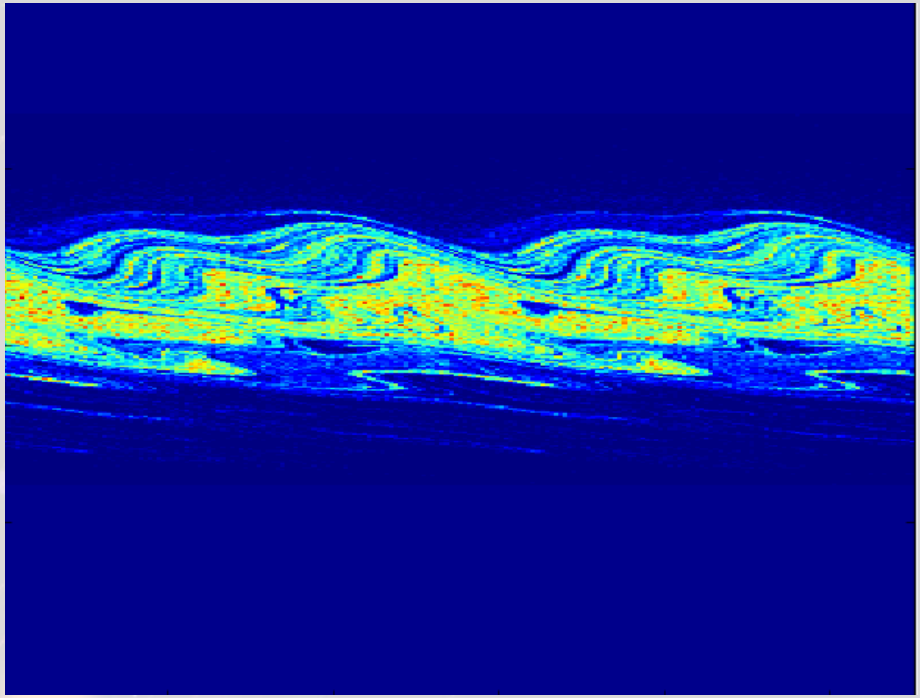
- Hollow bunches very good for space charge*
- Improved transmission in LEIR
- Captured distribution very sensitive to difference between F_{RF} and F_{beam}

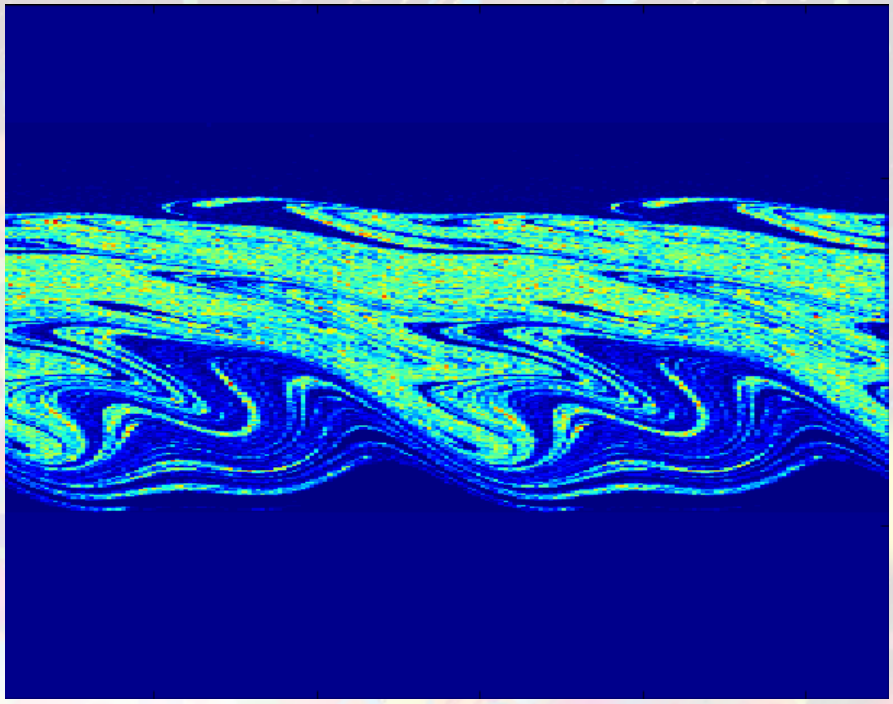
Lots of empty space

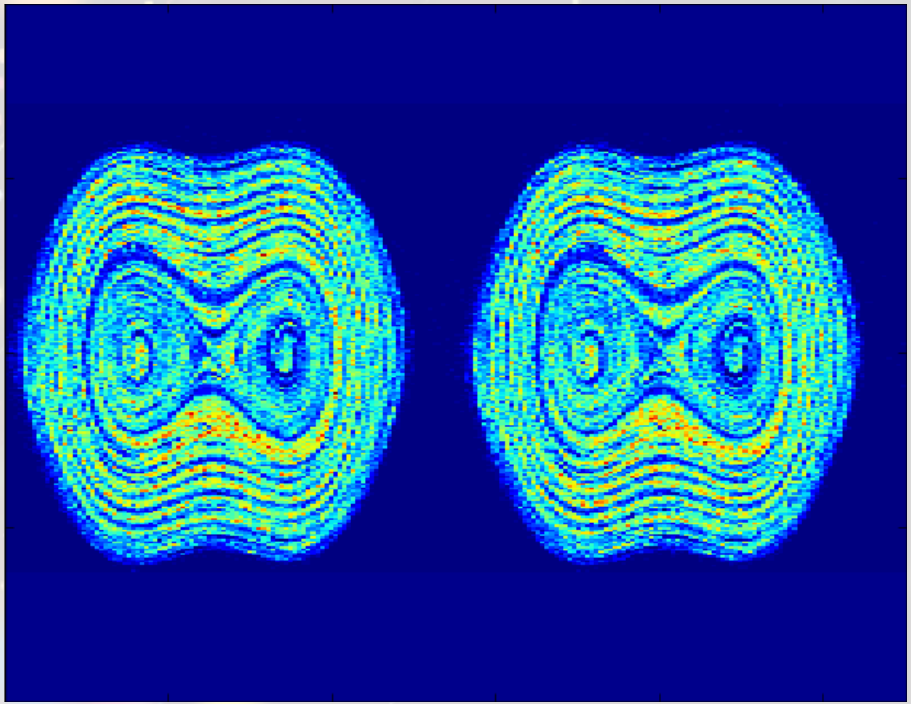


Application - LEIR

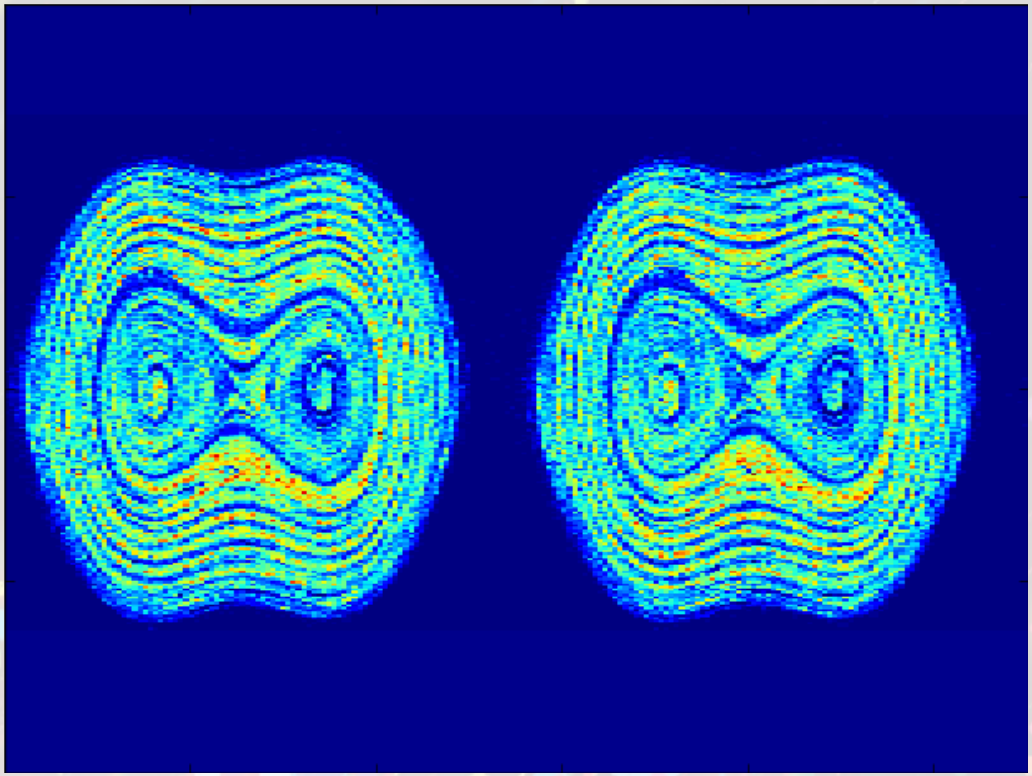


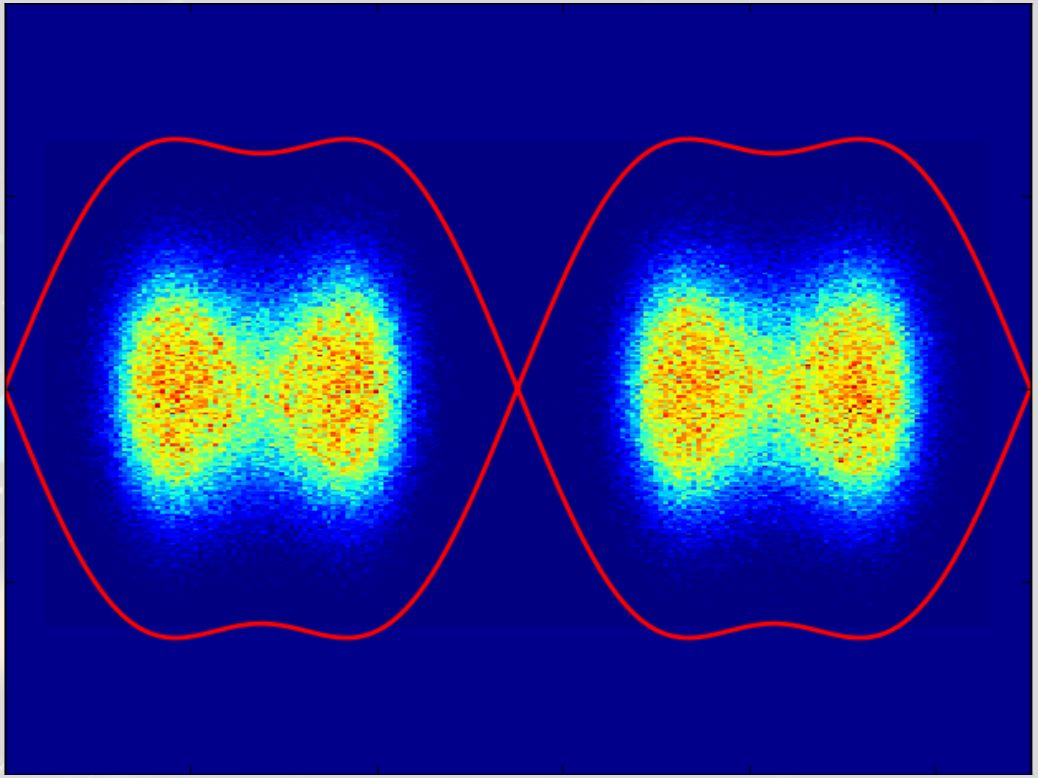






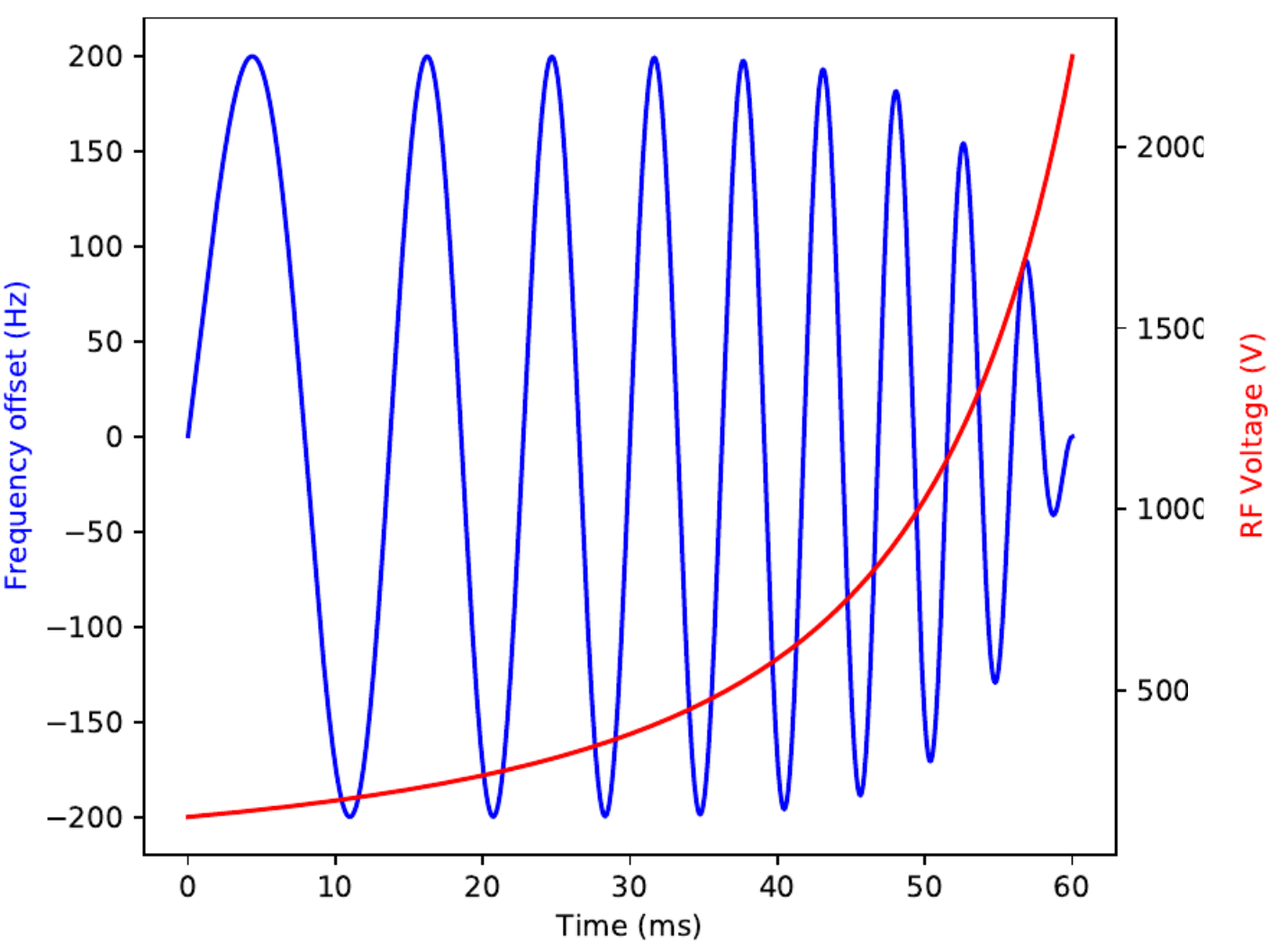
Application - LEIR





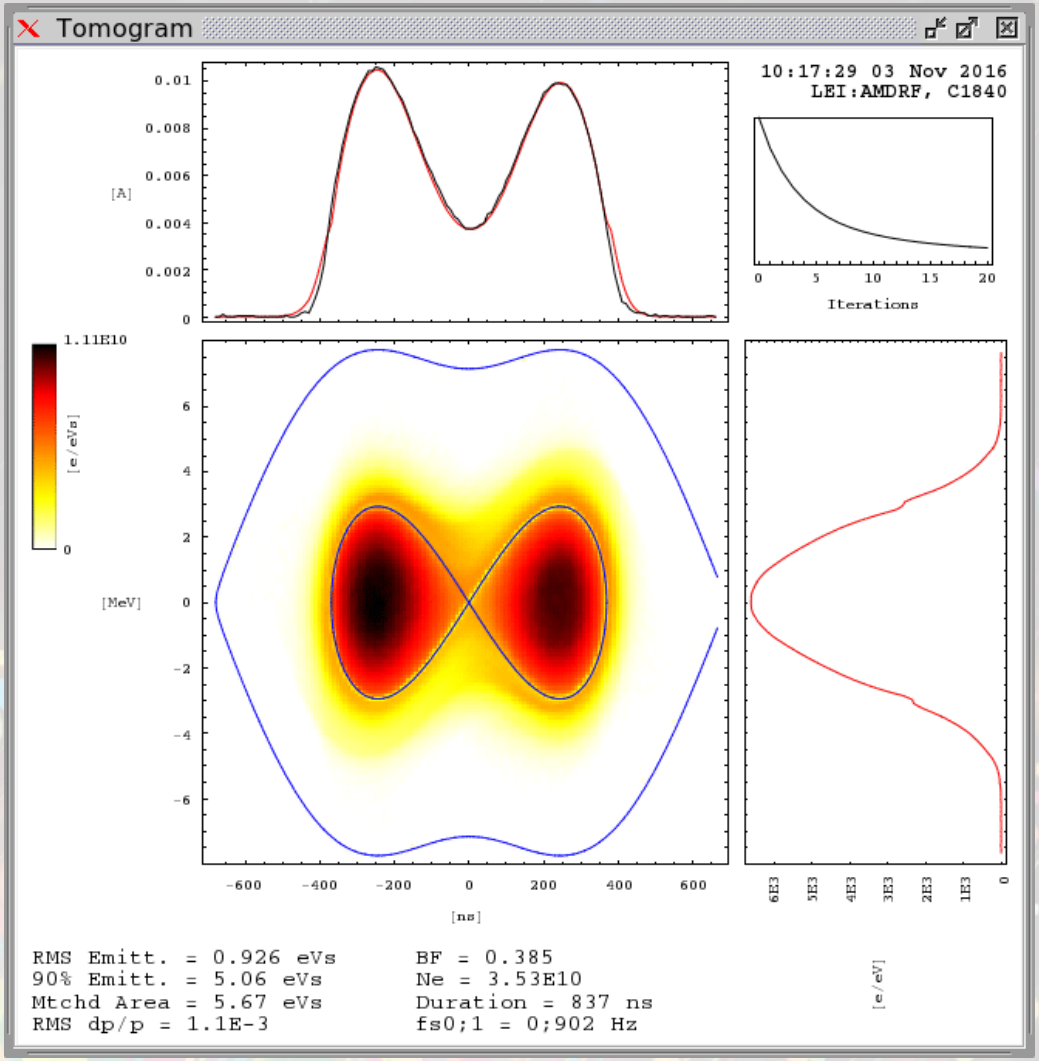
- Apply frequency modulation during the capture process
- Increase reproducibility
- increase emittance
- Further reduce losses

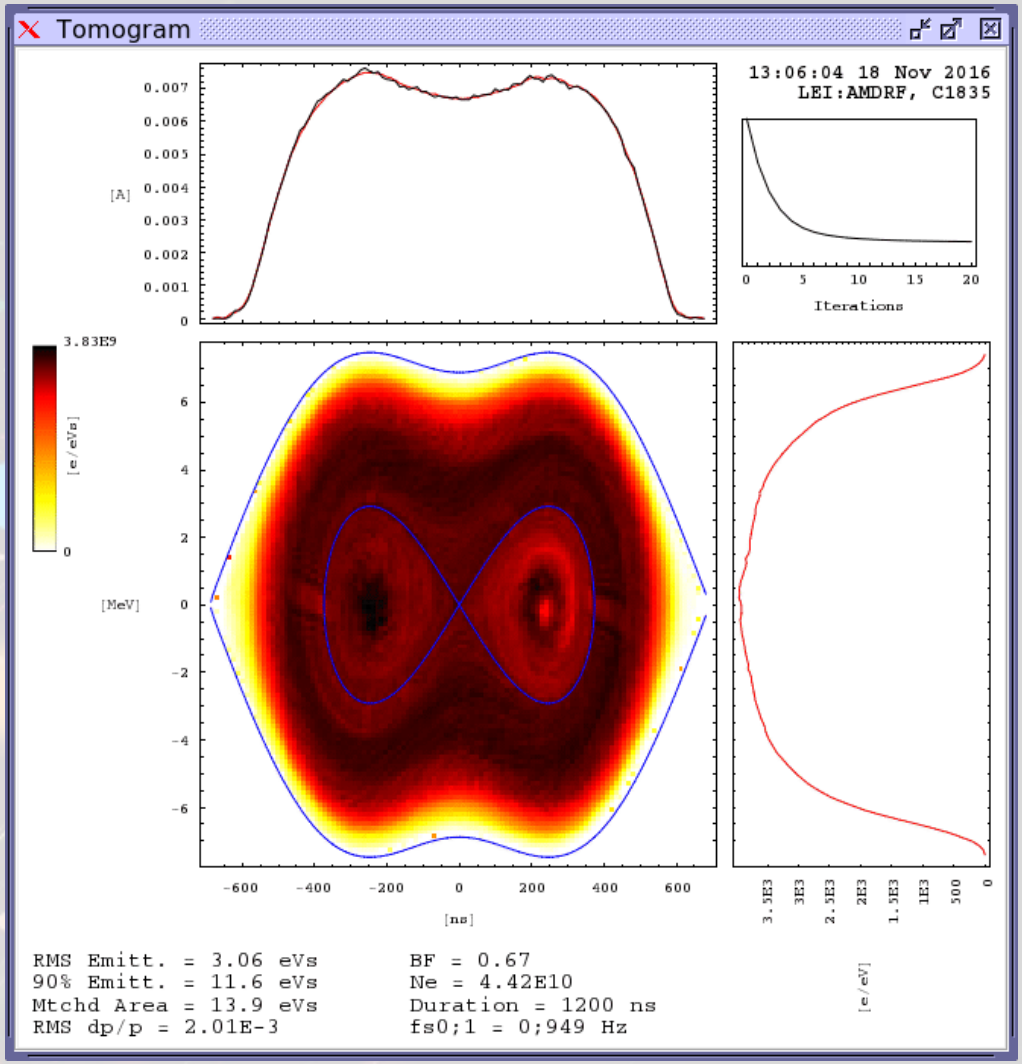
Application - LEIR



- Bucket is swept through the beam during the capture process
- Redistributes particles longitudinally to increase the captured emittance
- Frequency comparable to f_s – too fast and beam is not affected, too slow and beam is captured prematurely
- Amplitude proportional to voltage – maximum bucket offset comparable to final bucket height

Application - LEIR

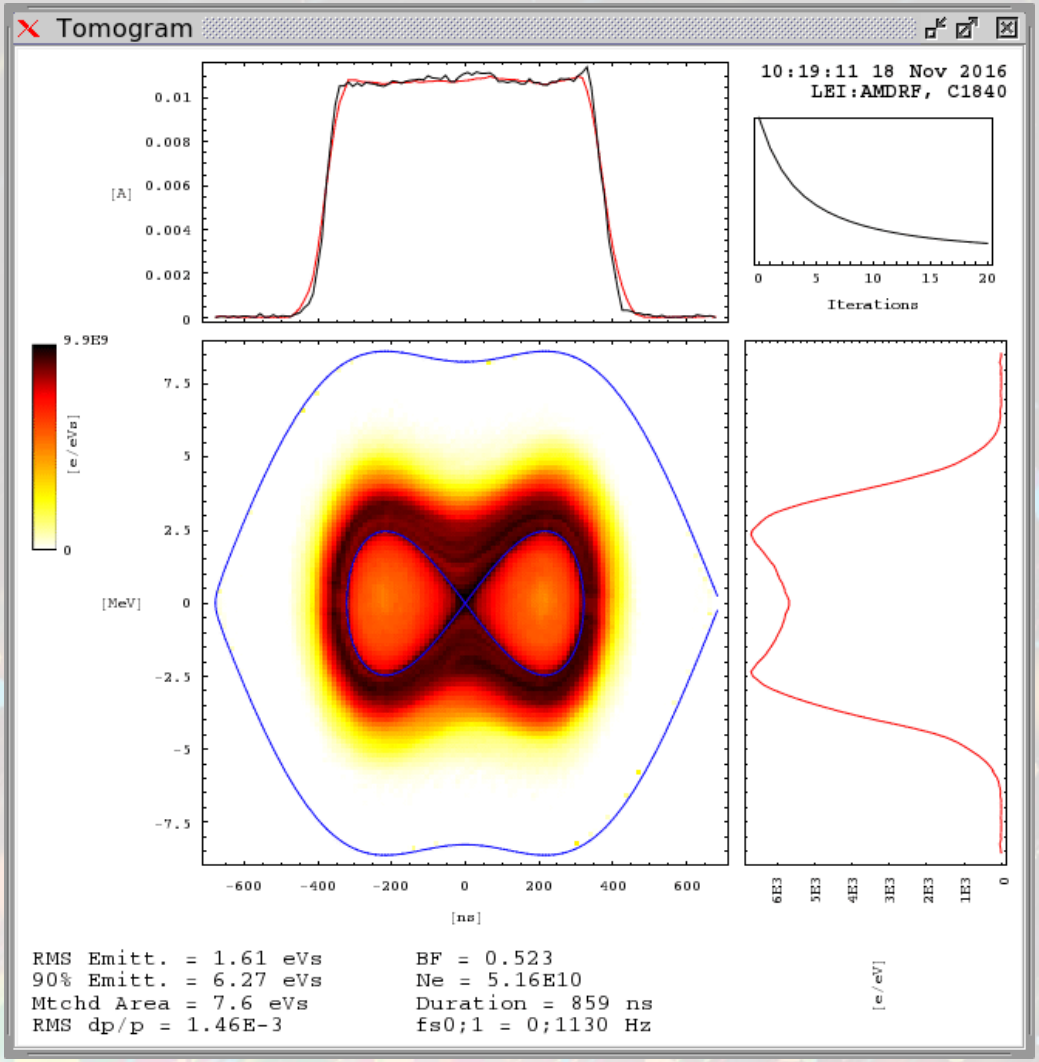


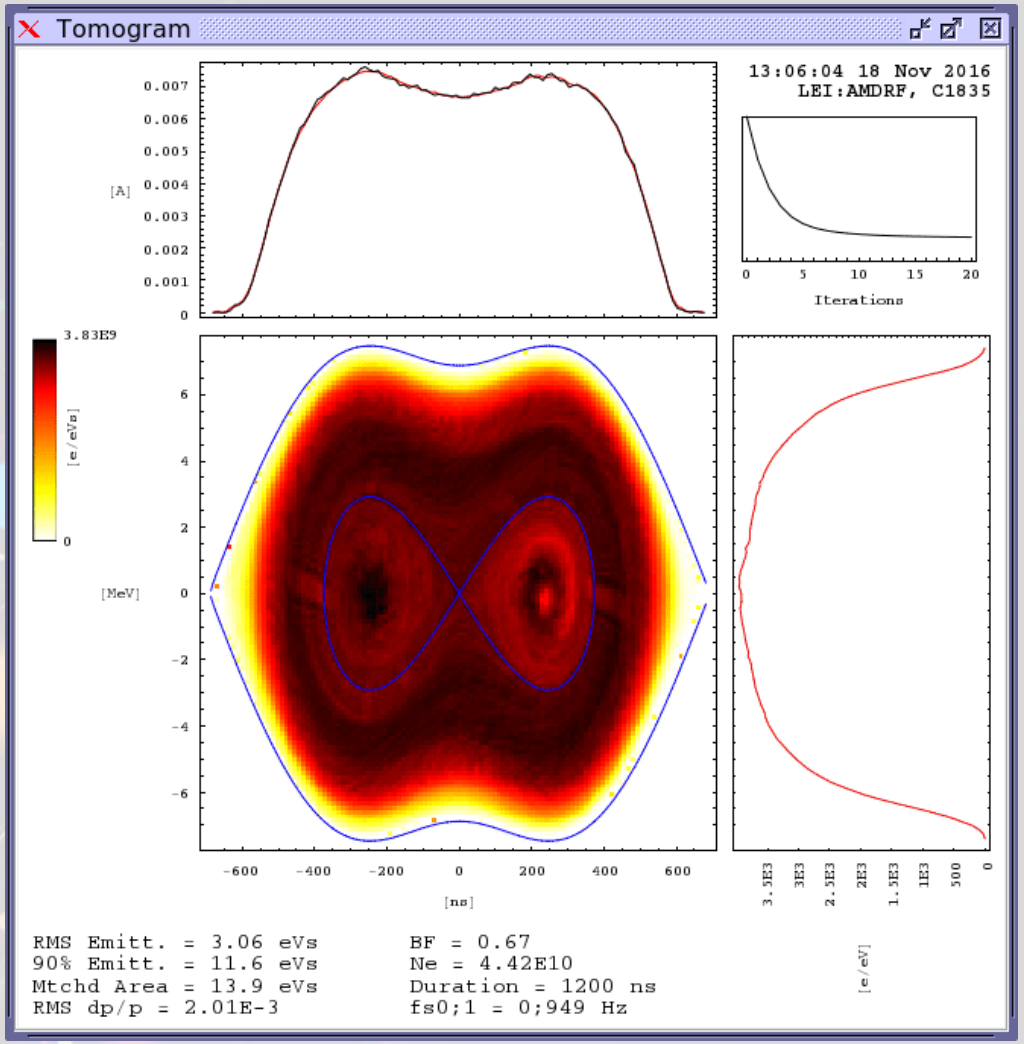


Bunching Factor: 0.385
RMS dp/p: 1.1E-3
Matched Area: 5.67 eVs

Bunching Factor: 0.67
RMS dp/p: 2.01E-3
Matched Area: 13.9 eVs

Application - LEIR





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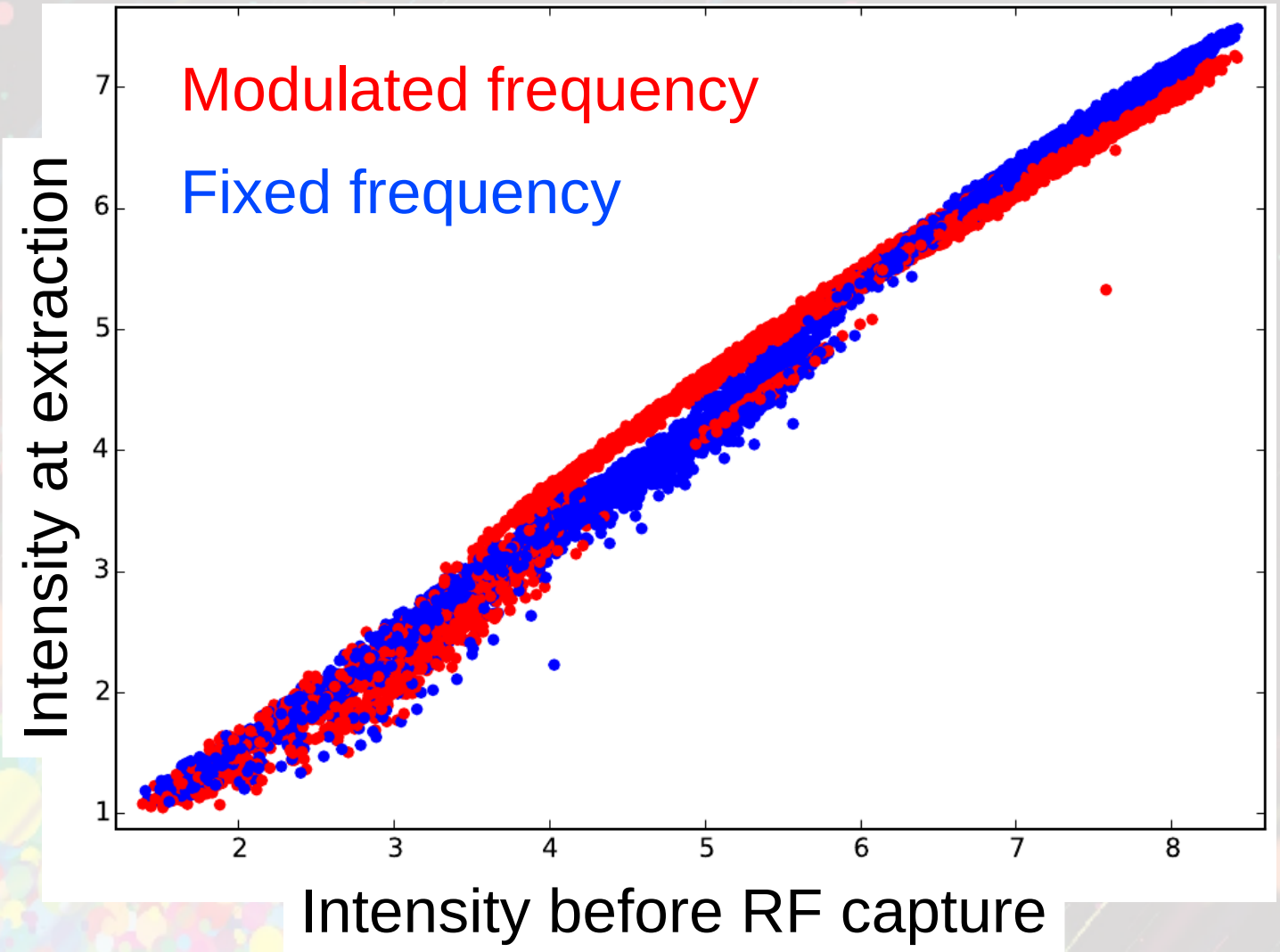
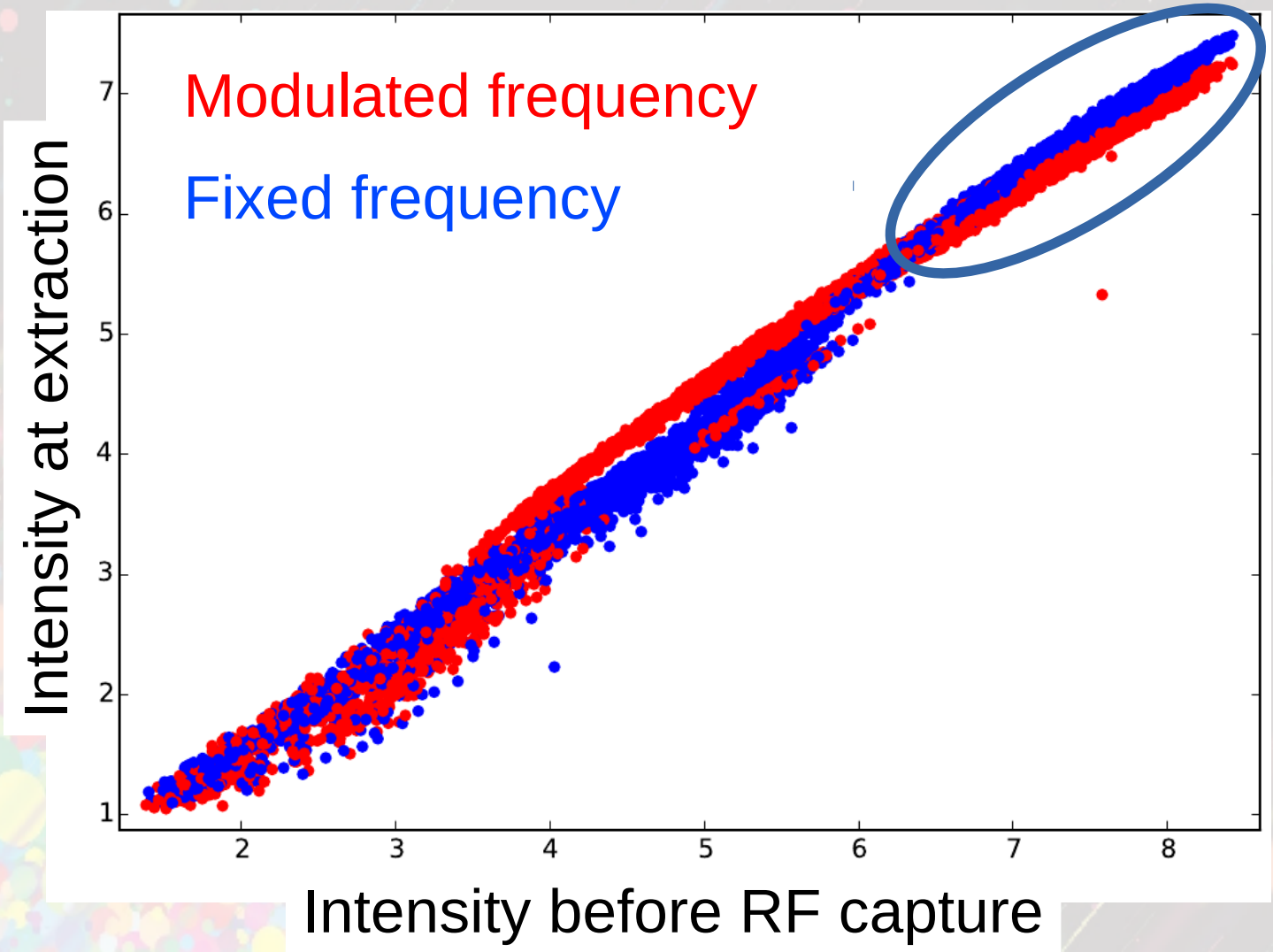
Application - LEIR



Application - LEIR



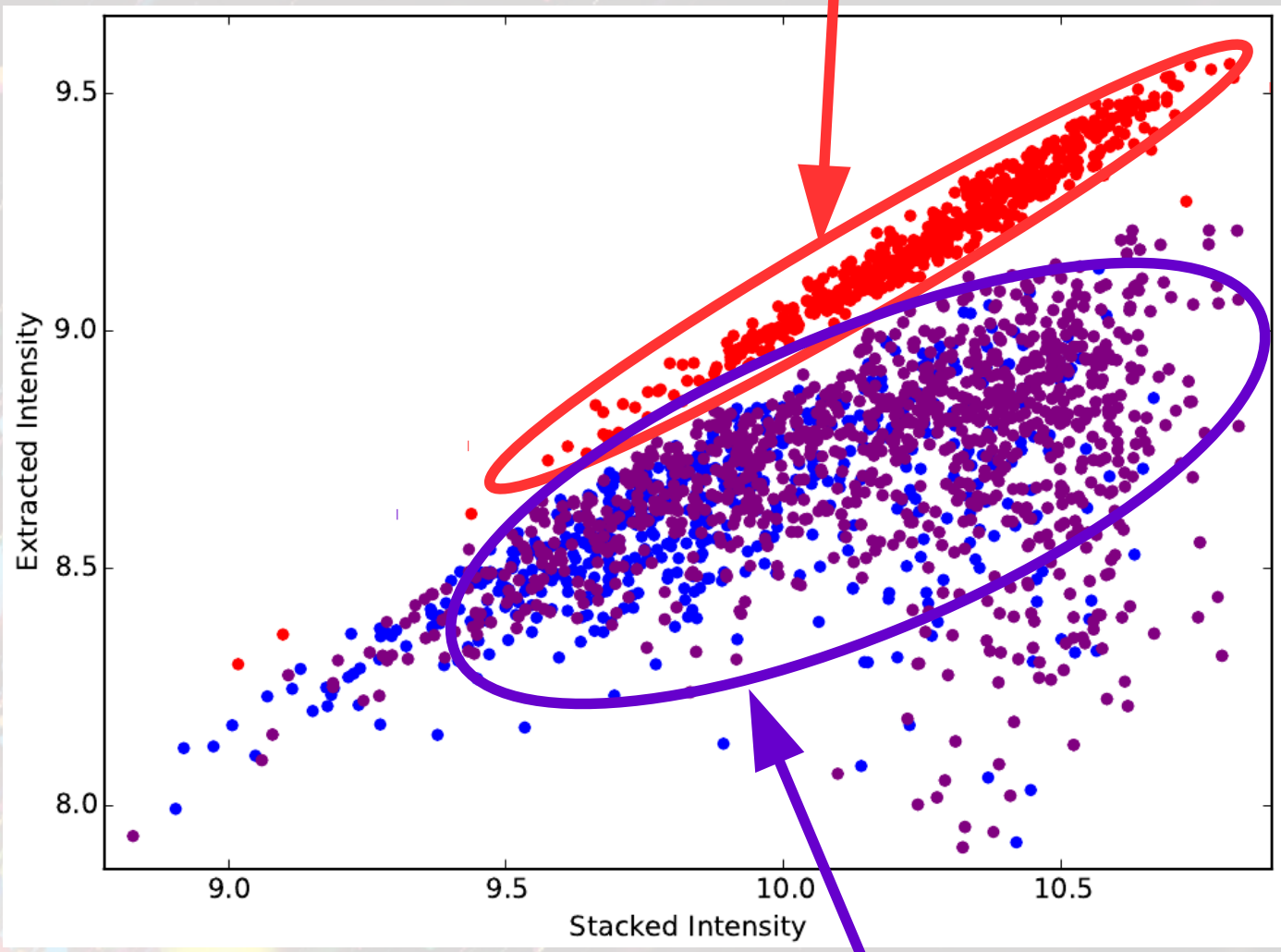
Large emittance worse at high intensity

Most likely explanation increased density in tune space on/near destructive resonance lines

Application - LEIR

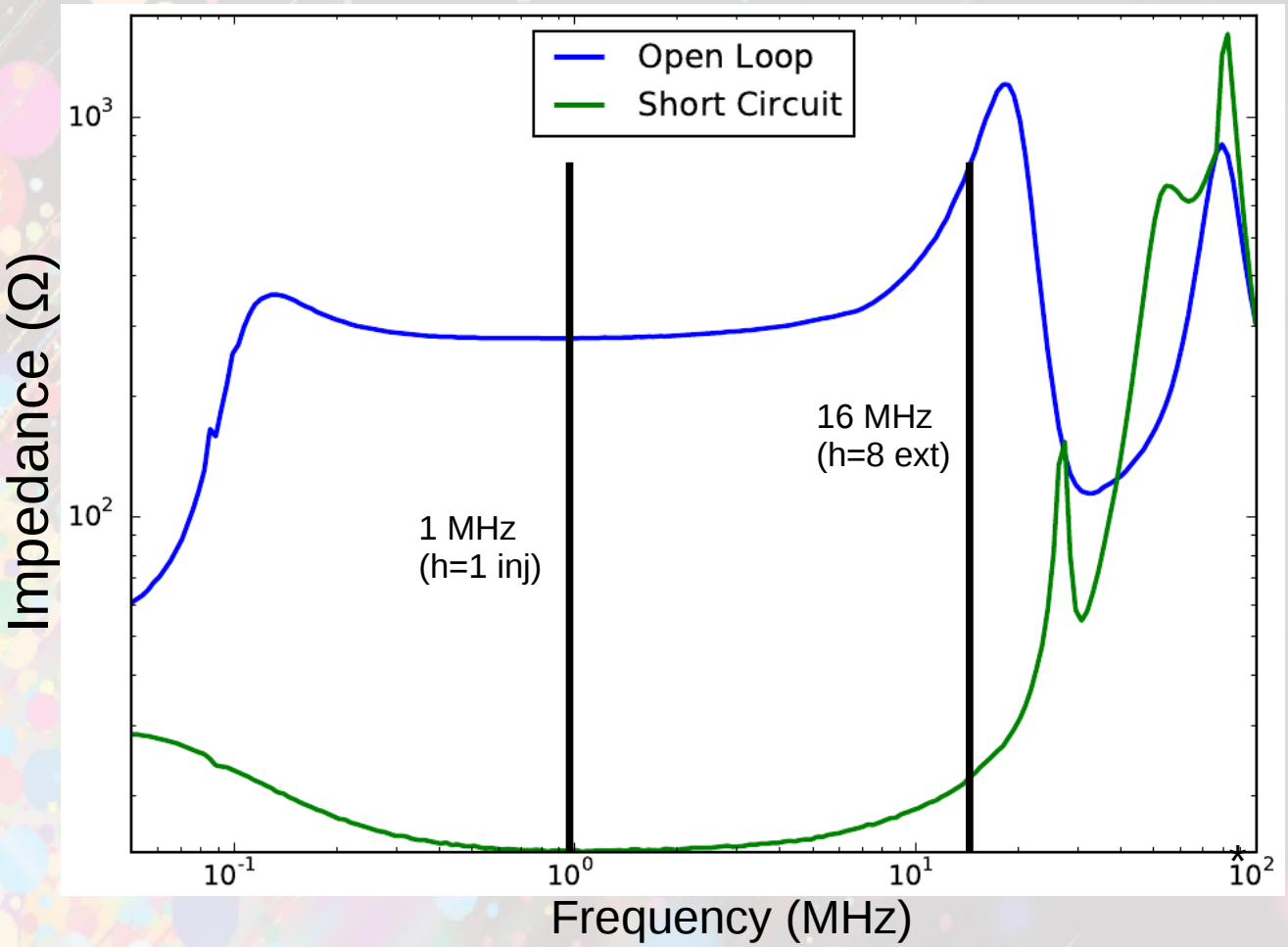
Increase Q_V ~ 0.02 at capture

Gain ~10% extracted intensity for high intensity shots



Application - PSB

- PSB future RF broadband Finemet cavities, total voltage is limit, not voltage per harmonic
- More flexibility, tailor injection bucket to required effect
- $V_1 = V_2$ only one possibility



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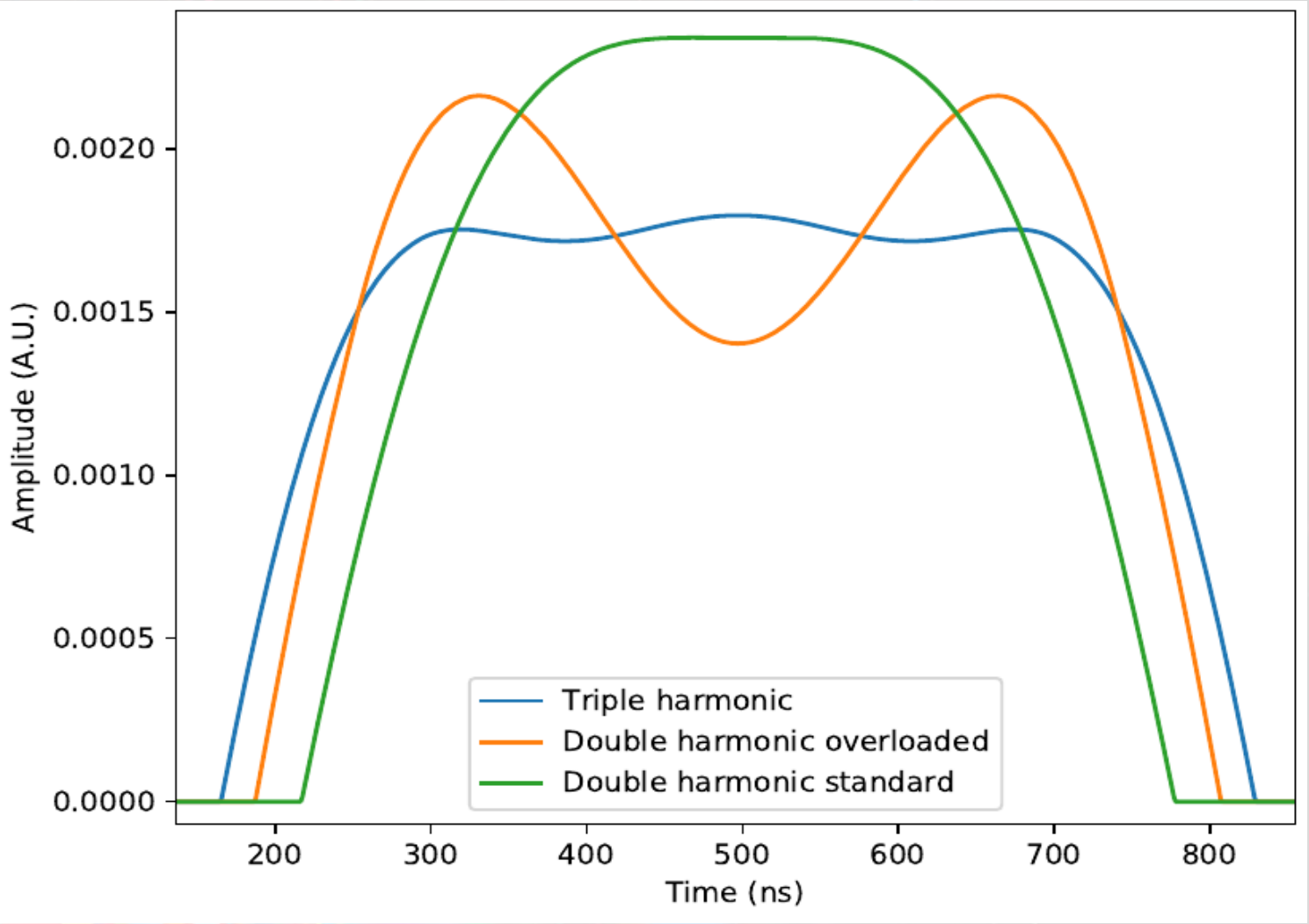

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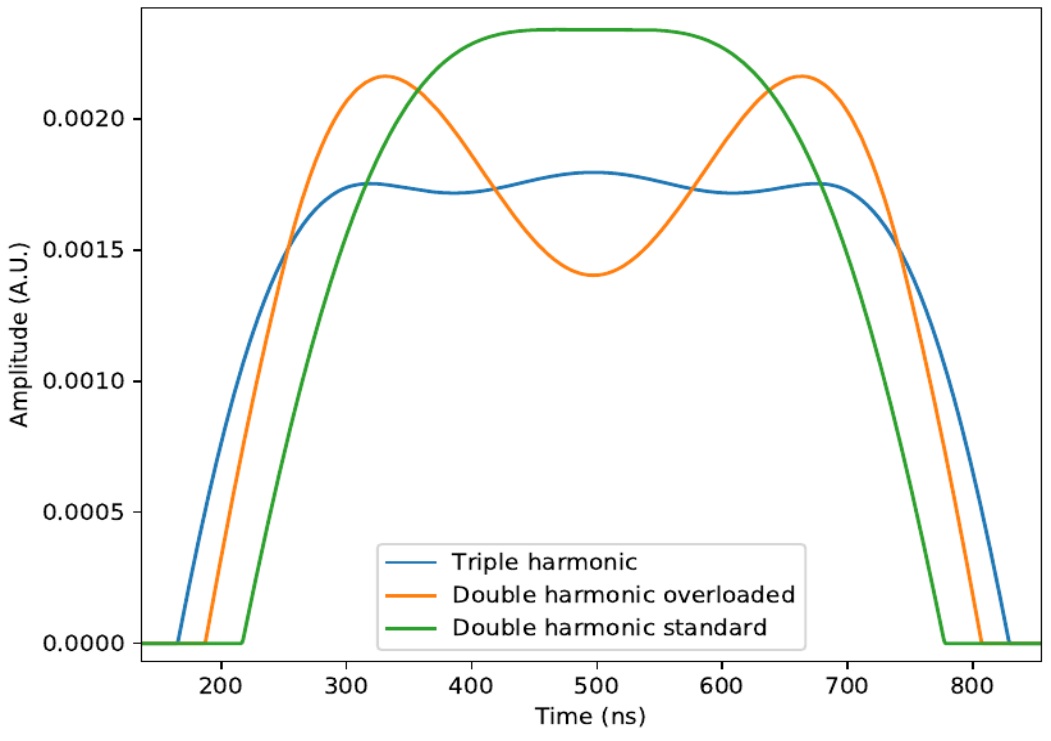
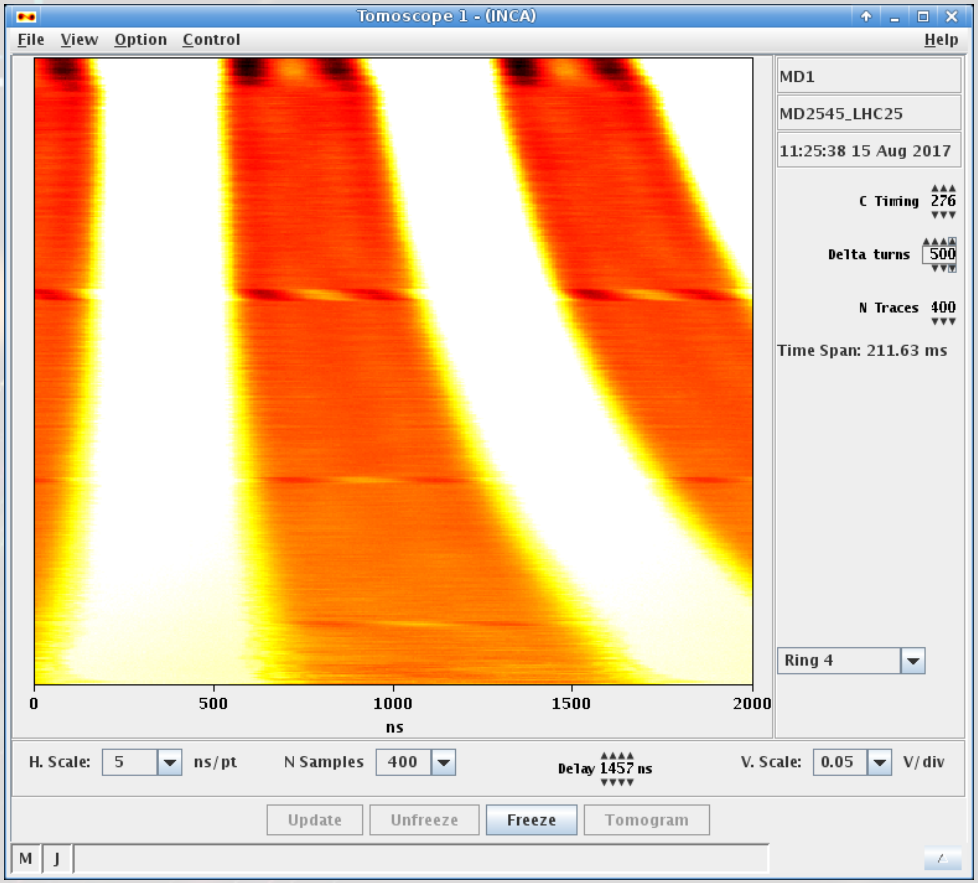
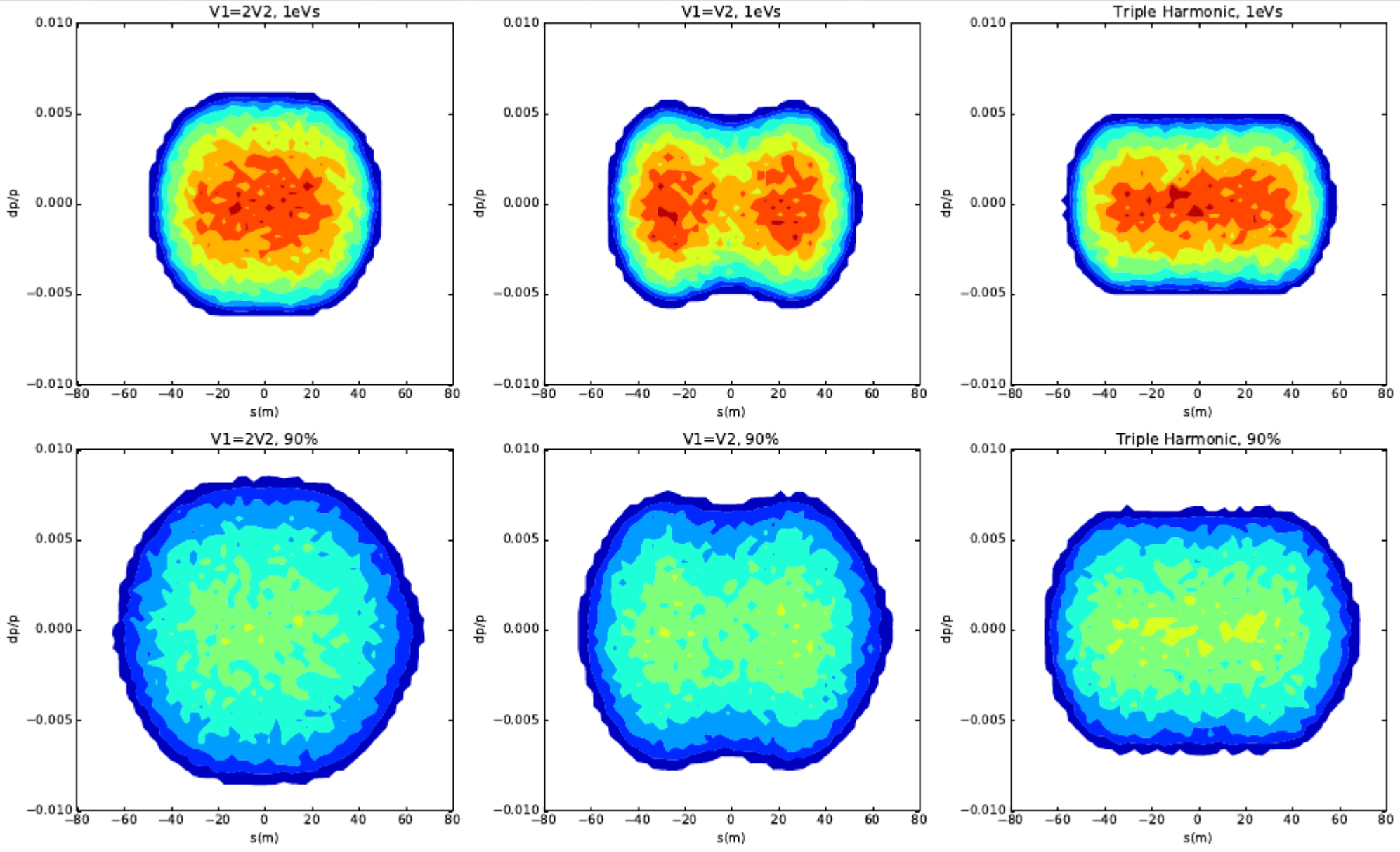
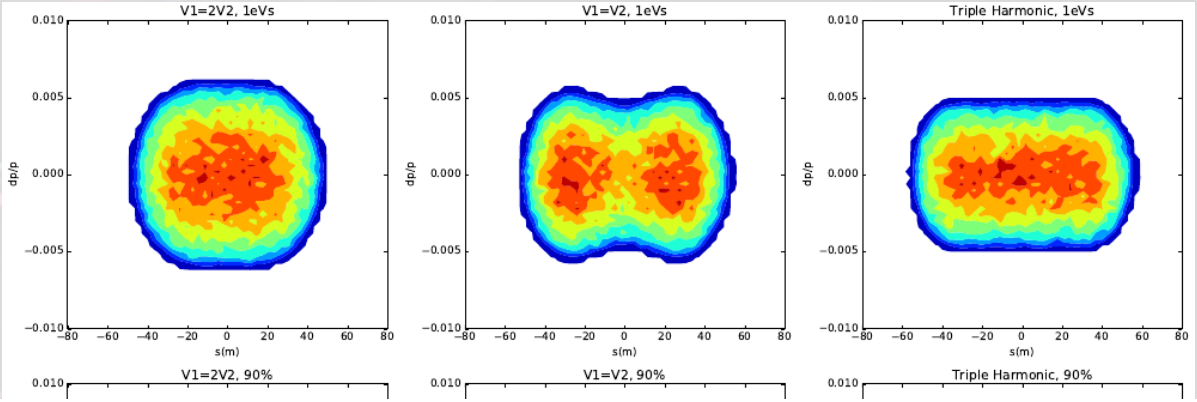


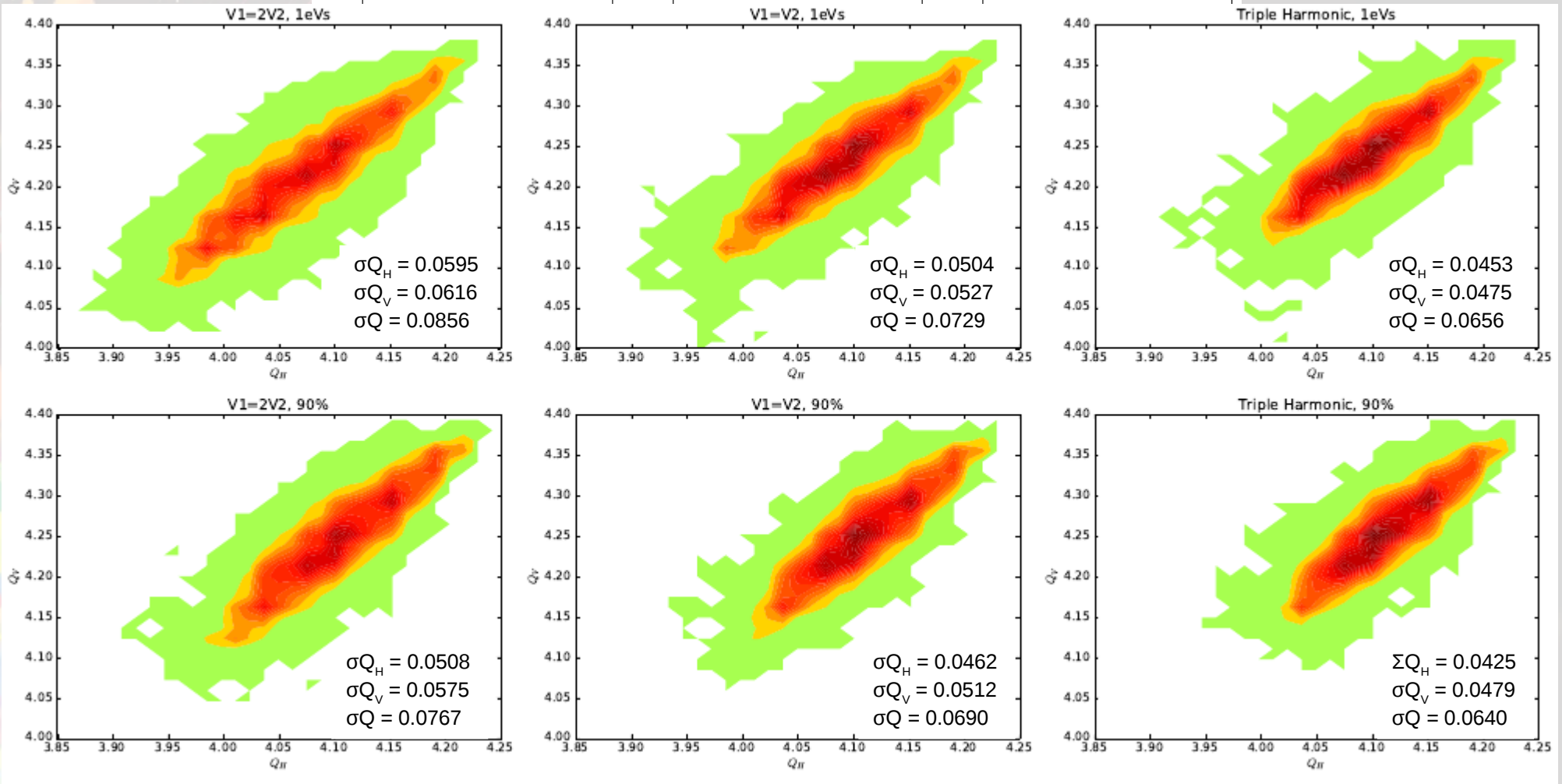


Application - PSB

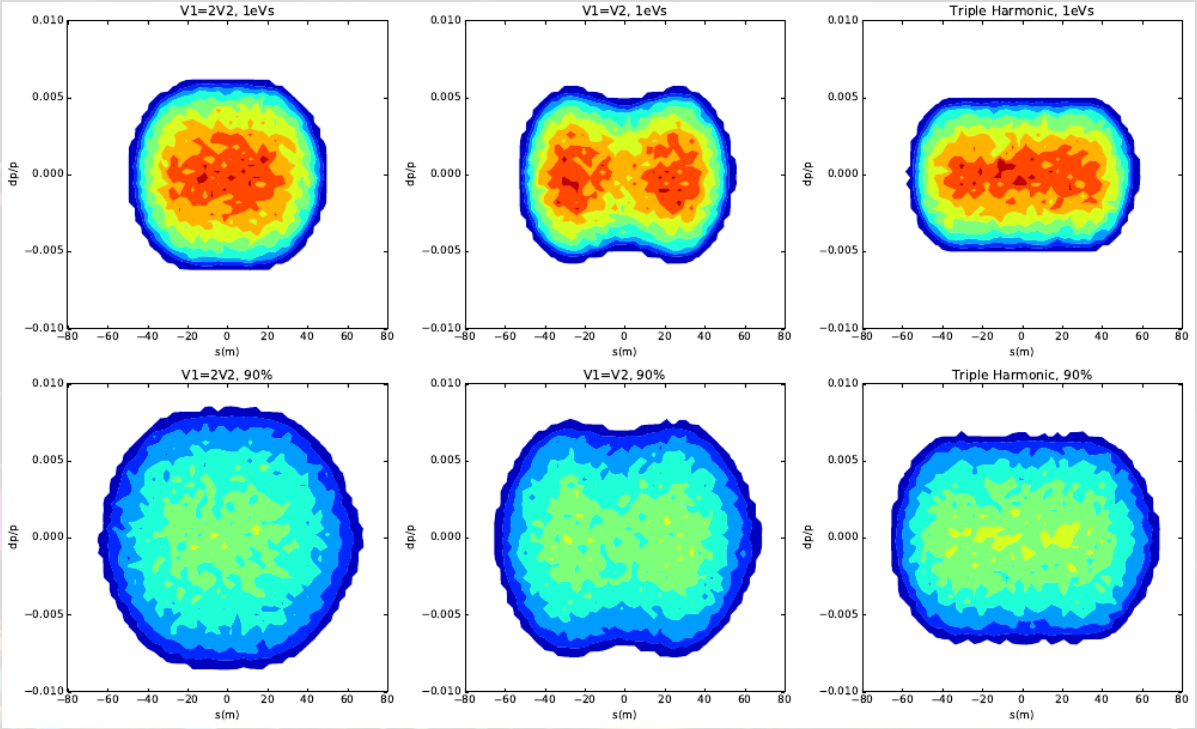


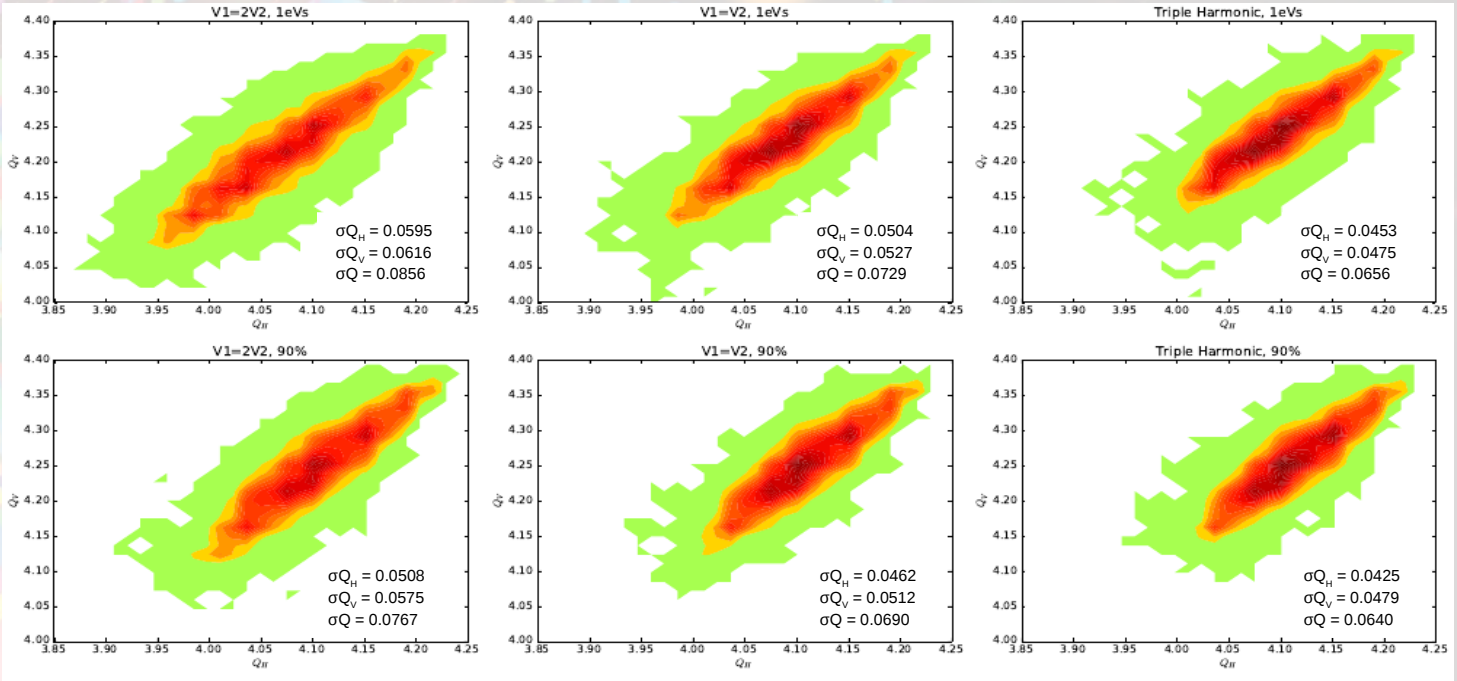
Application - PSB





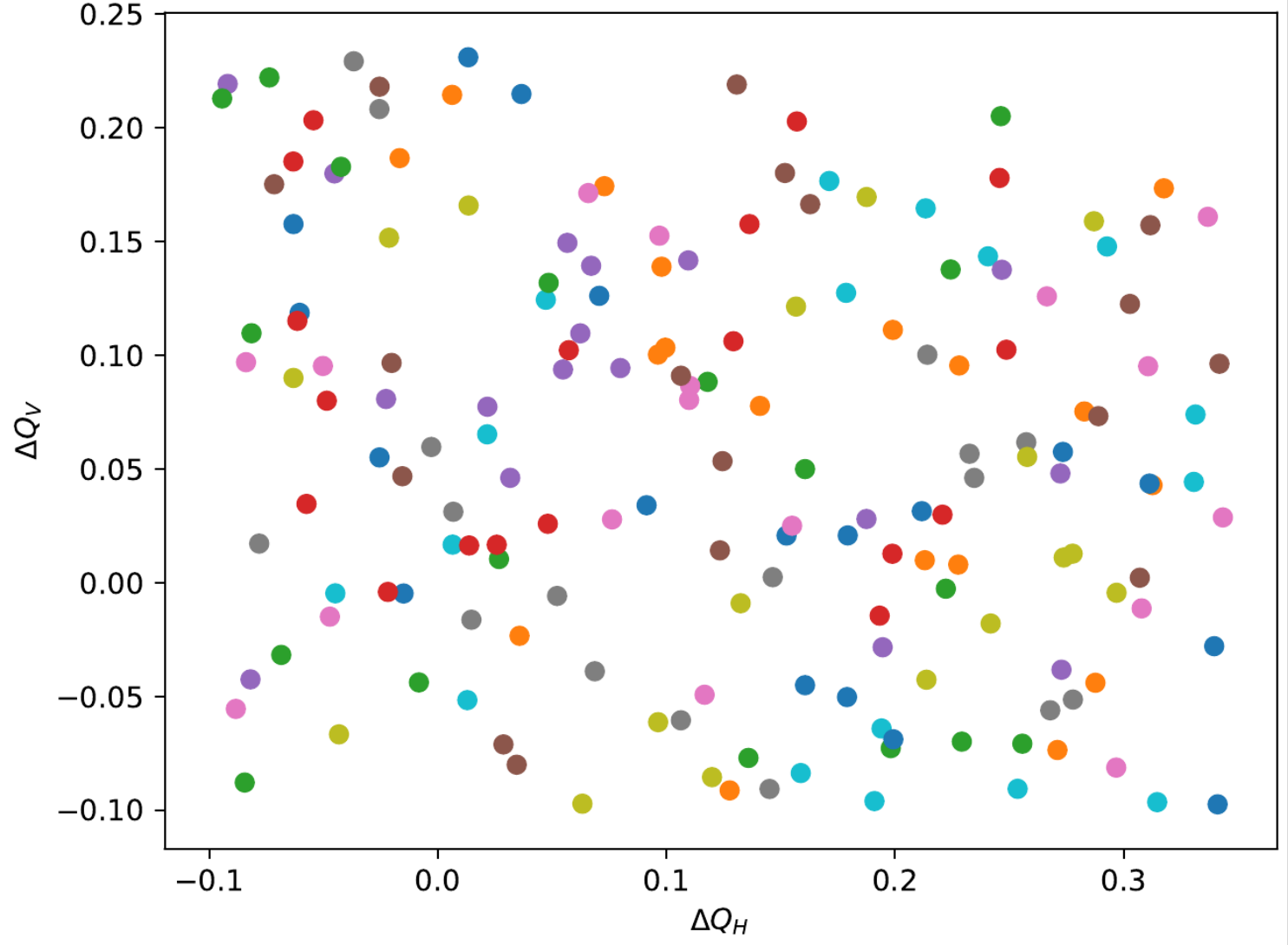
Application - PSB





Application - PSB

- As with LEIR capture ideal working point is likely to change due to footprint change
- Random sampling of around operational working point (ΔQ_H, ΔQ_V) at injection to find ideal working point and indicate relative size of footprint
- If footprint is smaller it should be possible to have a larger area of tune space with the same emittance growth



Application - PSB

Triple harmonic

Double harmonic

- As with LEIR capture ideal working point is likely to change due to footprint change
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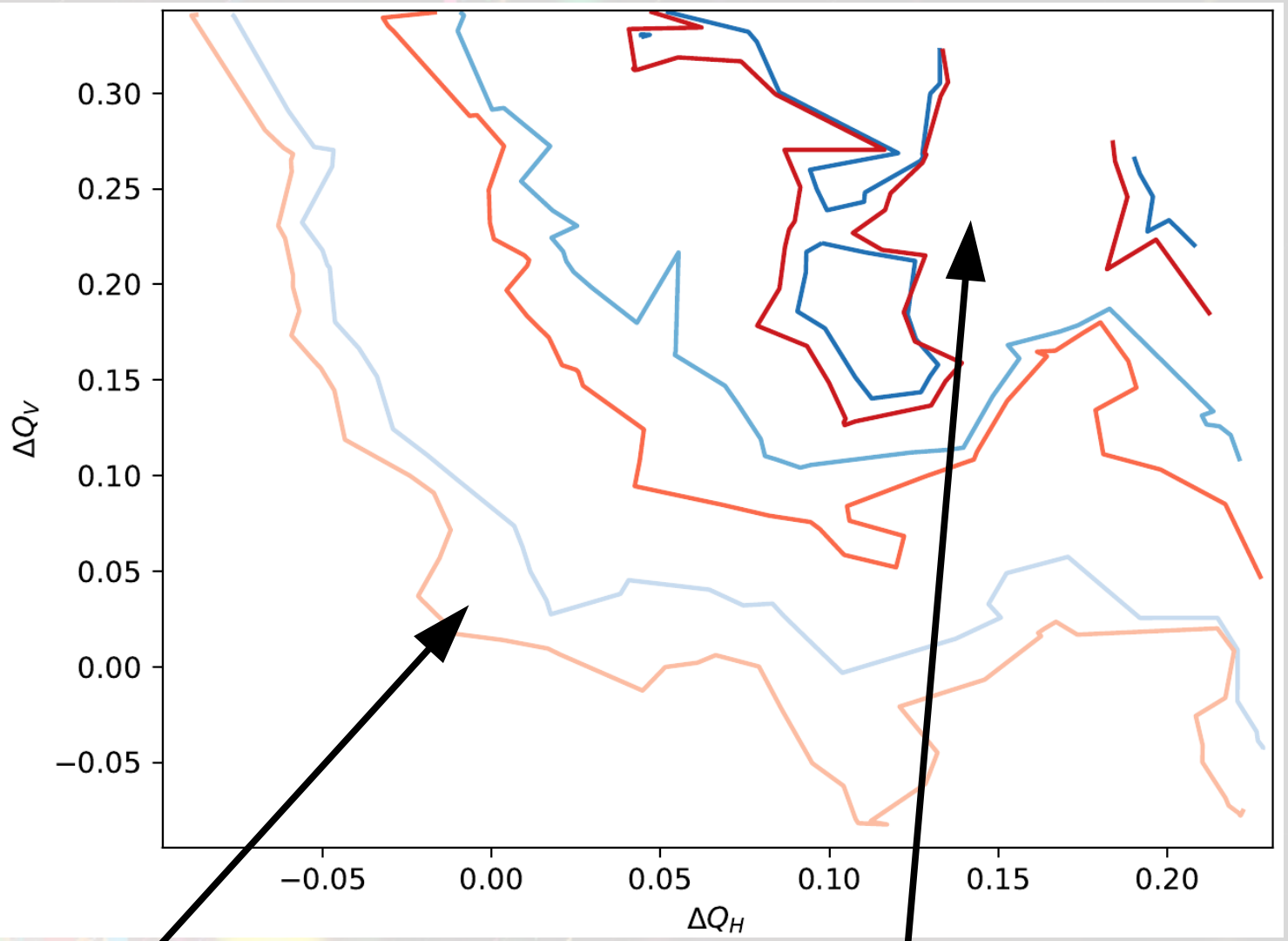

High emittance (large blow-up)

Low emittance (small blow-up)

Application - PSB

Triple harmonic

Double harmonic

- As with LEIR capture ideal working point is likely to change due to footprint change
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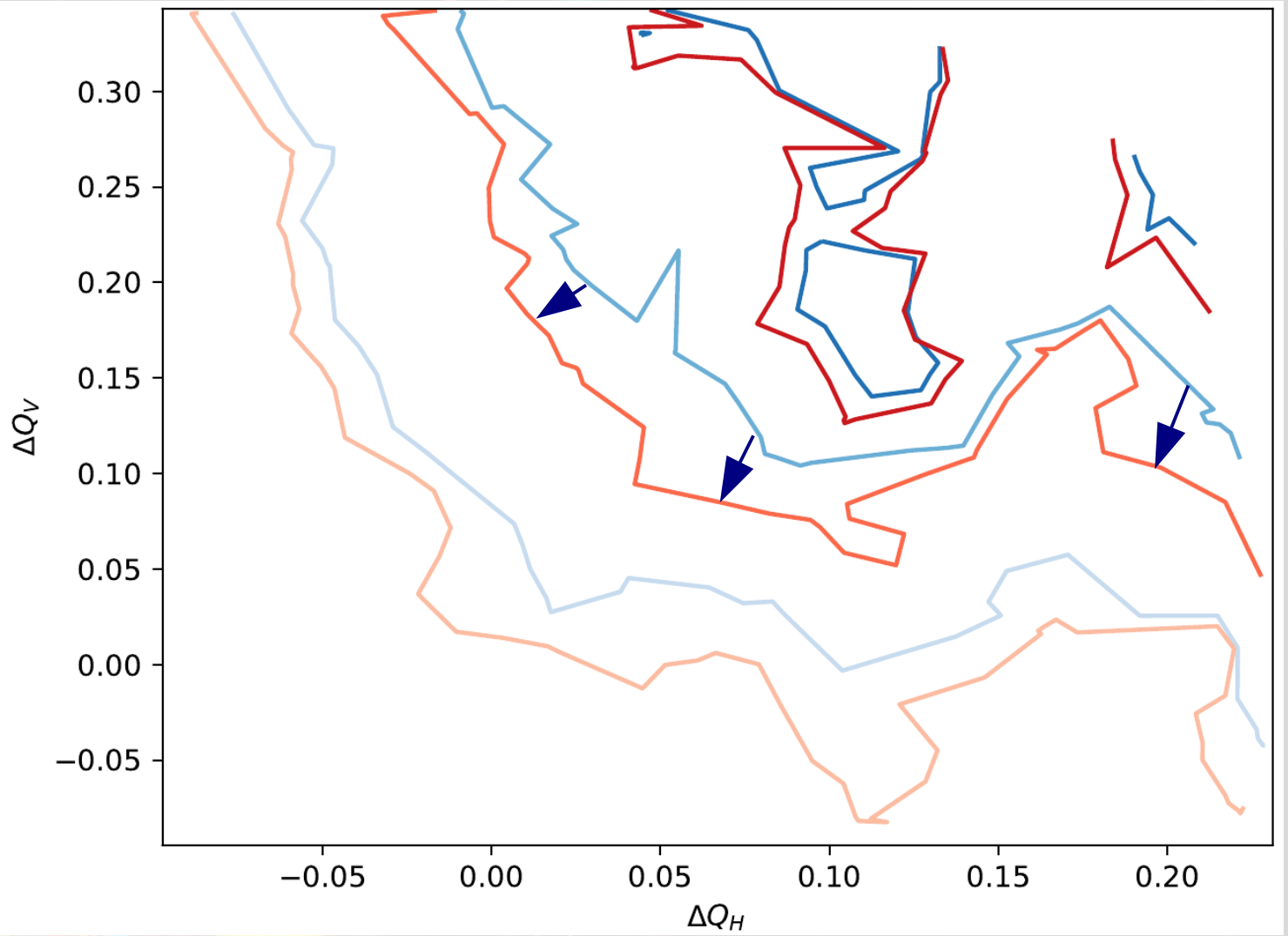
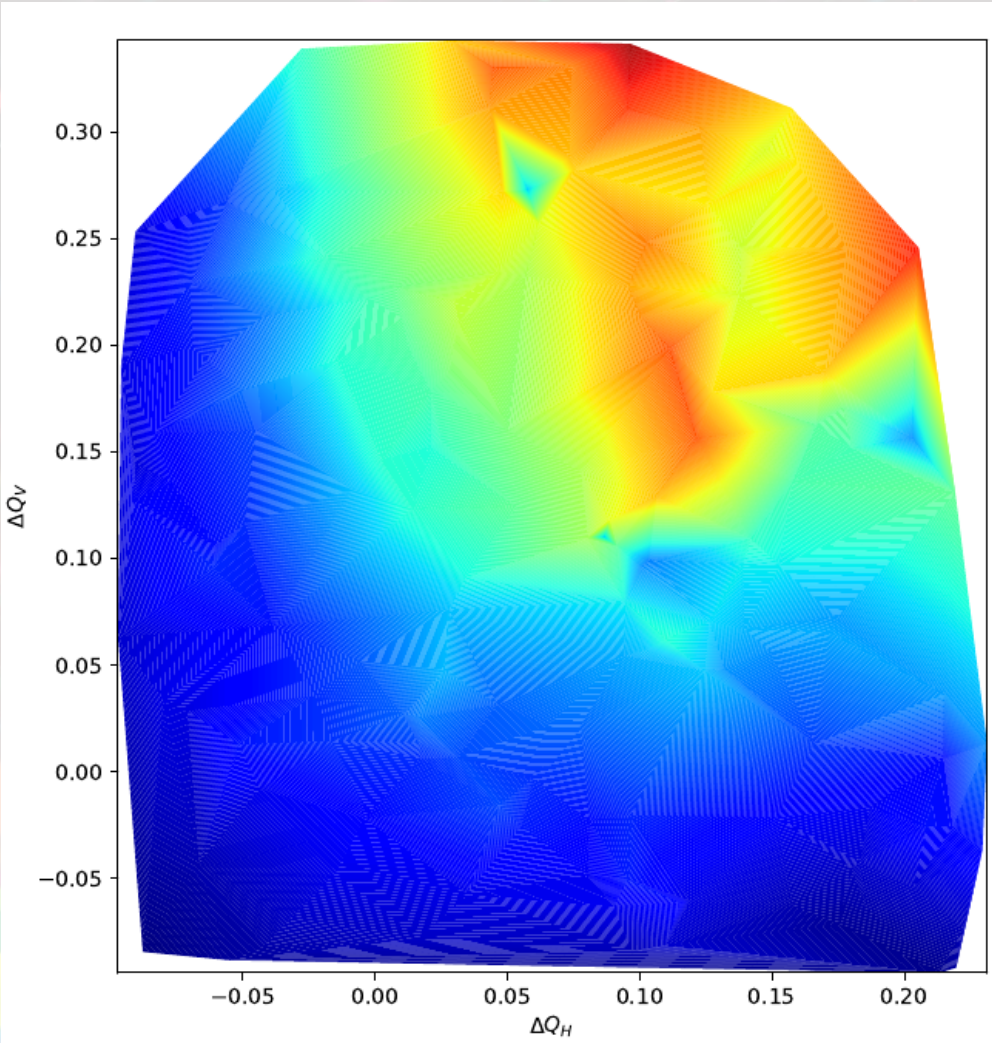
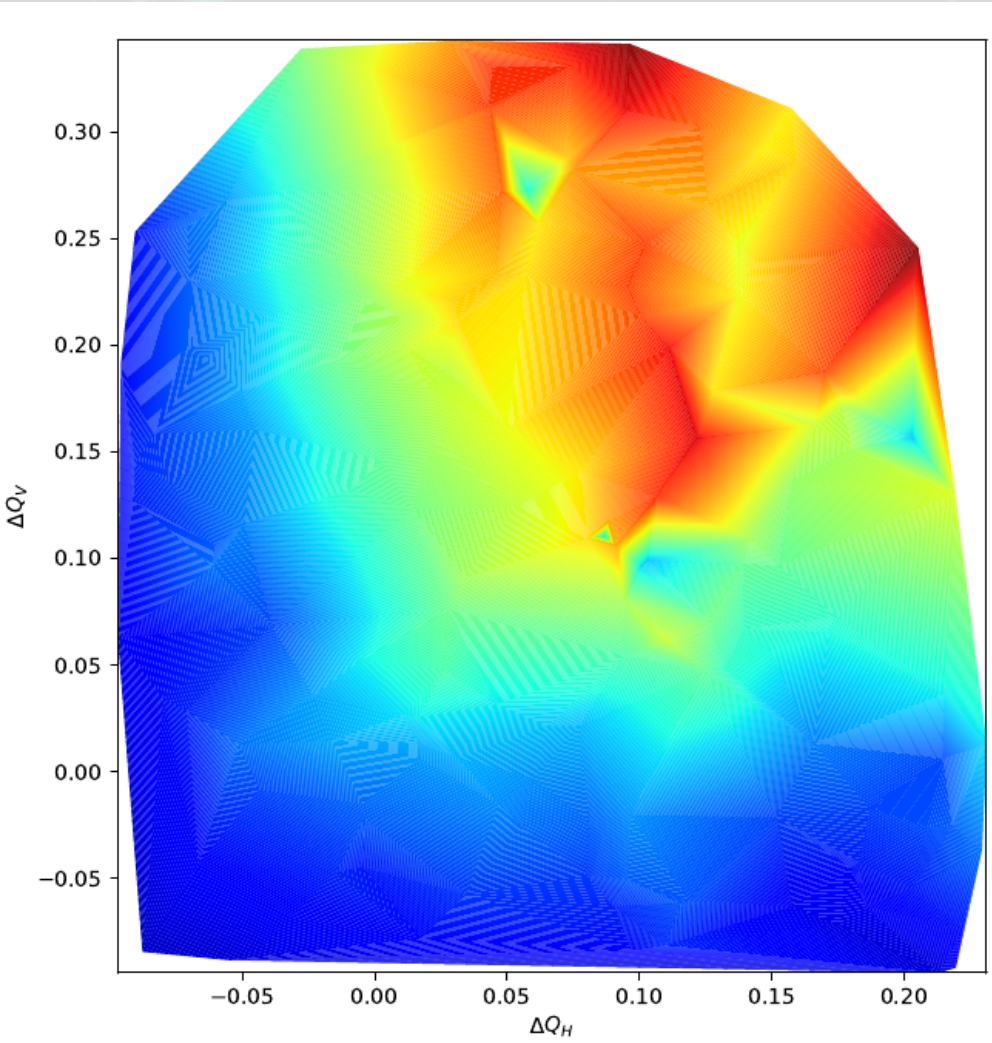


Application - PSB

Double harmonic

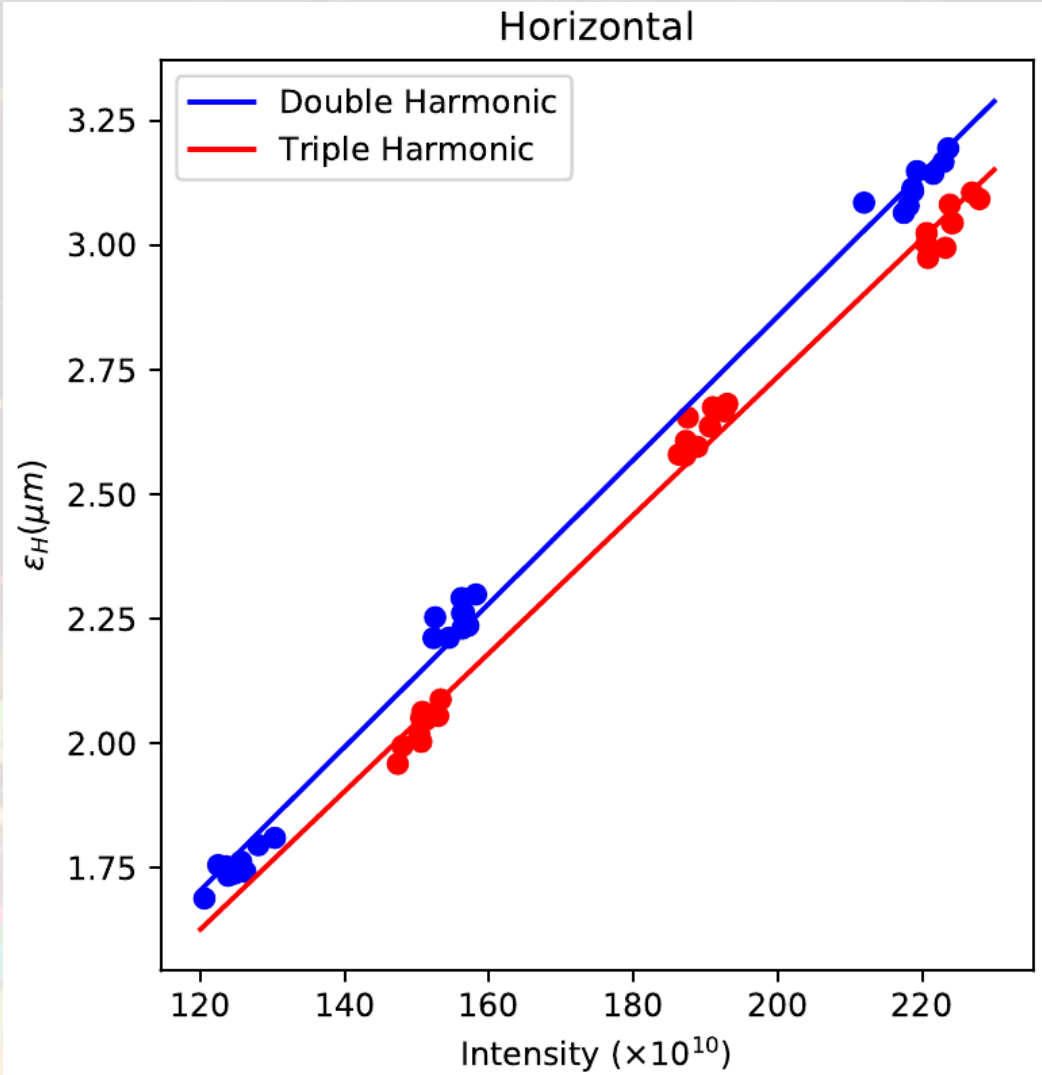


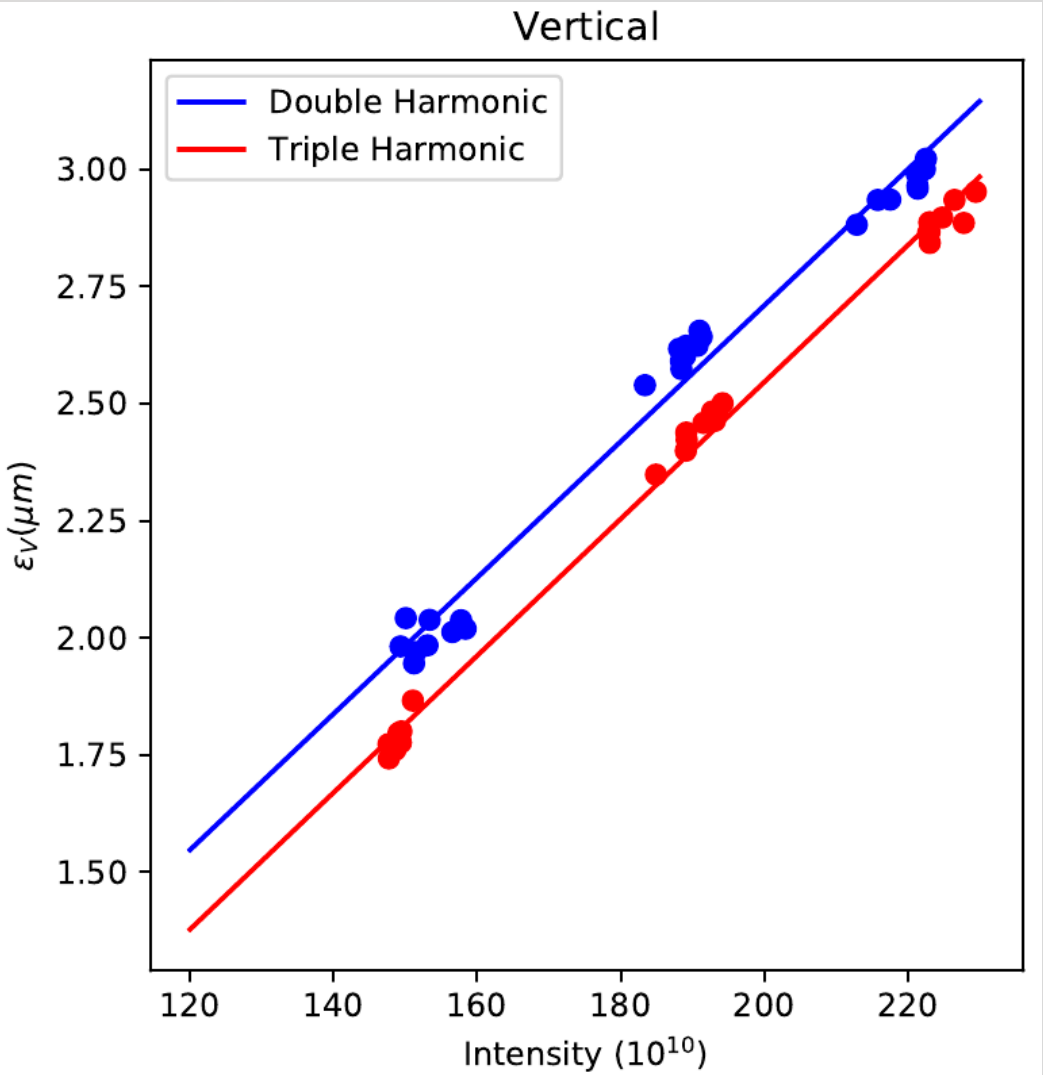
Triple harmonic



- Compare brightness across full (ΔQ_H, ΔQ_V) range
- Maximum brightness and “good” area appear larger for triple harmonic case

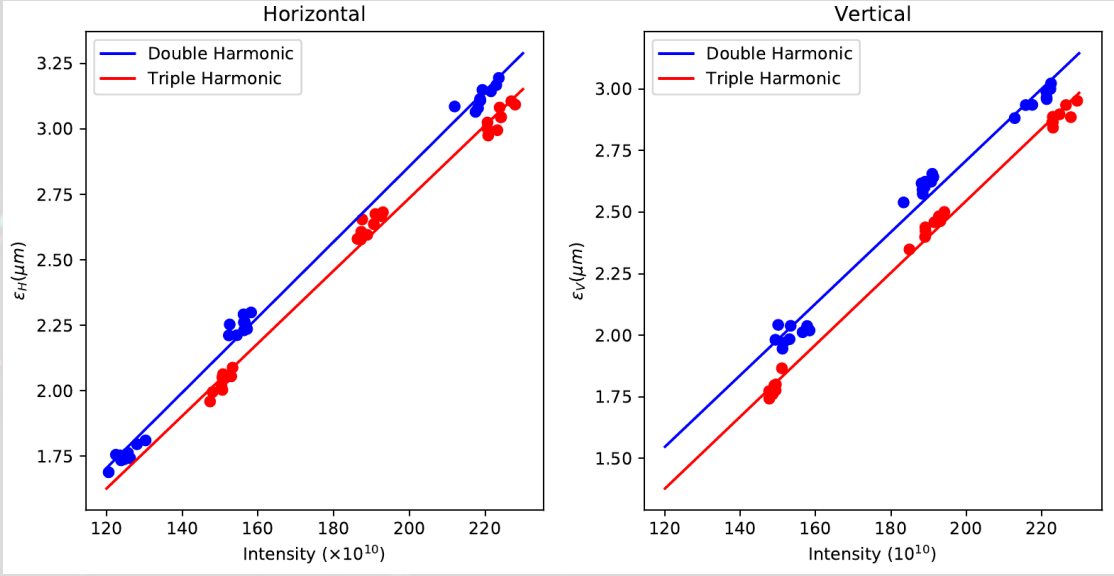
Application - PSB

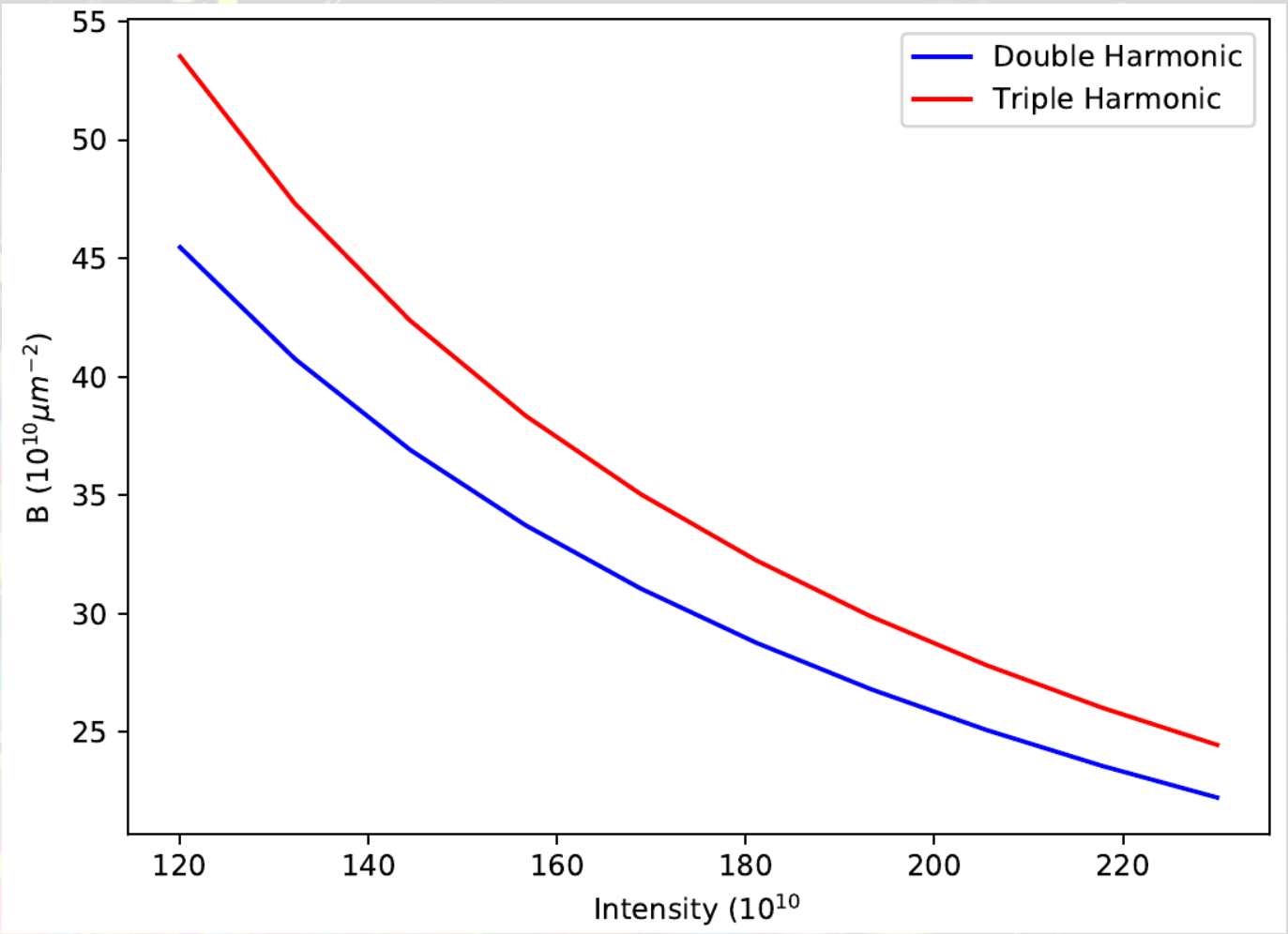




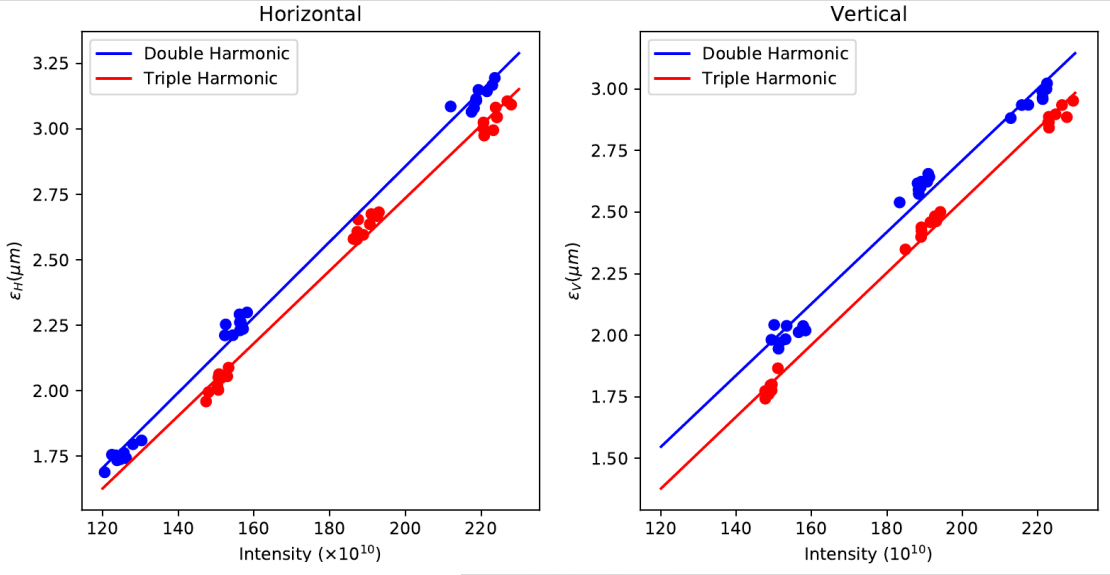
- Choose best working point for both double and triple harmonic cases and measure brightness curve
- ε_H reduced by ~0.1μm, ε_v reduced by ~0.2μm

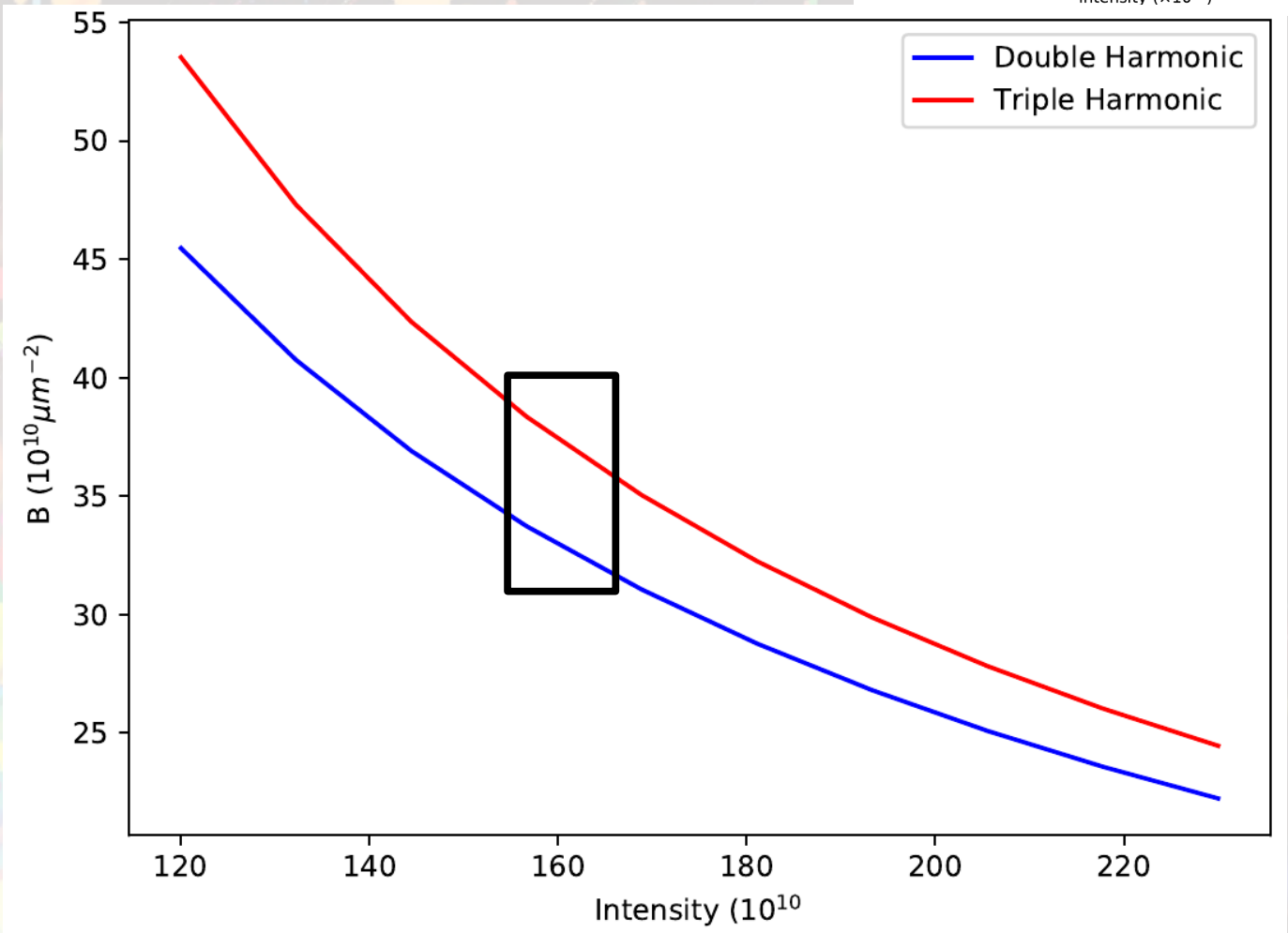
Application - PSB





Application - PSB

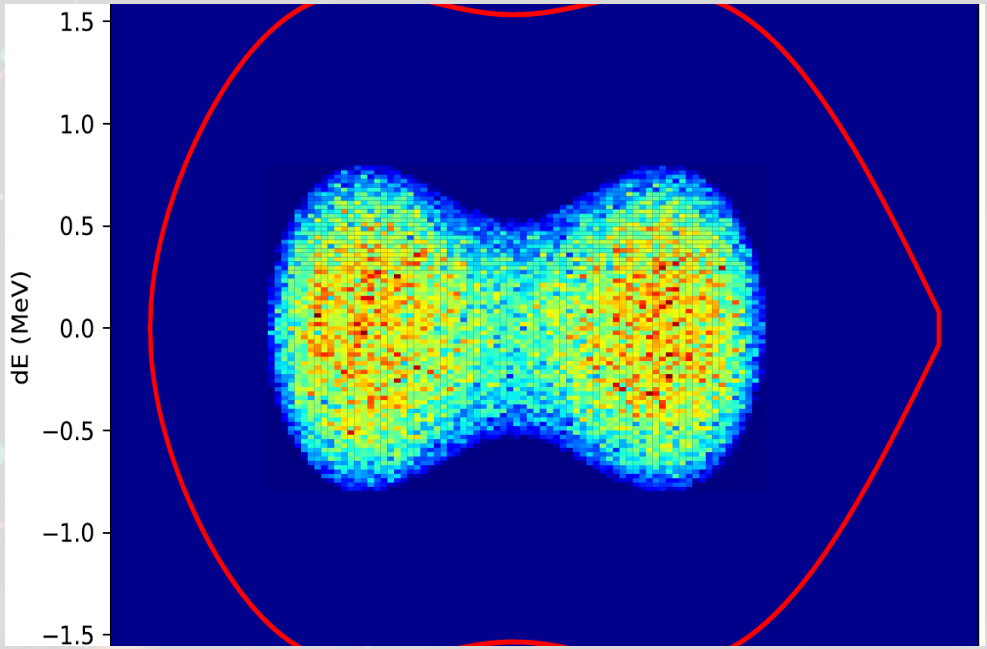


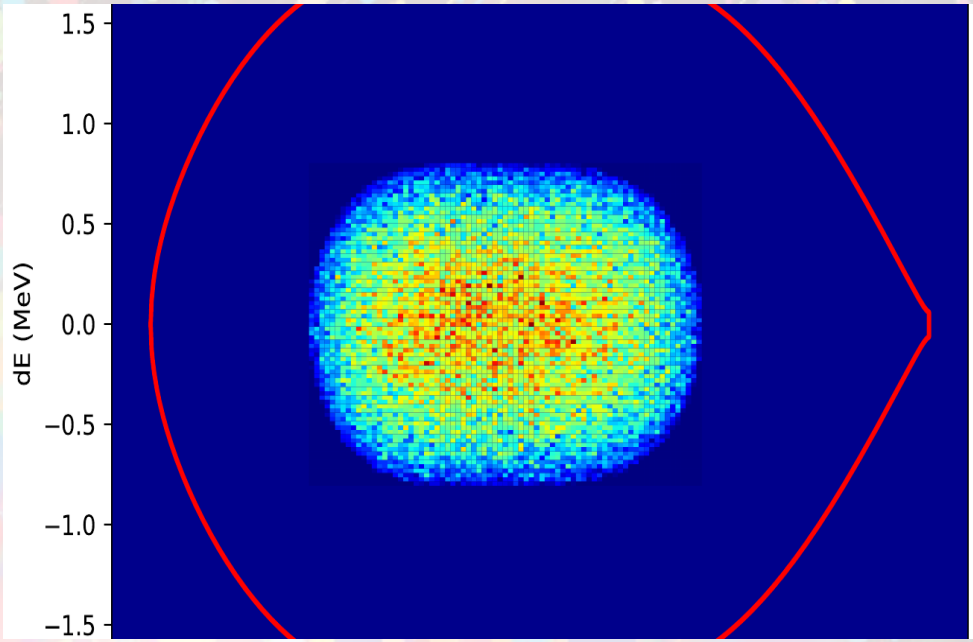


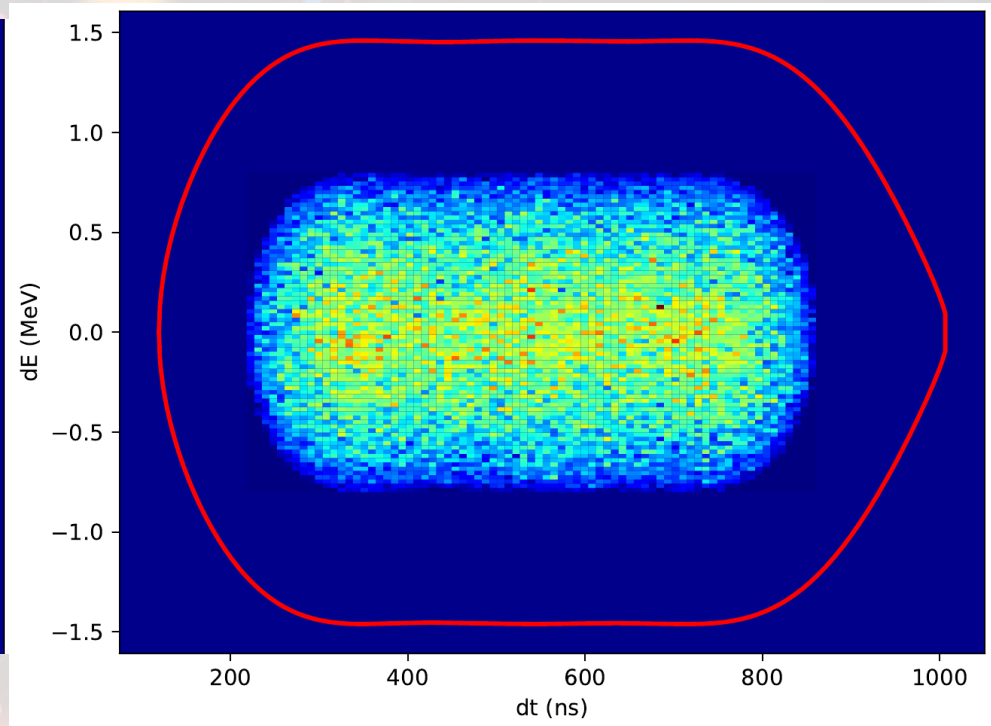
One version of LHC filling intensity (160E10) brightness is increased by approximately 10% for the same total voltage

Application - PSB

- Additional gain may be possible after LS2 due to longitudinal painting
- Longitudinal painting with +/- 0.8 MeV





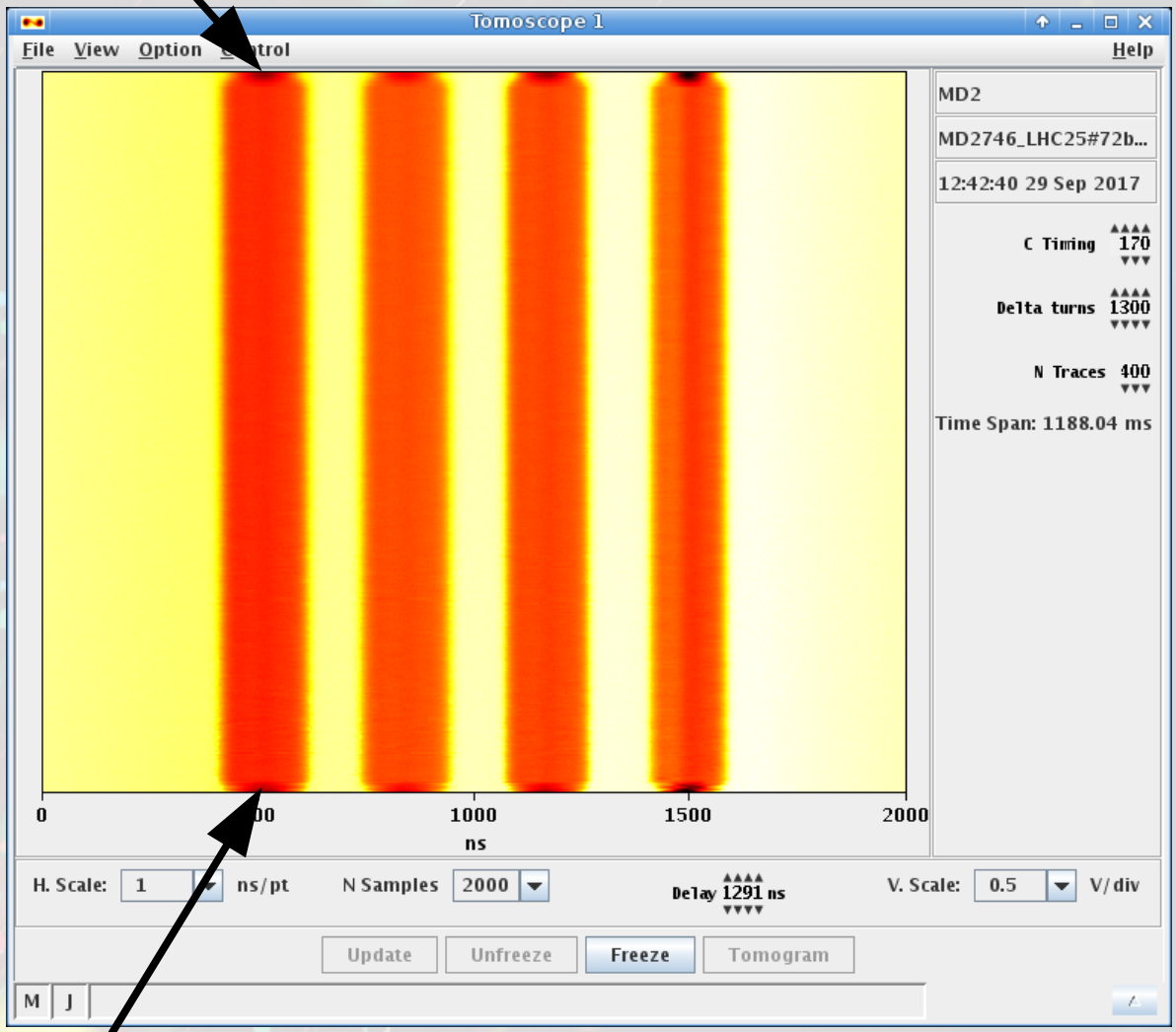


Future work

PS

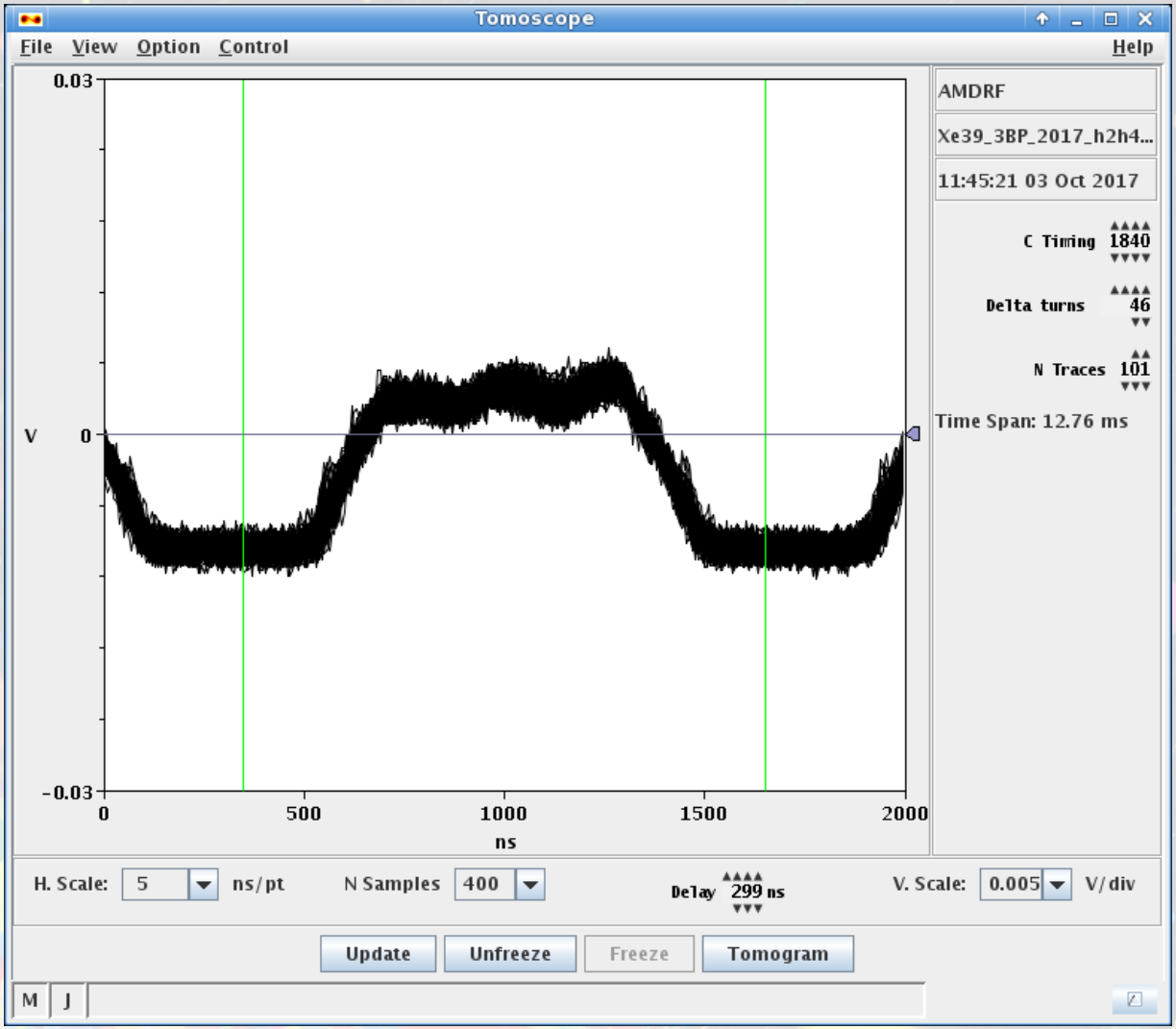
- LHC filling cycle has 2 injections
- 1.2s flat bottom for first injection waiting for second
- Ability to put beam into three harmonic bucket demonstrated for first time
- Cannot inject in multi-harmonic bucket, need to raise voltage over some ms, might be too late to prevent blow-up

Single harmonic for injection of second batch



Single harmonic for injection of first batch

Future work



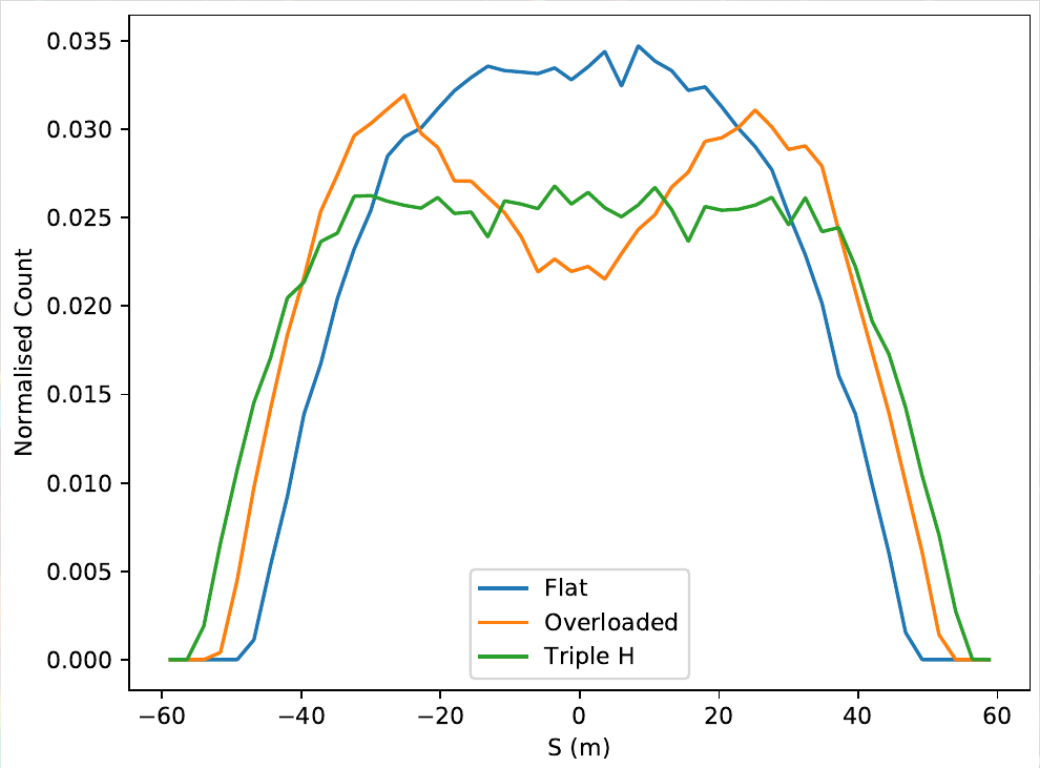
LEIR

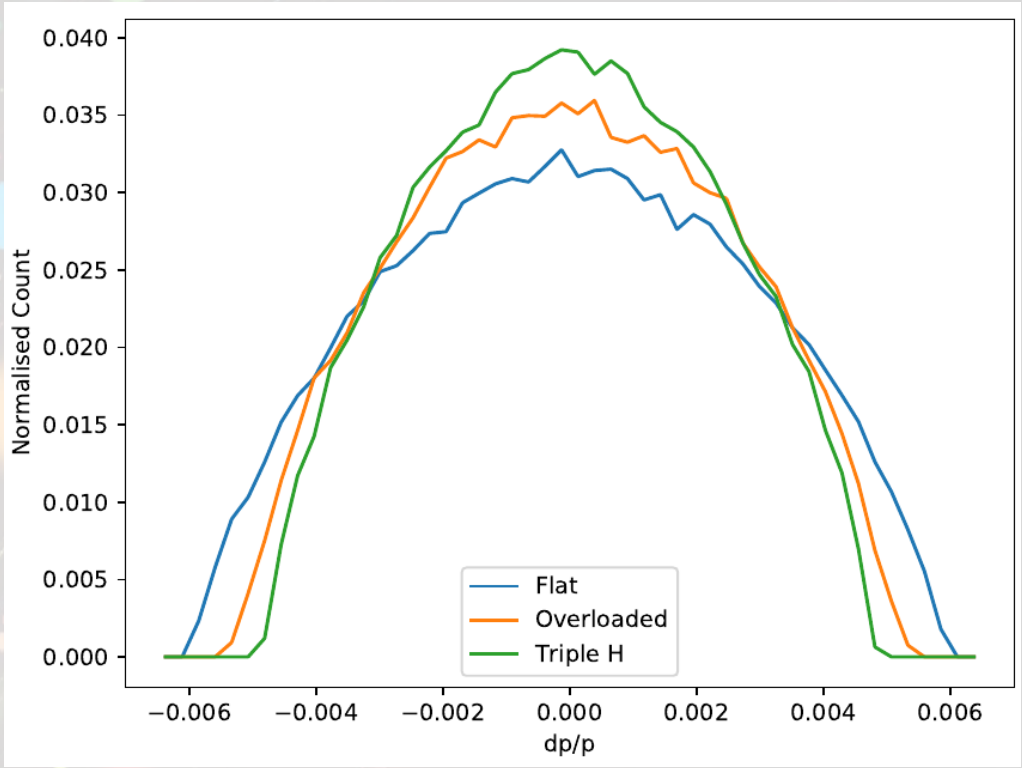
- Addition of third harmonic (h=6) has been provided
- Adiabatic capture into h=2+h=4+h=6 bucket demonstrated effectively
- Intensity problems prevented further investigations of intensity mitigation, but studies planned for near future

Conclusion

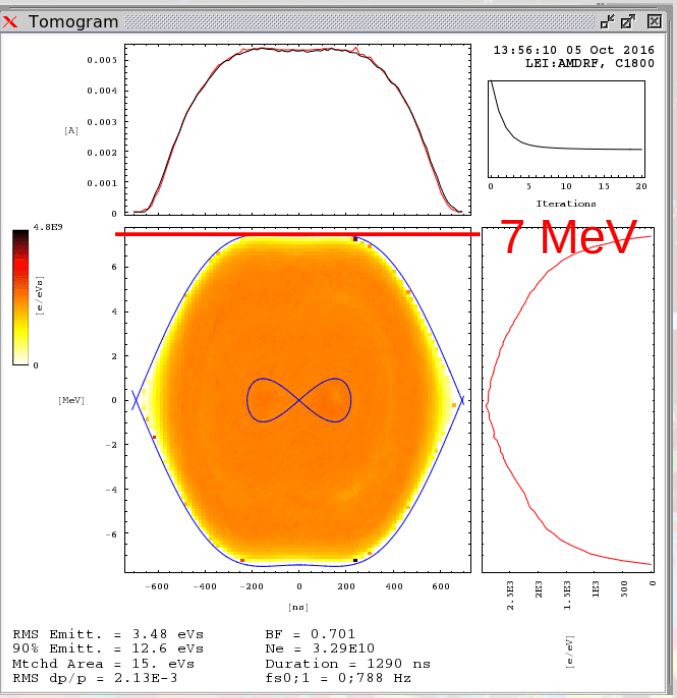
- Two regimes of interest, intensity limited and brightness limited
- Traditional longitudinal emittance blow-up ineffective – damage done too quickly
- RF frequency modulation during capture in LEIR provided maximum longitudinal emittance increasing extracted intensity
- Addition of third harmonic during capture in the PSB shows 10% increase in brightness for LHC filling cycle

Appendix

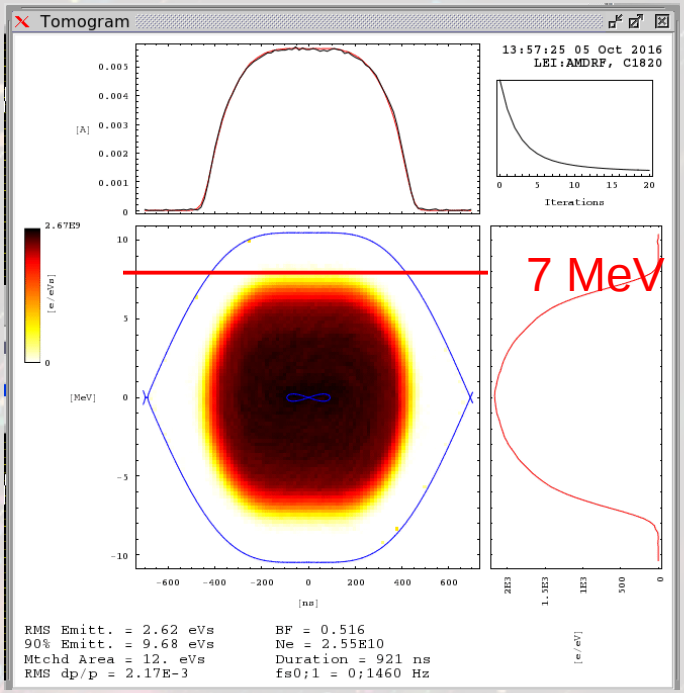

Normalised Count
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
−60
−40
−20
0
20
40
60
S (m)
Flat
Overloaded
Triple H


Normalised Count
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
−0.006
−0.004
−0.002
0.000
0.002
0.004
0.006
dp/p
Flat
Overloaded
Triple H

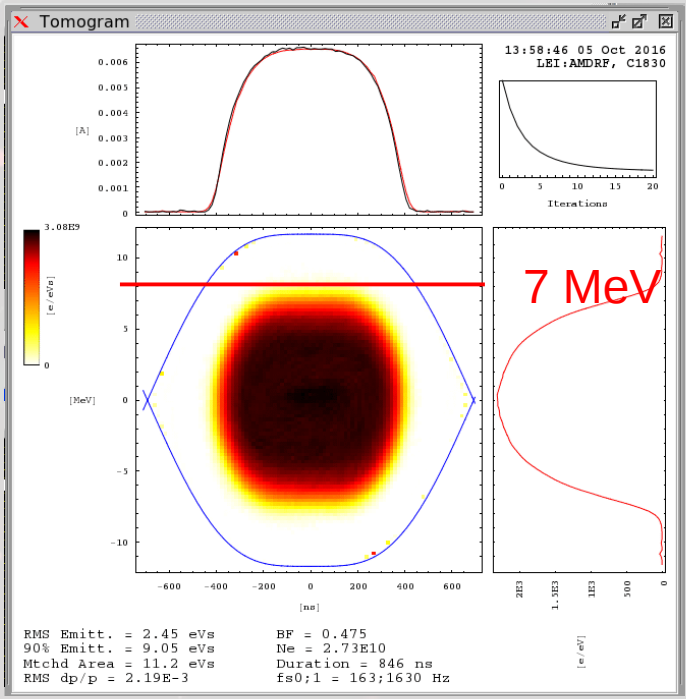
Appendix



C1800
15 eVs
dp/p: 2.13E-4

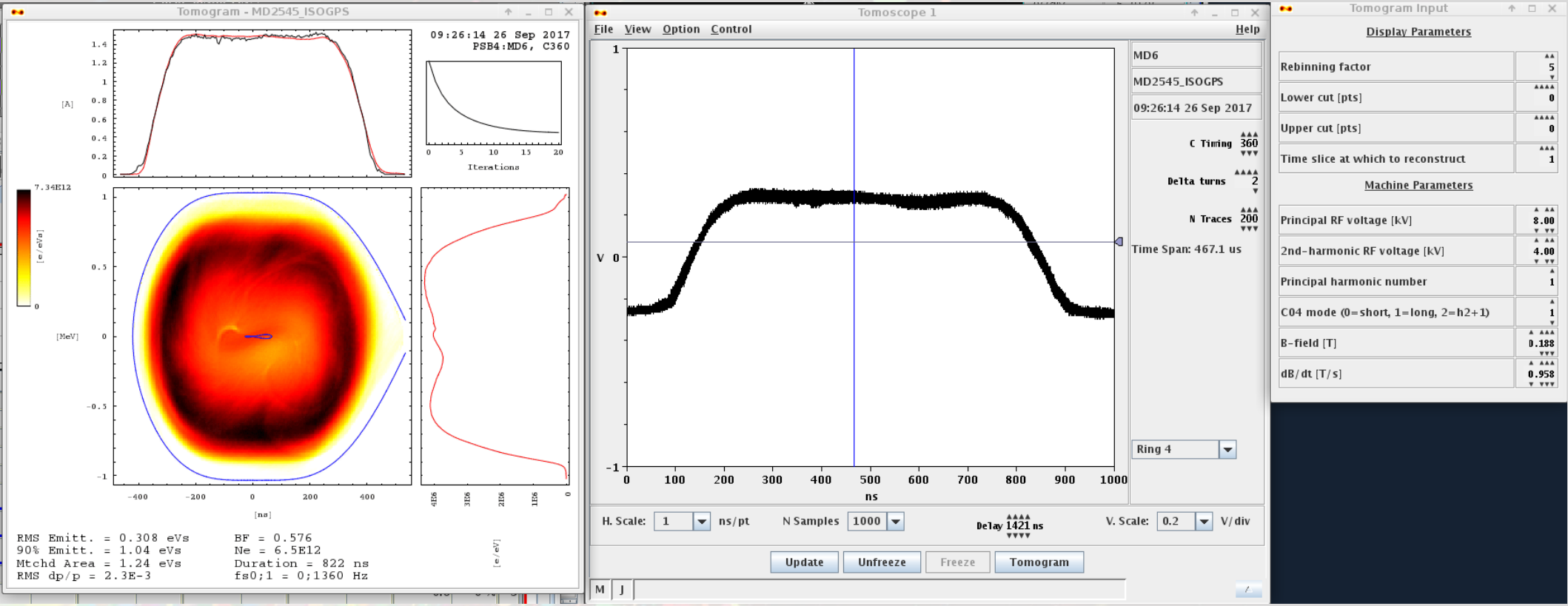


C1820
12 eVs
dp/p: 2.17E-4



C1830
11 eVs
dp/p: 2.19E-4

Appendix



Triple harmonic RF, tell Tomography $V_1 = 2V_2$, artificial hollow bunch