First experience with Crab Cavity MDs in the SPS

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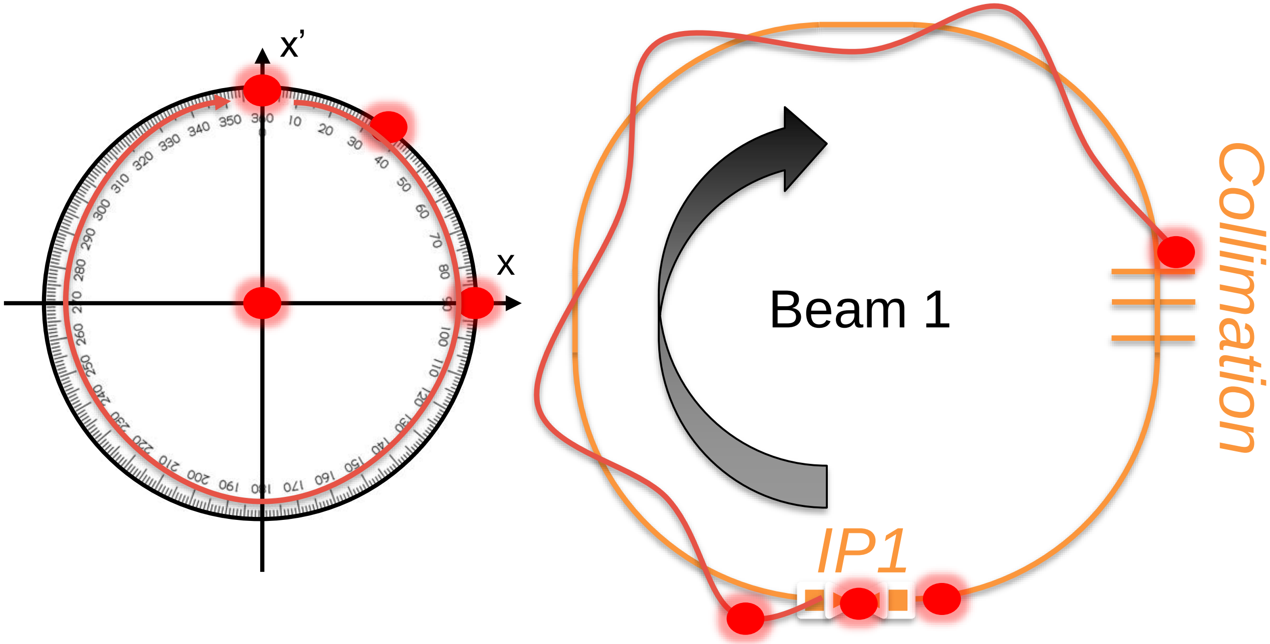
Betatron oscillations and phase advance



Transverse kick -> betatron oscillations
~harmonic oscillator with Quadropoles as the restoring force

Full turn phase advance (mod 360 degrees) = betatron tune
A kick resonant with the tune gives large excitations

Courtesy of M. Valette

Crab Cavities - what are they?

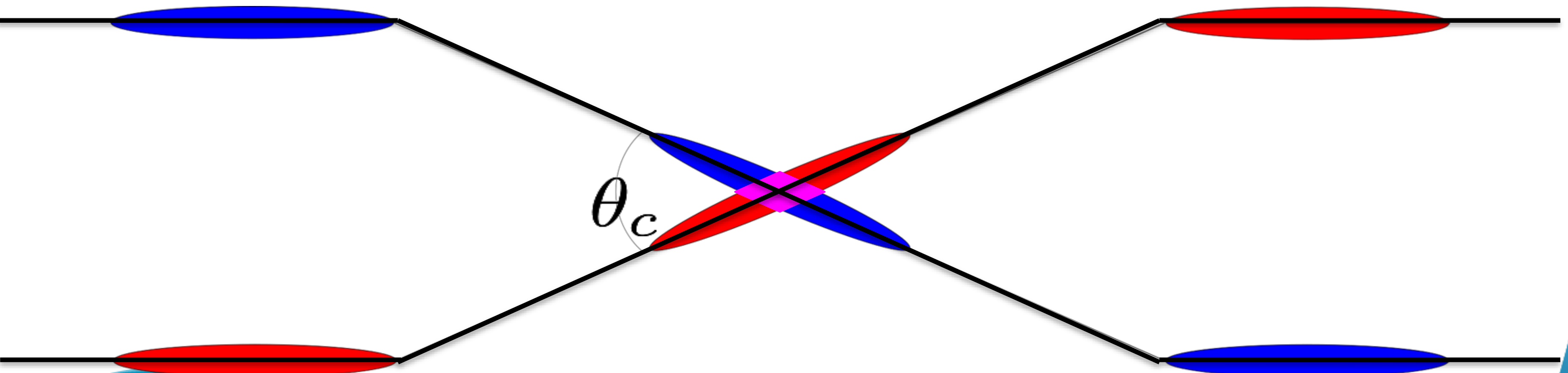
- In HiLumi LHC, due to smaller β* and to limit beam-beam effects the crossing angle will be increased
- → Lower luminosity:

$$L = \frac{n_b f_{rev} N_p^2}{4\pi\sigma_x^*\sigma_y^*} * F(\theta_c)$$

Geometric Factor

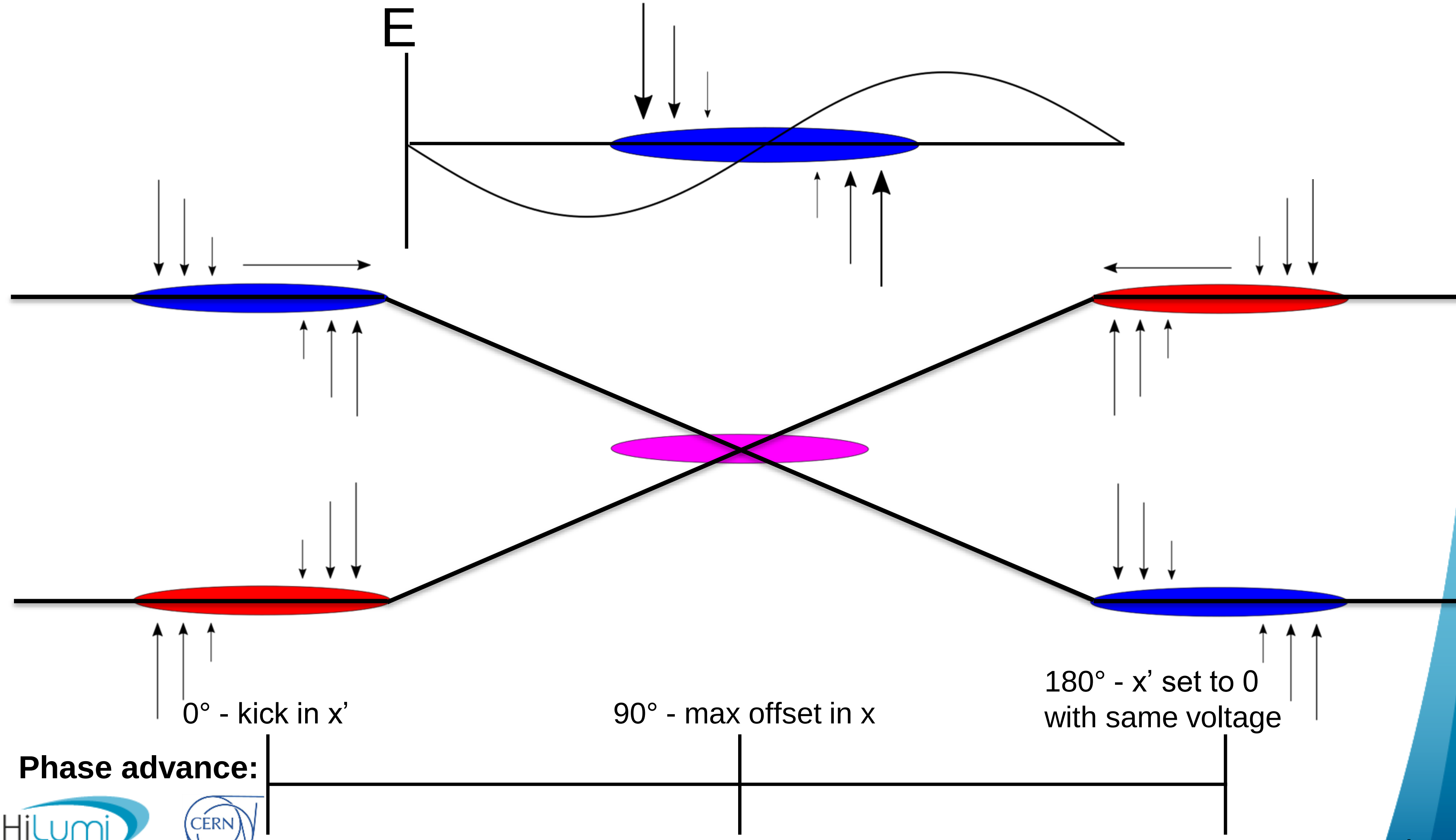
Piwinski Reduction (Geometric) Factor

	2012 LHC	2015 LHC	HL-LHC
$\theta_c[\mu rad]$	313	290	590
$F(\theta_c)$	0.88	0.85	0.31



Crab Cavities - what are they?

- Cavity with sinusoidal transverse kick - bunch is tilted - better overlap at crossing point

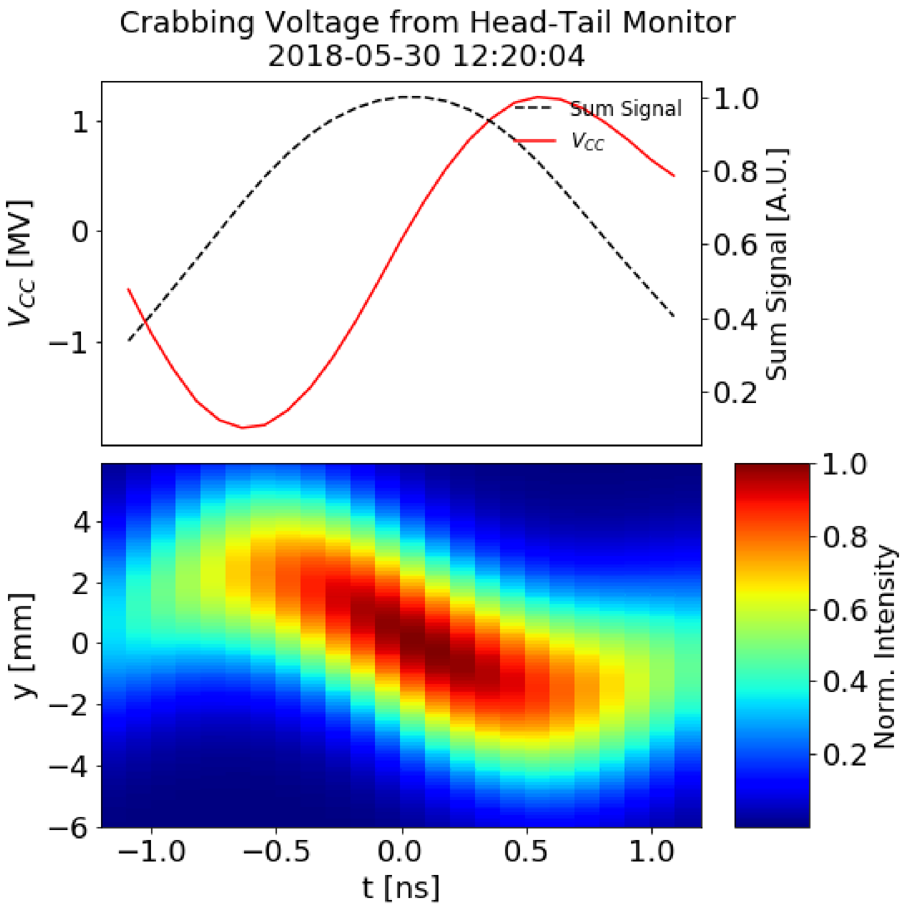


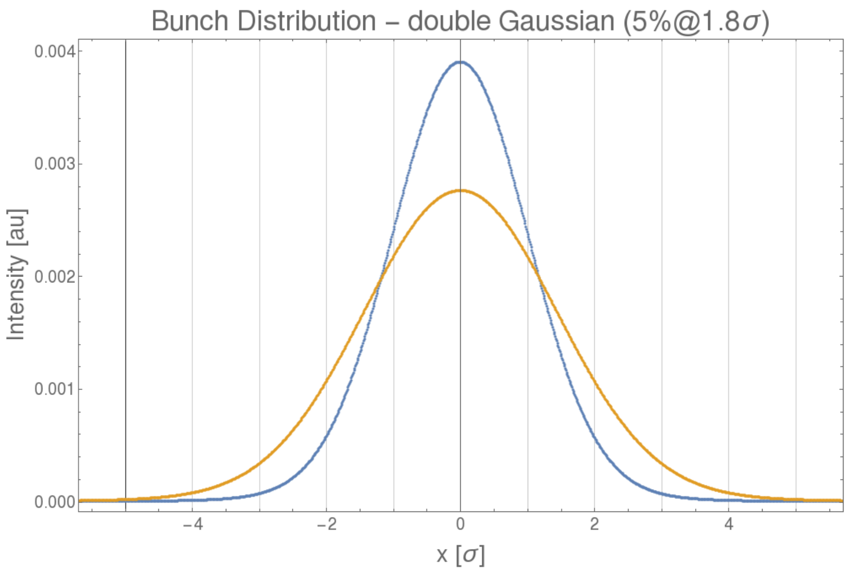
Why important to study for MPE?

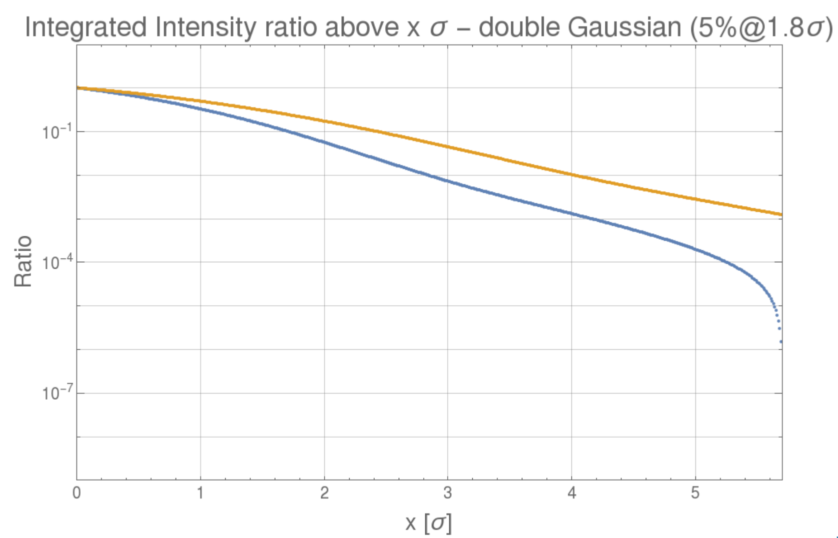
- CCs give strong transverse kick, short time constant - can potentially lead to large fast losses
- Can increase beam losses from other failures due to the crabbing
- Untested technology - SPS tests for validation
- SPS BIS must be defined for the CCs
  - What failures can occur?
  - What are their consequences?
  - How to detect them?
  - How probable are they?
  - How can they be mitigated?

Crabbed bunch shape

- A crabbed bunch has larger transverse tails
- Can increase losses from other failures, making non-critical failures critical





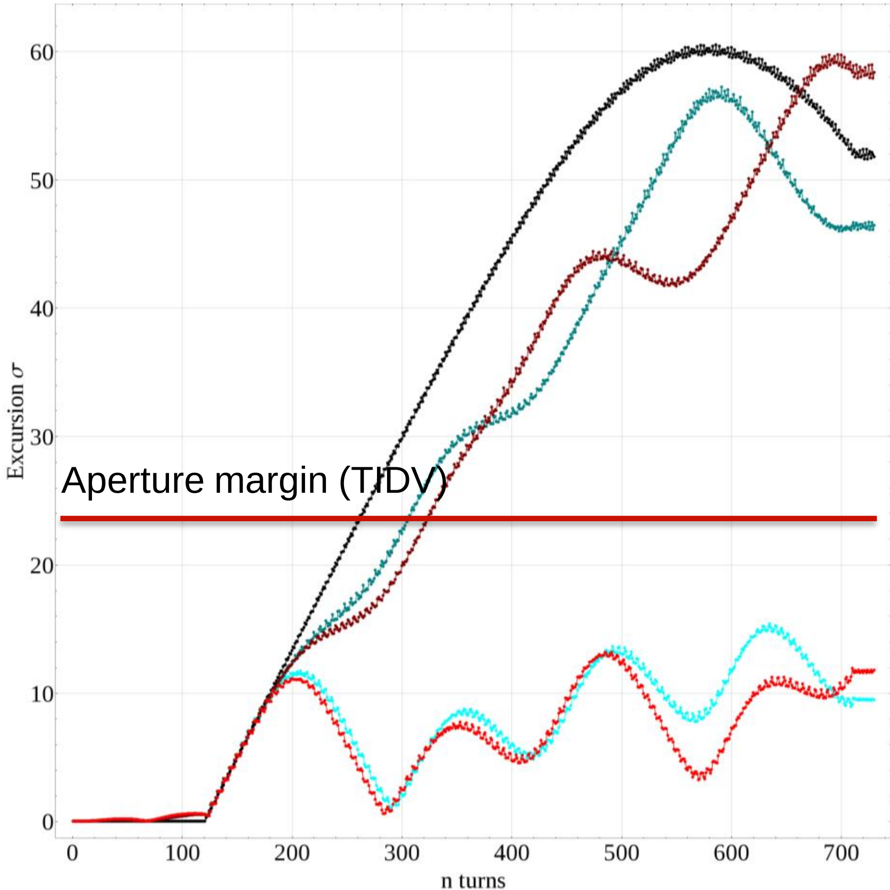


Detuning - resonance

- Worst case failure
- SPS RF and CC frequency difference resonating with the betatron tune
- Can lead to large orbit excursions within short times

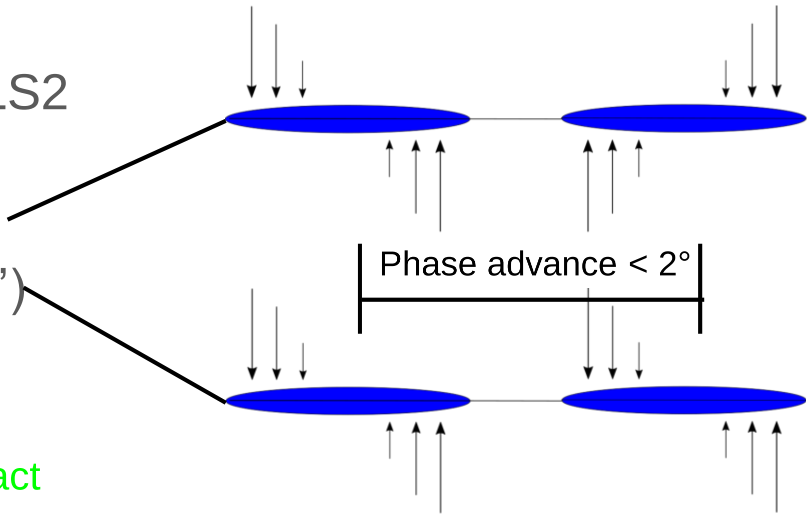
Example: 270 GeV with 2 MV:

- Rise time excursion: ~100 SPS turns
- Rise time **losses**: ~10 turns **(~200 μs)**
- SPS **BLM** reaction time, **up to 20 ms**

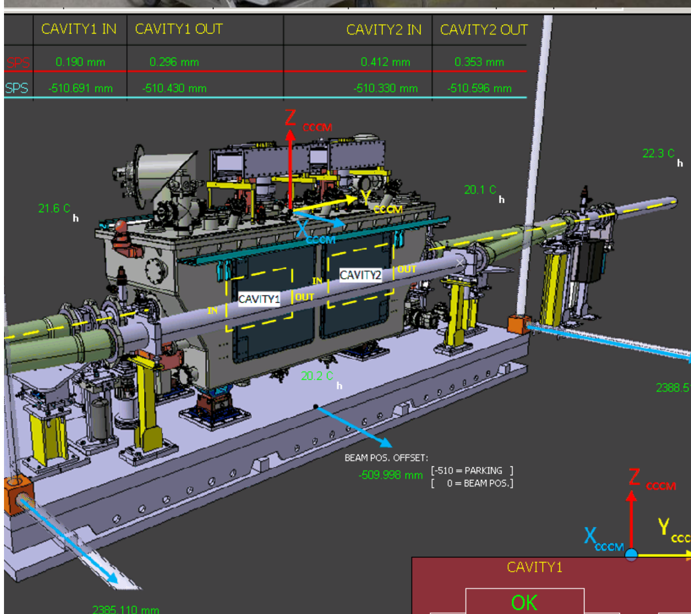


SPS Tests

- CCs to be validated in SPS before LHC installation
  - Two vertical CCs in 2018
  - Two horizontal CCs after LS2
- Operational Modes:
  - Anti-phased (Transparent)
  - Phased (CCs ‘cooperating’)
- Points to consider:
  - Lower energy than LHC
    - Less damage for beam impact
    - Less beam rigidity
  - Lower maximum intensity
  - SPS Aperture much larger than LHC



SPS installation



DQW

DQW

Courtesy of R. Calaga

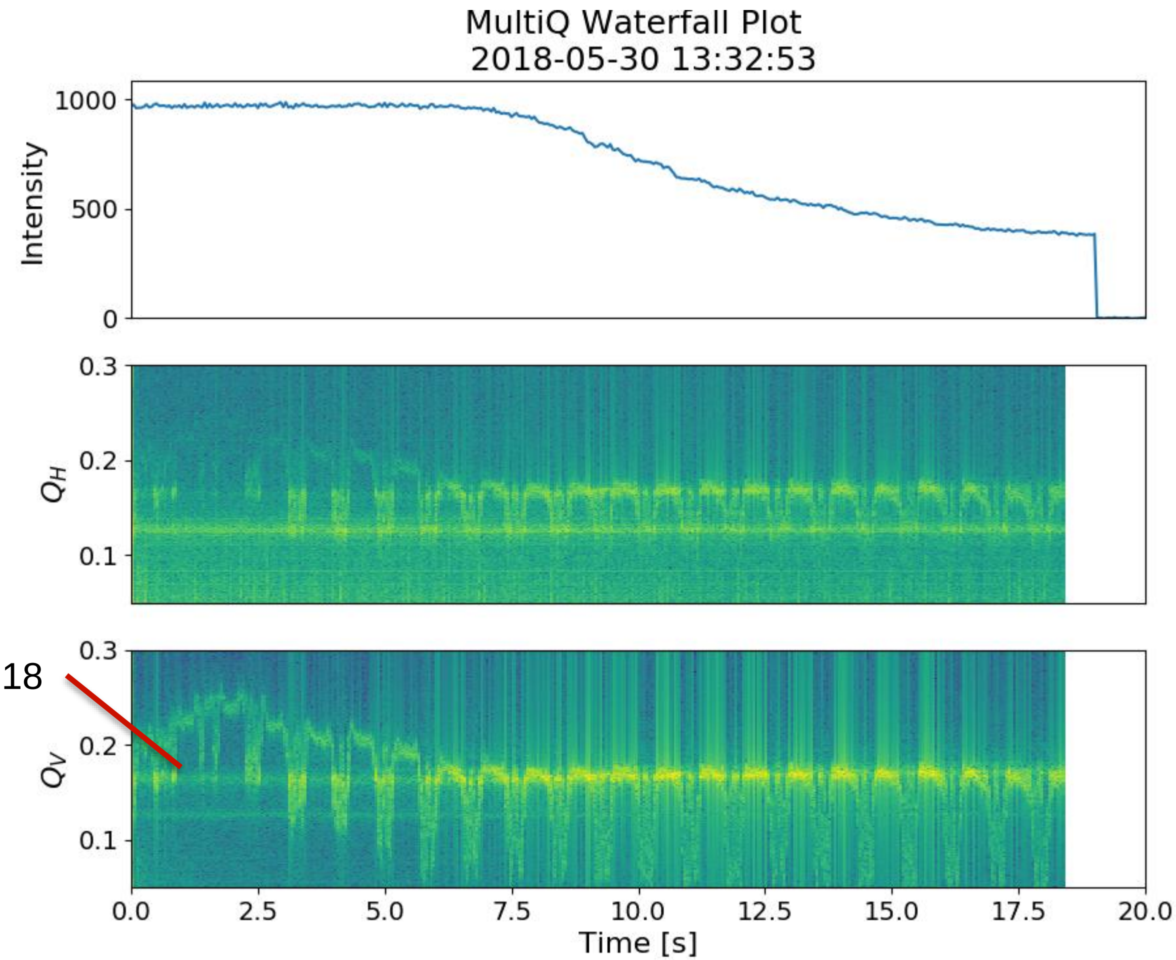
Observed failures

- Two significant failures observed so far:
  - **Slow:** Half beam lost over the cycle (~19 s) due to CC tuner adjustment
  - **Fast:** Whole beam lost in **~1.3 ms** due to large voltage during ramp

Slow loss failure

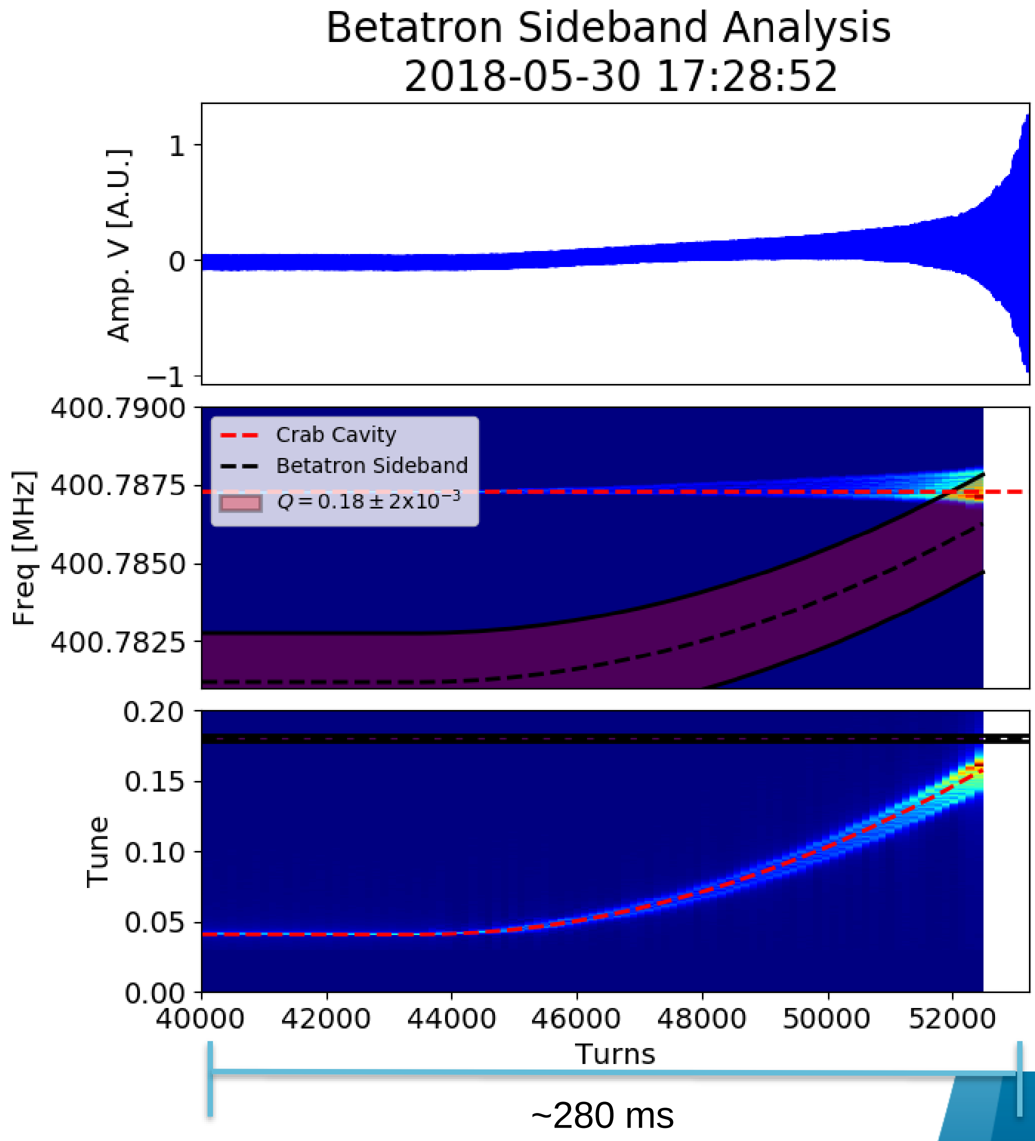
- Caused by CC1 tuner loop setup, crossing the vertical tune
- Slow failure, can be protected against by BLMs

Vertical betatron tune: 0.18



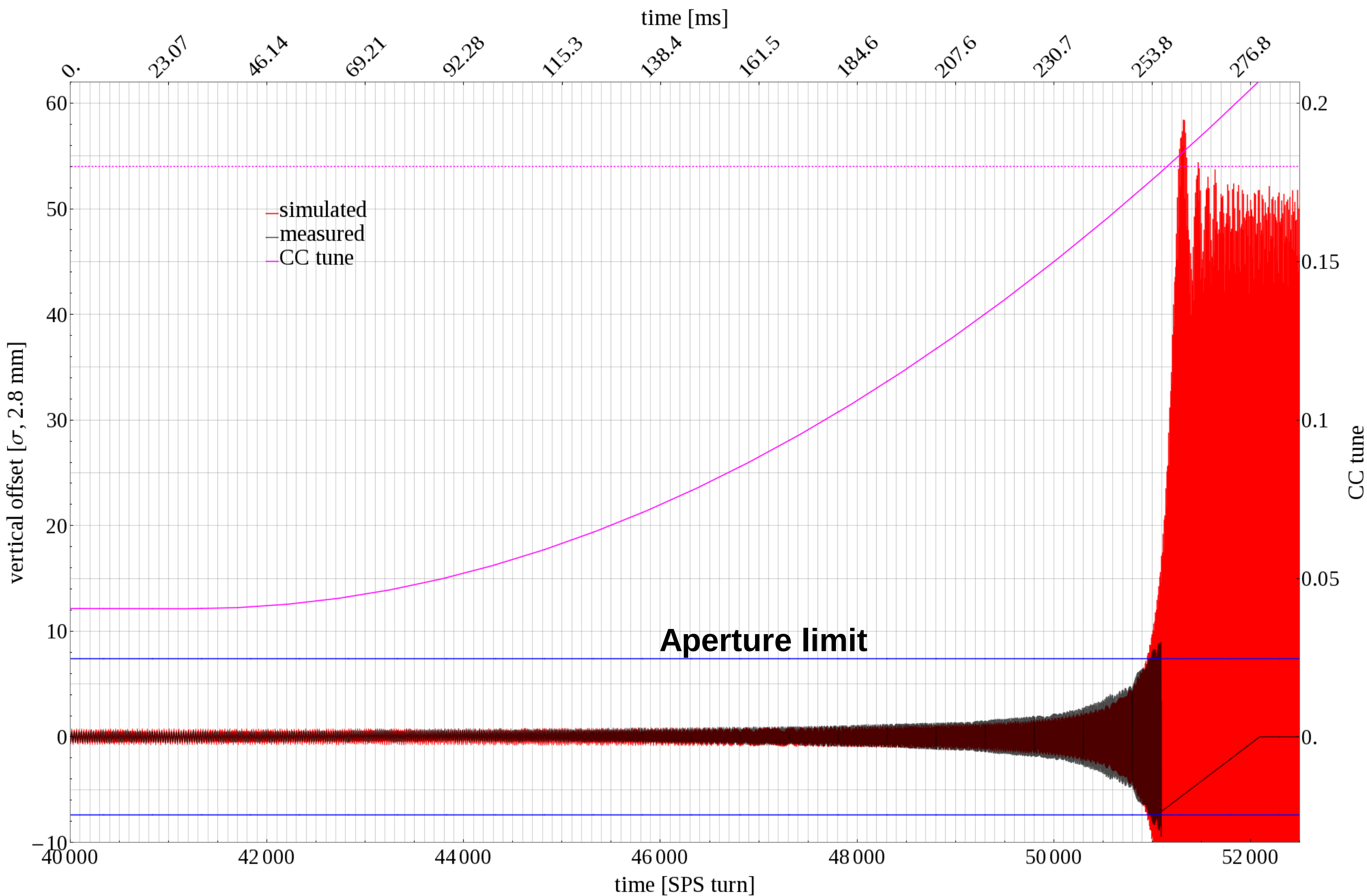
Fast loss failure

- CC1 at 1 MV and fixed frequency, with beam revolution frequency sweeping from 26 towards 270 GeV
- Effectively a change in the driving frequency of the beam by the CCs, leading to resonance at the tune (0.18); **full beam loss**.
- Lowering the voltage at start allowed proceeding through ramp.



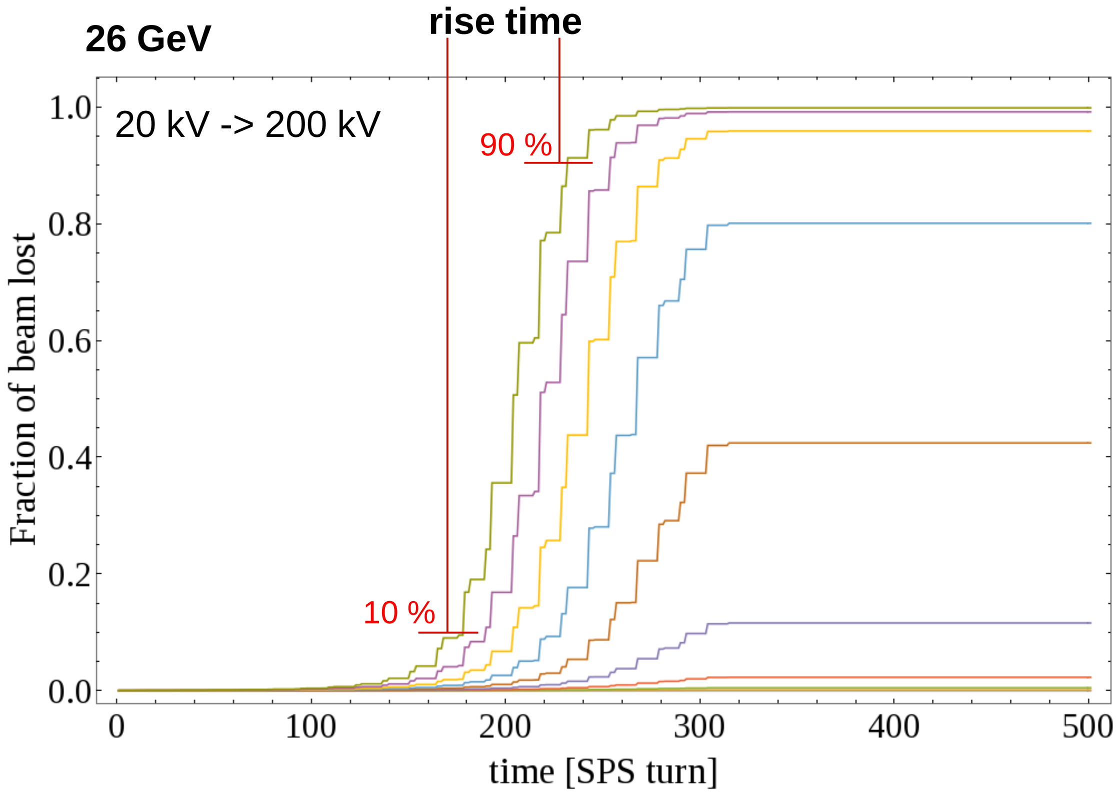
Fast loss failure – simulation

- Simulation of the ramp with 1 MV
- Can scale the simulation result with voltage and energy to calculate losses and time scales



Fast loss failure – time scales

- Bunch integrated outside aperture limit to determine losses
- Rise time of losses, < **~1 ms** (~50 turns)
- Reaction time of SPS BLM system, **up to 20 ms** (~900 turns)



Crab Cavity MDs summary

- No MP dedicated tests done yet
- Still working on the control of the Crab Cavities
- Crabbing achieved with both cavities up to ~1 MV per cavity, separately
- Synchronization with SPS RF successfull
- Crabbing at injection energy (26 GeV) and 270 GeV
- Various interlocks implemented and tested
- Beam loading measured *(results pending analysis…)*
- Several unintentional beam losses
- 7 (planned) out of 10 MDs left
- MP dedicated tests and appropriate interlocks implemented before going to high beam intensity

Extras

$$L = \frac{n_b f_{rev} N_p^2}{4\pi\sigma_x^*\sigma_y^*} * \frac{1}{\sqrt{1 + (\frac{\theta_c \sigma_z}{2\sigma_x^*})^2}}$$

$$\left.\frac{\phi(t)}{dt}\right._{max} = \frac{\omega}{2Q_L}\sqrt{\frac{8(R/Q)Q_L P_{max}}{A_0^2} - 1}$$

$$\omega = 2\pi * 400.789 * 10^6 \ rad/s$$

$$Q_L = 5.3 * 10^5$$

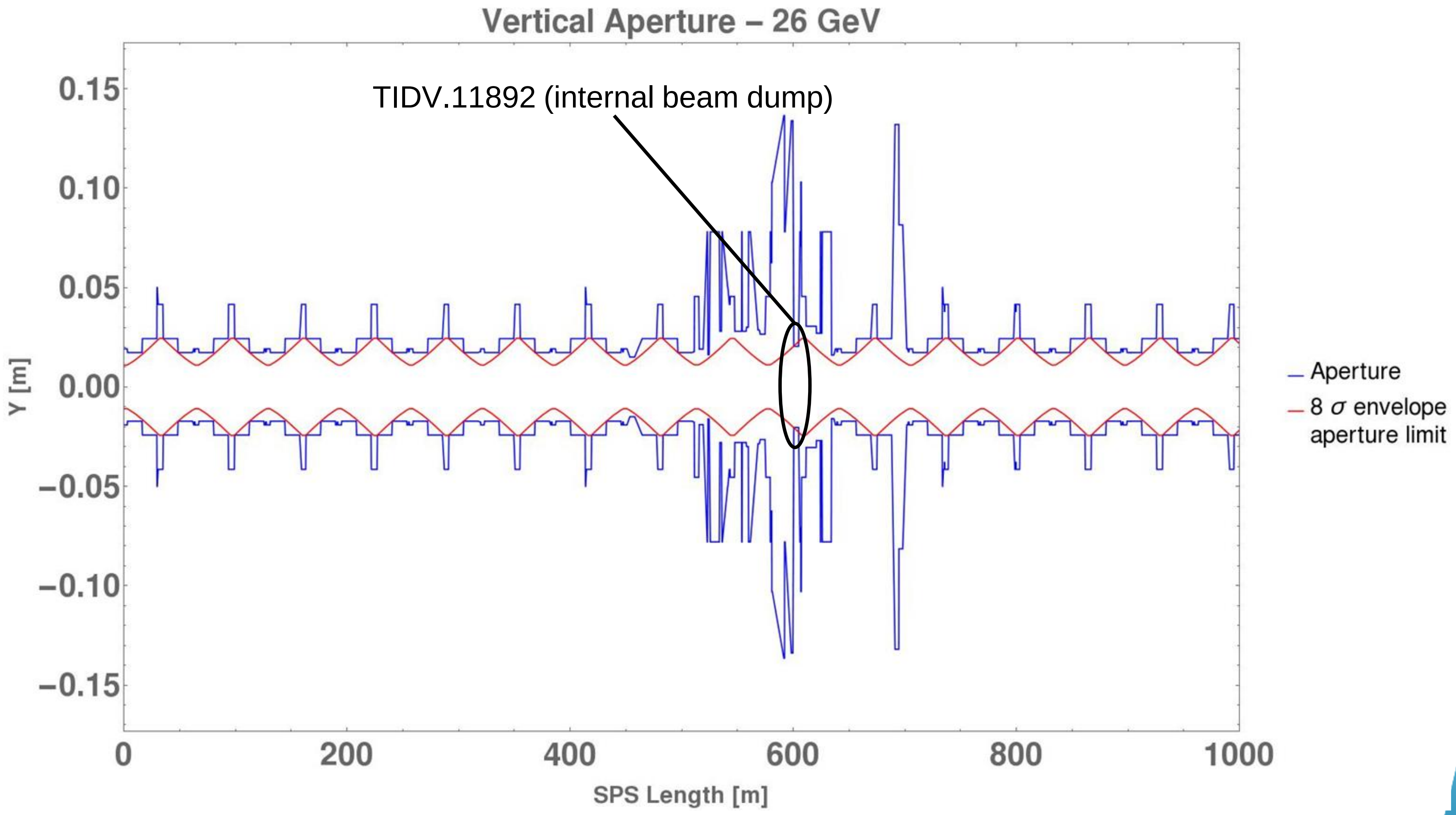
$$R/Q = 429 \ \Omega$$

$$P_{max} = 100 \ kW$$

$$A_0 = Cavity \ Voltage$$

SPS Aperture - where will losses occur?

- Bottleneck at 8σ for injection energy, 26 GeV



Normal operation

Maximum kick:

- 26 GeV: 1.12 σ/MV // 3.12 mm/MV
- 270 GeV: 0.35 σ/MV // 0.3 mm/MV

Aperture at 20.4 mm (7.3 σ at 26 GeV, 23.6 σ at 270 GeV)

For ”slowly” ramping cavities, no significant losses expected. However, if fast voltage change occurs, oscillations up to ±7 mm/MV at 26 GeV are possible.

Bonus pictures

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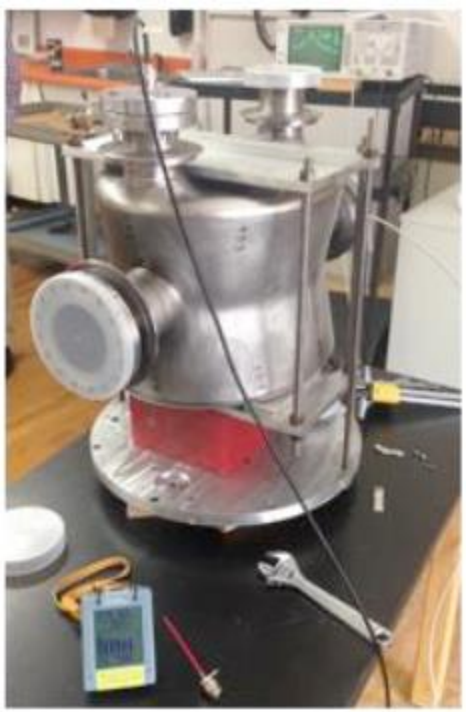
RFD



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RF Dipole