Use of Crab Cavities for Short X-ray Pulse Production in Rings

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Outline

- Review of Zholents' concept
- Basic analysis of x-ray slicing
- Lattice options
- Simulation code and methods
- Emittance degradation mechanisms
- Error sensitivities
- Photon beam modeling and predictions
Zholents' Transverse Rf Chirp Concept

Cavity frequency is harmonic $h$ of ring rf frequency

Ideally, second cavity exactly cancels effect of first if phase advance is $n*180$ degrees

Pulse can be sliced or compressed with asymmetric cut crystal

(Adapted from A. Zholents’ August 30, 2004 presentation at APS Strategic Planning Meeting.)

$^1$A. Zholents et al., NIM A 425, 385 (1999).

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Estimating X-ray Pulse Duration

- X-ray pulse duration can be estimated assuming gaussian distributions\(^1\)

\[
\sigma_t \approx \frac{E}{\partial V/\partial t} \sqrt{\frac{\beta_{id}}{\beta_{rf}}} \sqrt{\frac{\varepsilon_y}{\beta_y}} + \sigma_{y', \text{rad}}^2
\]

Electron beam energy

Rate of change of deflecting voltage

Unchirped e-beam divergence (typ. 2-3 \(\mu\text{rad}\))

Divergence due to undulator (typ. \(~5 \mu\text{rad}\))

For 4 MV, 2.8GHz (h=8) deflecting system, get \(~0.6\) ps

- Vertical emittance matters because it affects the electron beam divergence

\(^1\)M. Borland, PRSTAB 8, 074001 (2005).
Lattice Options

1 sector spacing
2 ID + 1 BM

2 sector spacing
4 ID + 2 BM

Beta function increase required to get the right phase advance

Helps compression by making divergence smaller

After V. Sajaev, ASD/APG/2004-11
Simulation Code and Methods

- Used **elegant**\(^1\) for all simulations
  - Parallel version used for most computations\(^2\)
- Modeled lattice with
  - First-order bending magnets (\(\rho=38\)m)
  - Canonically-integrated quadrupoles and sextupoles
- Modeled deflecting cavities with RFDF (RF DeFlector) element
  - Idealized top-hat longitudinal and radial field profile
- Synchrotron radiation modeled with a lumped element (SREFFECTS)
  - Gives correct damping rates and equilibrium properties

Emittance Degradation

- Second cavity can't exactly cancel effect of first
  - Vertical emittance will grow
- Effects present in a perfect machine
  - Momentum compaction and beam energy spread
    - Rms phase spread in second cavity relative to first
  - Sextupoles between cavities
    - Amplitude-dependent phase advance variation in transport between the cavities
    - Coupling from y to x
  - Chromaticity and beam energy spread
    - Rms phase advance spread in transport between cavities
- Additional effects in an imperfect machine
  - Lattice errors
  - Rolled elements between cavities
  - Roll of cavities about beam axis
  - Rf phase and voltage errors

\[^{1}\text{M. Borland, PRSTAB 8, 074001 (2005).}\]
Optimizing Sextupoles

- Sextupoles are the dominant emittance growth source.
- APS has individual supplies for each sextupole.
  - We can tune the sextupoles to minimize emittance growth\(^1\)
  - Use optimizer in **Pelegant** to vary interior sextupoles and minimize the single-pass growth.
- Important factors in making this work\(^2,3\)
  - Use lattice with lower vertical beta functions.
  - Small/zero chromaticity between cavities.
  - Don't let sextupoles change too much.
- If these are not respected, dynamic aperture is hard to recover.

\(^1\) M. Borland, PRSTAB 8, 074001 (2005).
\(^2\) V. Sajaev, ASD/APG/2005-06.
\(^3\) M. Borland and V. Sajaev, Proc. PAC2005, 3886-3888.
Emittance Growth for Optimized Configurations

- Starting vertical emittance is 20 pm (0.8% coupling)\(^1\)
  - Normal operation is 30~40 pm
- Working points based on present operations\(^1\)
- Hybrid-mode results are for intense bunch only

\(^1\)L. Emery, private communication.
Lattice Errors

- Lattice errors can result in
  - Phase advance errors
  - Beta function errors
- Sources include
  - Beamline steering
  - Power supply drift
  - Misalignments
- Lattice correction gives
  - 1% beta function errors\(^1\)
  - <0.001 tune error\(^2\)

\(^1\)V. Sajaev and L. Emery, EPAC 2002, p. 742
\(^2\)L. Emery
May have quad and sextupole roll
- Roll is ~0.25 mrad rms
- Performed random roll simulations with 20 seeds
- No coupling correction was employed

\(^1\)H. Friedsam
Cavity Roll

- Cavities may be rolled relative to machine vertical
- Simulated two cases
  - Cavities rolled the same amount (CM)
  - 2\textsuperscript{nd} cavity only rolled (C2)
- Neither is a problem at few mrad level
Intercavity Voltage Error

- Imparted errors to one of the cavities

![Graph showing the relationship between \( \varepsilon_y \) and \( \Delta V_2/V_2 \) in percentage]
Intercavity Phase Error

Most difficult issue is orbit disturbance outside the intercavity region.
X-ray Slicing Simulation

- X-ray pulse duration can be estimated assuming gaussian pulse shapes
  \[ \sigma_{y',\text{rad}} \approx \sqrt{\frac{\lambda}{2L_u}} \]

- Program \textit{sddsurgent}\textsuperscript{1} computes the radiation pattern for given undulator parameters

- Includes detailed central cone distribution and off-axis higher-harmonics

- Convolve this with electron distribution from \textit{elegant}

- Drift and slit simulation done with \textit{elegant}

\textsuperscript{1}H. Shang, R. Dejus, R. Walker, M. Borland.
26.5m is the distance to an aperture in the ID7 beamline. Aperture is typically set at 0.5 mm in both planes. (E. Dufrense.)
X-ray Slicing Results (2.4-m U33, 10keV)

- Two slits at 26.5 m
  - Vertical slit is varied from ±100 mm to ±0.010 mm
  - Fixed horizontal slit of ±0.25 mm (E. Dufrense)
    - Helps to remove the 2nd-harmonic pollution
Results for Constant 1% Transmission

- 24-bunch mode better due to smaller emittance
- Diminished returns evident even at 4 MV
- No compelling reason to go above 4 MV
  - Even 2 MV might be acceptable...
Effect of Photon Energy (4 MV, 1% Trans.)

- Problem: intrinsic divergence of the photon beam increases as photon energy decreases
- Assumed 2.4-m ID: variously used U18, U33, and U55 devices

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Details of X-ray Slicing for Hybrid Mode

Back-chirp pulses have about 3% of the intensity of the central pulse.

2nd harmonic pulses seen with up to ~2% of central intensity.

Slits: H=0.5 mm, V=0.2 mm

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Details of X-ray Slicing for 24 Bunch Mode

Back-chirp pulses have about 0.02% of the intensity of the central pulse and are not seen here.

2nd harmonic pulses seen with up to ~2% of central intensity.

Slits: H=0.5 mm, V=0.2 mm
Conclusion

- Zholents' scheme for making short x-ray pulses was simulated in detail.
- Emittance growth is a primary concern:
  - Sextupole optimization makes this manageable.
  - Deflecting voltage is limited, however.
- Predicted pulse durations approach 1ps FWHM for hard x-rays.
- Pulse structure has complex features due to higher harmonics, long electron bunch.
- Tolerances are tight but seem achievable.
- APS is pursuing this as part of our upgrade.