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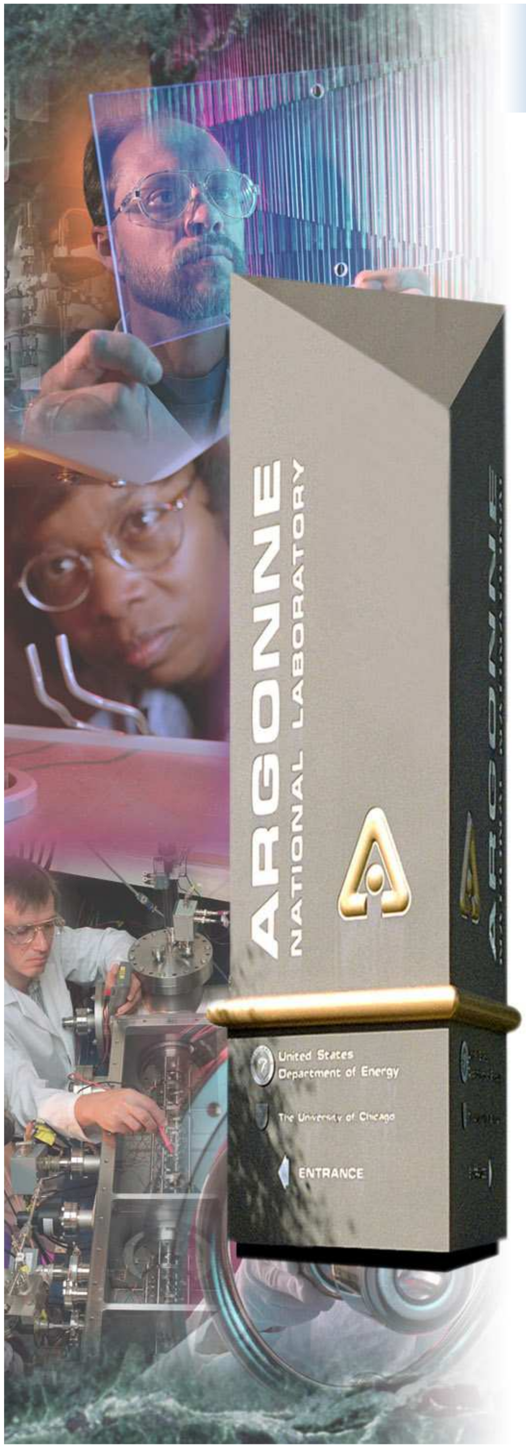

Rf and x-ray optics issues in generating ultra short pulses at APS with deflecting cavities

Katherine Harkay

Accelerator Physics Group

Accelerator Systems Division

Advanced Photon Source

Diamond Light Source, September 16, 2005

THE UNIVERSITY OF CHICAGO

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Outline

- Science case
- Introduction to rf deflection
- Rf deflecting cavities
  - RT vs SC
  - Challenges
- X-ray optics
- R&D plan
- Summary

*Feasibility study group**

Beam dynamics

- M. Borland
- Y.-C. Chae
- L. Emery
- W. Guo
- K.-J. Kim
- S. Milton
- V. Sajaev
- B. Yang

A. Zholents, LBNL

RF

- K. Harkay
- D. Horan
- R. Kustom
- A. Nassiri
- G. Pile
- G. Waldschmidt
- M. White

V. Dolgashev, SLAC

Undulator radiation & x-ray optics

- L. Assoufid
- R. Dejus
- D. Mills
- S. Shastri

* All affiliated with APS except where noted

Science drivers for ps x-rays

APS Strategic Planning Workshop (Aug 2004): Time Domain Science Using X-Ray Techniques

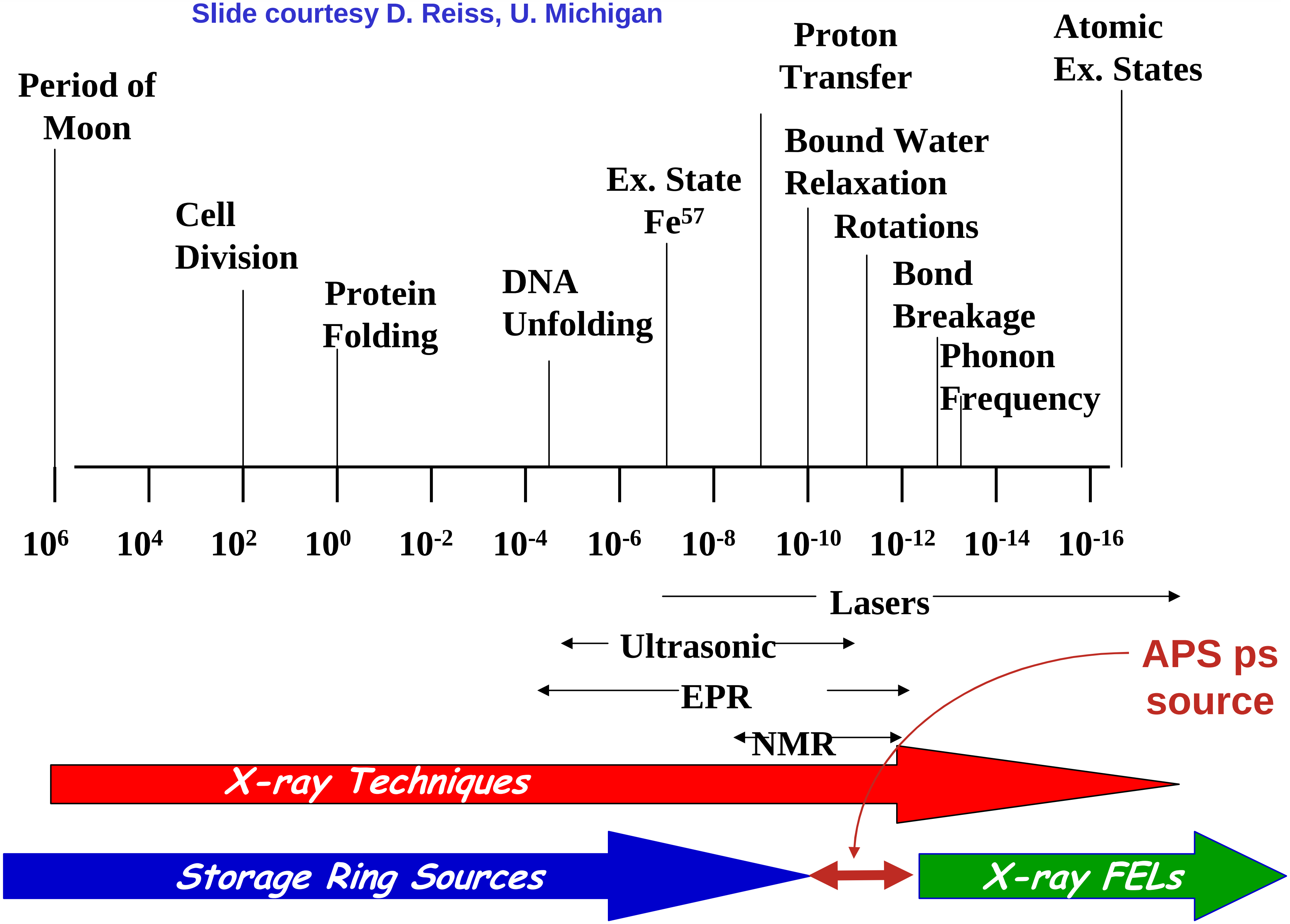
"…by far, the most exciting element of the workshop was exploring the possibility of shorter timescales at the APS, i.e., the generation of 1 ps x-ray pulses whilst retaining high-flux. This important time domain from 1 ps to 100 ps will provide a unique bridge for hard x-ray science between capabilities at current storage rings and future x-ray FELs."

Atomic and molecular dynamics, coherent/collective processes:

- Atomic and molecular physics
- Condensed matter physics
- Biophysics/macromolecular crystallography
- Chemistry

APS User's Meeting: Workshop on Generation and Use of Short X-ray Pulses at APS (May 2005)

Slide courtesy D. Reiss, U. Michigan



X-ray FELs & storage ring ps sources are complementary

XFELs can provide

- fs pulses
- Ultrahigh peak power
- Ultrahigh brightness
- Lower avg. repetition rate

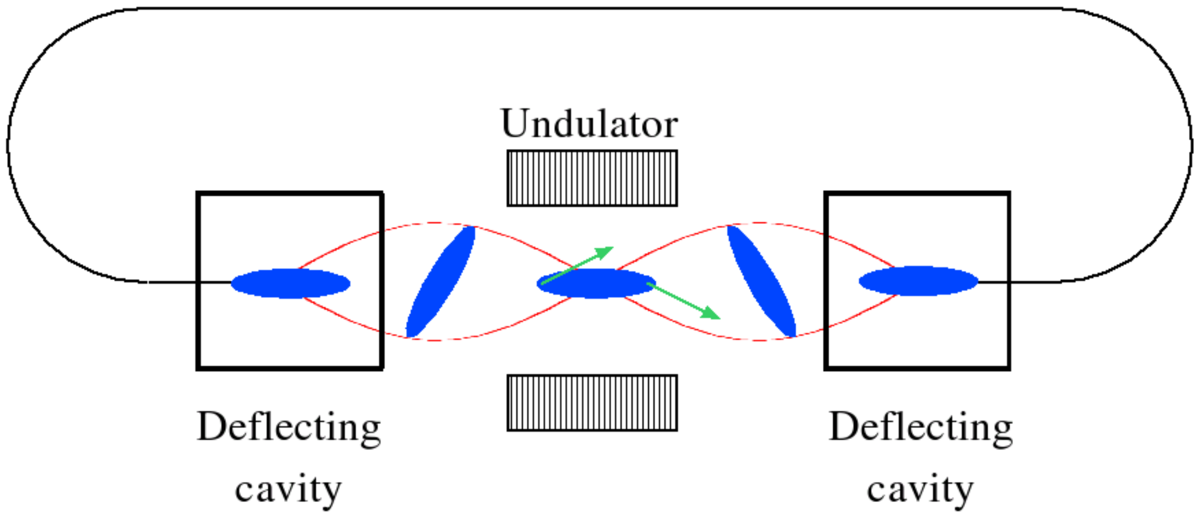
Storage rings can provide

- ~1 ps pulses
- Energy tunability
- Spectral stability
- Flux comparable to 100 ps
- High repetition rate

Note: Femtoslicing not practical at APS (calc per A. Zholents)

Energy modulation $\Delta E=7\sigma_e$ requires:
~10 mJ laser pulse at λ_L=400 nm and τ=50 fs
giving ~ 100 fs x-ray pulse with ~ 10^5 photons per pulse
BUT: looks difficult at a high rep. rate

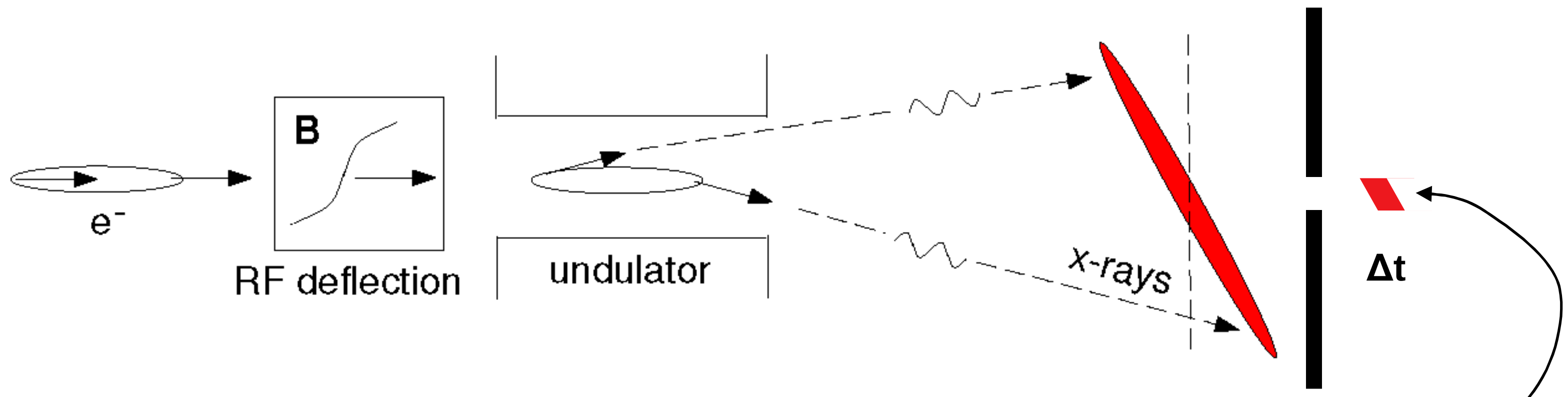
Crabbing scheme†



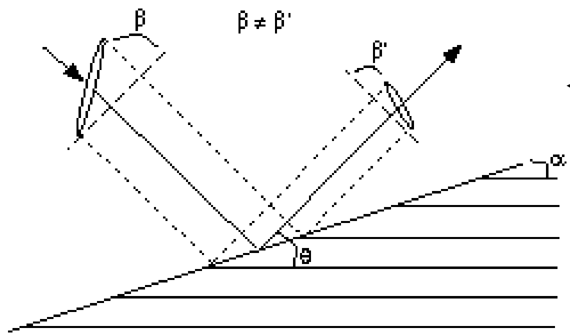
- Deflecting ("crab") cavity operating in TM_{110} mode; phased such that B_x deflects head and tail of bunch in opposite directions vertically (chirp, not tilt)
- Electron (& photon) vertical momentum correlated with longitudinal position as bunch evolves through lattice
- Second crab cavity at nπ betatron phase cancels kick; rest of storage ring nominally unaffected

† **A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A425 (1999)**

Generation of ps-pulses



Slitting alone



or add compression using asymmetric cut crystal; throughput ~ 2-15x better

Compressed pulse length (linear rf):

$$\sigma_{t,xray} = \frac{E}{2\pi h f_0 V}\sqrt{\sigma_{y',e}^2 + \sigma_{y',rad}^2}$$

For APS: h=8, 6 MV deflect. voltage, $\sigma_{y',e}$ = 2.2 μrad, and $\sigma_{y',rad}$ = 5 μrad; the calc'd compressed x-ray pulse length is ~0.36 ps rms.

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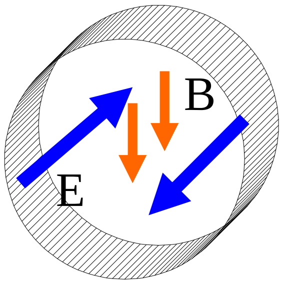
Crabbing and parasitic modes (KEKB)†

TM110

500MHz

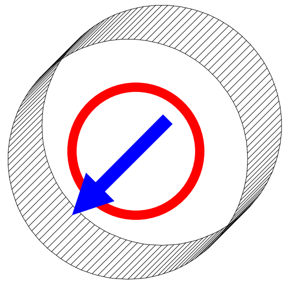


Crab Mode (h):
Bϕ, Ez off axis

Unwanted modes →

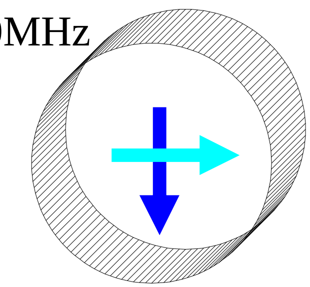
TM010

324MHz



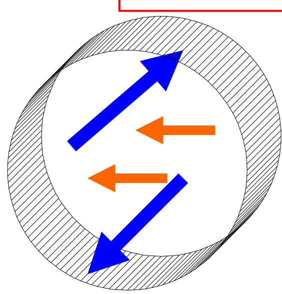
TE111

720MHz



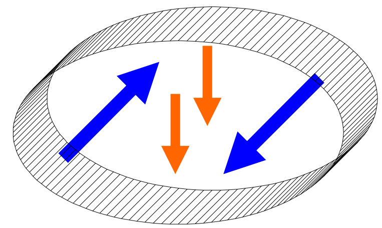
TM110

500MHz



TM110 - like Mode

500MHz



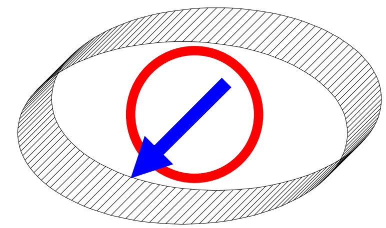
Crab Mode

Unwanted modes →

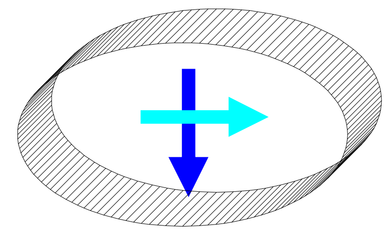
The squashed cell shape cavity scheme was studied extensively at Cornell in 1991 and 1992 for CESR-B under KEK-Cornell collaboration.

TM010 - like Mode

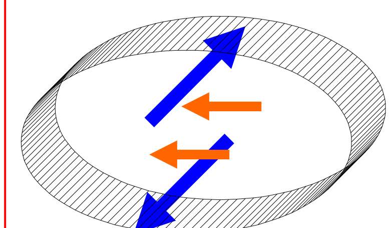
413.3MHz



650.5 MHz / 677.6MHz



700MHz



† Courtesy K. Hosoyama, KEK, APS ps workshop (2005)

Parasitic modes (cont)

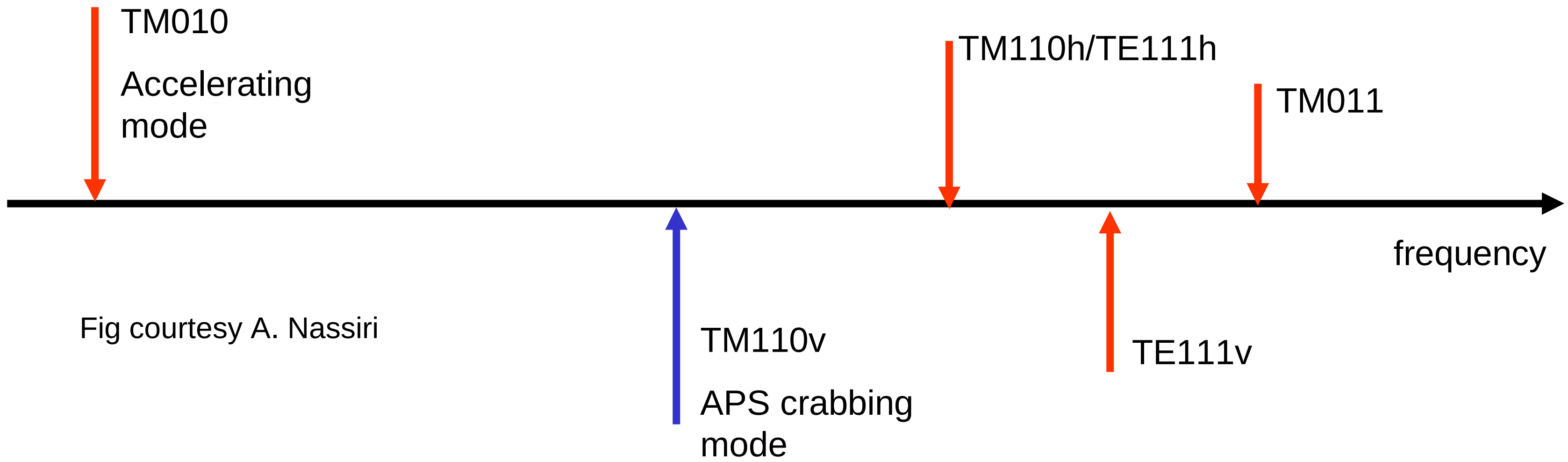


Fig courtesy A. Nassiri

- Vertical crabbing mode (APS): horiz axis “squashed”
- Maximize mode separation for optimized damping
- HOMs above beam pipe cutoff, propogate out
- Lower-order mode (TM_{010}) may strongly couple to beam; freq. below cutoff, adopt KEKB coaxial line strategy (for SC)
- Multiple cells produce multiplicity of parasitic modes (issue for SC)
- Orbit displacement causes beam loading in crabbing mode; adopt KEKB criterion of $\Delta y = \pm 1$ mm (for orbit distortions $\pm$ 0.1 mm)
- Generator power increased to compensate; de-Q to decrease sensitivity

Instability thresholds from parasitic mode excitation

(per Y-C. Chae)

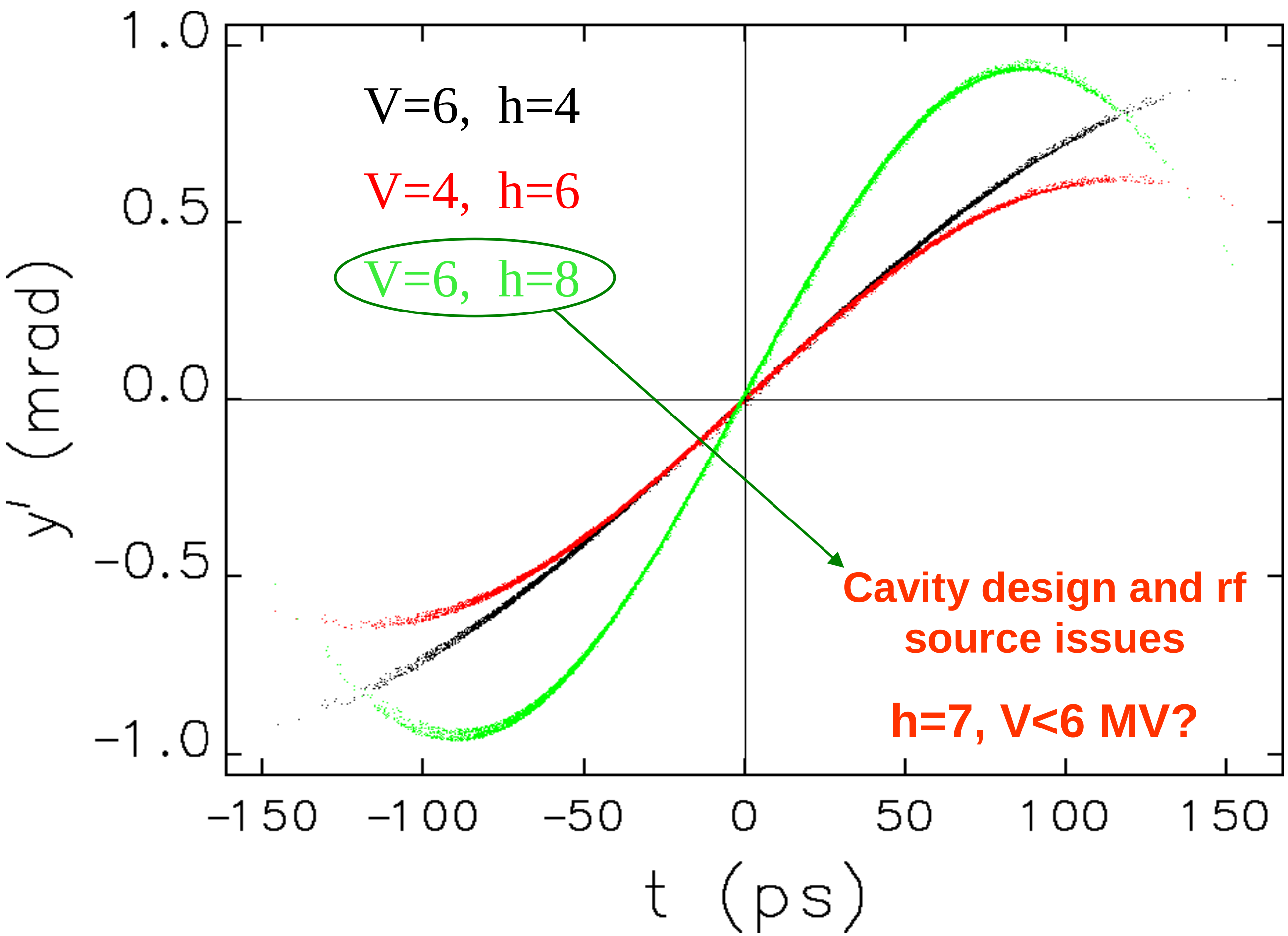
APS parameters assumed: I = 100 mA, E = 7 GeV, α=2.8e-4, $\omega_s/2\pi$=2 kHz, ν_s=0.0073, β_x = 20 m

	Longitudinal	Transverse
Growth Rate, τ_g^{-1} (s^{-1})[1]	$\tau_g^{-1} = \frac{\alpha I_{tot}}{4\pi(E/e)\nu_s} \sum_p \omega_p \operatorname{Re} Z_z(\omega_p)$ $< \frac{\alpha I_{tot}}{2(E/e)\nu_s}\left(R_s \times f_p\right)$	$\tau_g^{-1} = \frac{\omega_0 I_{tot}}{4\pi(E/e)} \beta_\perp \sum_p \operatorname{Re} Z_t(\omega_p)$ $< \frac{\omega_0 I_{tot}}{4\pi(E/e)} \beta_\perp R_t$
Impedance[2] (Ω; Ω /m)	$Z_z(\omega) = \frac{R_s}{1 + jQ(\omega/\omega_r - \omega_r/\omega)}$	$Z_t(\omega) = \left(\frac{\omega_r}{\omega}\right) \frac{R_t}{1 + jQ(\omega/\omega_r - \omega_r/\omega)}$
Damping Rate, τ_d^{-1} (s^{-1})	212	106
Shunt Impedance[2]	$R_s = V^2/2P$	$R_t = (c/\omega_r) R_s / b^2$
Stability Condition: $\tau_g > \tau_d$	$R_s \times f_p < 0.8 M\Omega - GHz$	$R_t < 2.5 M\Omega / m$

[1] A. Mosnier, Proc 1999 PAC.

[2] L. Palumbo, V.G. Vaccaro, M. Zobov, LNF-94/041 (P) (1994; also CERN 95-06, 331 (1995).

Parameters/constraints: what hV is required?



Can get the same compression as long as h*V is constant

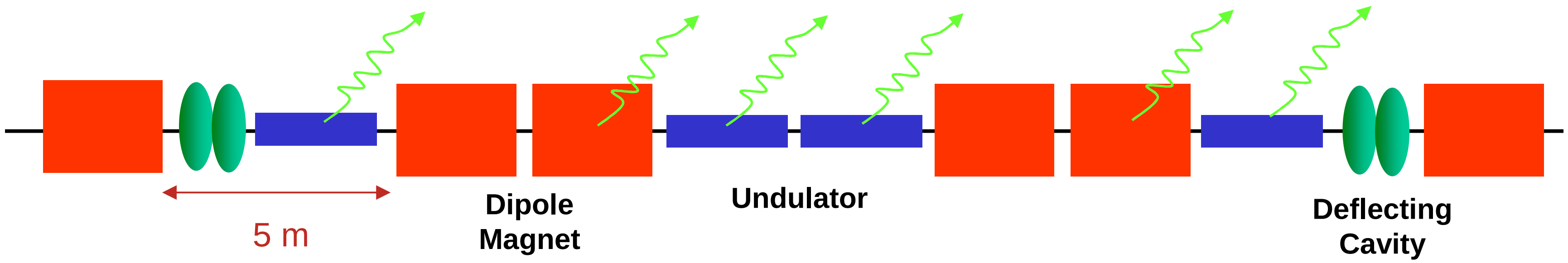
Higher V and lower h: more linear chirp and less need for slits

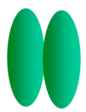
Higher h and lower V: smaller maximum deflection and less lifetime impact

Higher h and maximum V: shortest pulse, acceptable lifetime

Coutesy M. Borland, APS ps Workshop, May 2005

Space constraints at APS





M. Borland, Phys. Rev. ST Accel. Beam 8, (2005)

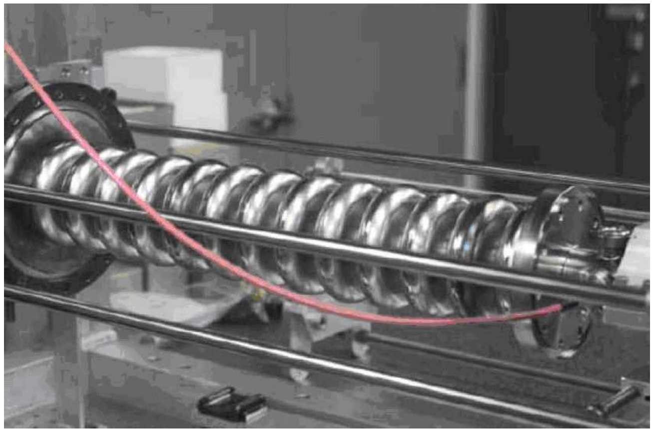
- Nominal 2-sector implementation shown: 4 IDs and 2 BMs
- Nominal insertion length available for rf cavities: 2.5 m

Summary of rf design considerations

- Goal ≤1 ps in crab insertion
- No impact of crab cavities on performance outside insertion
- Beam dynamics simulation study (M. Borland)
  – h ≥ 4 (1.4 GHz)
  – Deflecting voltage ≤ 6 MV (lifetime)
- Availability of 100-kW class rf amplifiers limits study to h = 8 (2.8 GHz)
- Available insertion length for cavities nominally 2.5 m (could be extended)
- Effects of errors: emittance growth or orbit kicks (M. Borland)
  – Intercavity phase error < 0.04 for $\langle y' \rangle / \sigma_{y'} < 10\%$
  – Intercavity voltage difference < 0.5%
- Significant parasitic mode damping requirement (Y-C Chae)

Deflecting cavity international effort (select)

- Deflecting cavities pursued for many applications by many research institutions.
- 1960's – BNL investigated S-band RT cavity for beam separator; other labs also
- 1970's - CERN investigated 2.86 GHz SC cavity for separating kaon beam
- 1991 - Cornell tested 1.5 GHz scale model
- 1993 to present – KEK prototyped 500 MHz cavity for crab crossing, colliding beams. Installation planned in 2006.
- SLAC developed RT SW deflecting cavity as a LC damping ring fast kicker
- 2000 to present – FNAL prototyping 3.9 GHz CKM deflecting cavities (also now ILC).
- 2004 to present – APS investigating deflecting cavity design options for ps pulse generation.
- Present – CERN, ALS, others exploring crab cavity concepts, HOM-free, for ILC, etc



G. Waldscchmidt, K. Harkay

Room temperature (RT) vs. superconducting (SC) rf
(K. Harkay, A. Nassiri)

- No installed "crab cavity" in existing synchrotron facilities
- KEKB plans to install two SC single cell cavity in March 2006
- RT pulsed system allows user to "turn off" ps pulse via timing (~1 μs pulse, 0.1 – 1 kHz rep rate) (M. Borland, P. Anfinrud)
- SC system runs CW, rep rate up to bunch spacing; some experiments desire high rep rate (no pump probes) (D. Reiss)
- Either option requires dedicated R&D effort

RT vs. SC rf

- RF sources
  - for SC option are available with minimal reconfiguration
  - for RT are non-typical and modification is required (1 kHz)
- Cavity fill time vs. susceptibility to phase noise
  - Long for SC cavity; makes it less susceptible
  - Short for RT structure; makes it more susceptible
- Need to compensate frequency detuning
  - Due to pulse heating for RT case
  - From microphonics for SC case

RT vs. SC rf

- Suppression of parasitic modes
  - Challenging for SC cavity, multiple cell cavities in particular
  - Well understood for RT structure
- Need to study and understand transients during pulsing of RT structure and its effect on SR beam. How does it affect “non-crab” beamline users?
- Cost: SC option approx 2x RT option
- Overall, SC option is more attractive
  - May offer a greater degree of compatibility with normal SR operation
  - Compatible with future development of higher rep rate pump probe lasers
  - Opportunity for APS to gain SC rf expertise

RT rf deflecting cavity study for APS

Frequency	2.82 GHz
Deflecting Voltage	6 MV
Available power	5 MW or 2.5 MW
Length	<2.4 m
Transverse HOM	<2.5 MOhm/m
Longitudinal HOM	< 0.8 MOhm*GHz

RT rf slides courtesy:

V. Dolgashev, SLAC, APS Beams and Applications seminar, June 2005

and

A. Nassiri

Design consideration

- Limited available power ≤ 5 MW   10 MW option
- Large aperture ~2 cm => Low impedance
- Maximum surface electric fields < 100 MV/m
- Pulsed heating < 100 deg. C => maximum surface magnetic field < 200 kA/m for 5 μs pulse
- Deflecting mode degeneracy fixed by wall deformation during tuning
- “Smooth” coupler – no field amplification on edges

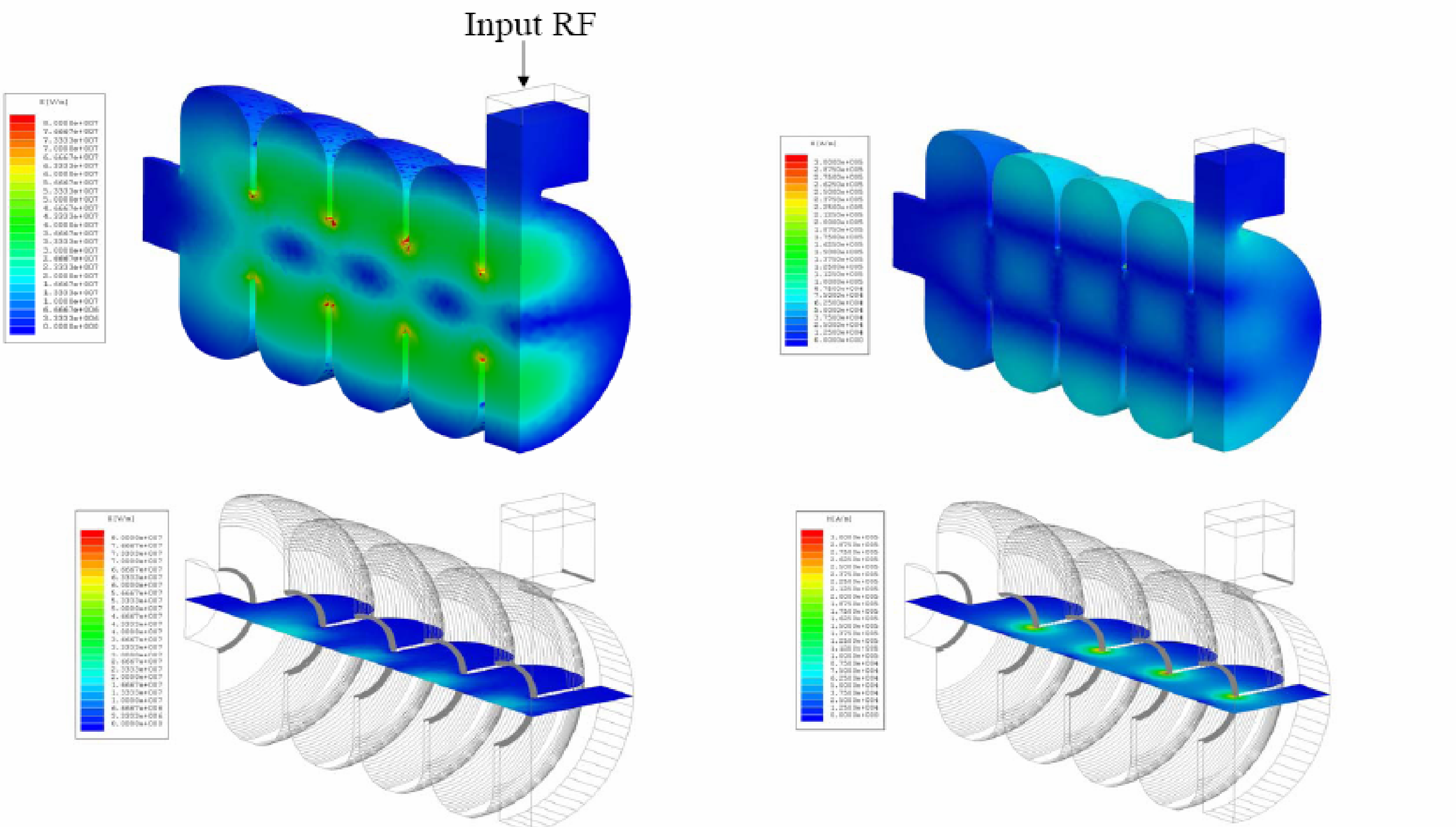
V. Dolgashev, SLAC, APS seminar, June 2005

Structure types: standing wave vs. traveling wave

	SW	TW
Efficiency/length Deflection vs. power	High	Low
Filling time	Proportional to the quality factor Generally slow	Proportional to the group velocity and structure length Generally fast
Deflecting field vs. number of cells n	Scales as $\sqrt{n}$	Scales as $n\left(1 - e^{-\alpha n}\right)$ α = attenuation
Maximum number of cell	Limited to about 10 because of mode overlapping	In principle there are no limitations
Circulator	Generally needed to protect klystron	Not necessary
Temperature sensitivity	Need automatic tuning system or a very good temperature stabilization to maintain the cavity on resonance	Less temperature sensitivity

Courtesy A. Nassiri

9 Cells SW Deflecting Structure



Surface electric field for 5 MW of input power, maximum filed ~70 MV/m

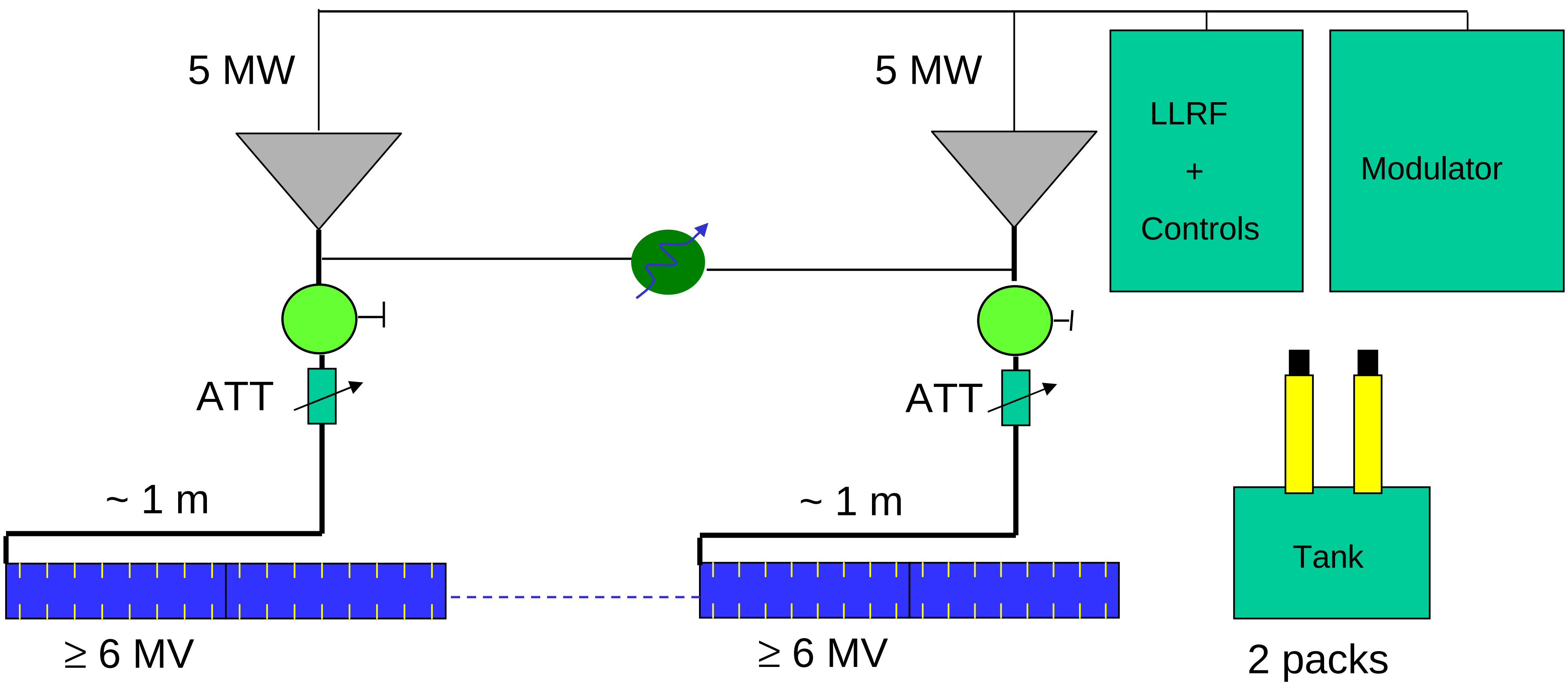
Surface magnetic field for 5 MW of input power, maximum filed ~30 kA/m

V. Dolgashev, SLAC, APS seminar, June 2005

Configuration

- Two 5 MW pulsed klystrons
- One modulator
- Two 18-cell 1- meter structures

Courtesy A. Nassiri



Modulator

- 5 MW Klystron
- 5 μsec pulse length (MAX)
- 1 kHz rep rate
- Average power 25 kW
- Beam Voltage 150 kV
- Beam current 85 A
- 60 KV DC power supply
- Pulse rise time (10%-90%) <1μsec
- Pulse fall time (10%-90%) <1μsec
- Pulse voltage variation ≤ ±0.1%

Courtesy A. Nassiri

Pulsed RF source

- Between 5 to 10 MW pulsed at 2815 MHz (8×351.93 MHz)
- Requires 1 kHz pulse repetition rate
- Pulse length ~ 5 μs
- No “off the shelf” klystron to buy
- Closest:

CPI VKS-8262F 2.856 GHz

5 MW Peak

16.3 μsec pulse length

400 Hz rep rate **P_{ave}=32 kW**

- Modified CPI klystron

2.815 GHz

5 MW Peak

5 μsec pulse length

1 kHz rep rate **P_{ave}=25 kW**

VKS-8262 Klystron

Courtesy A. Nassiri

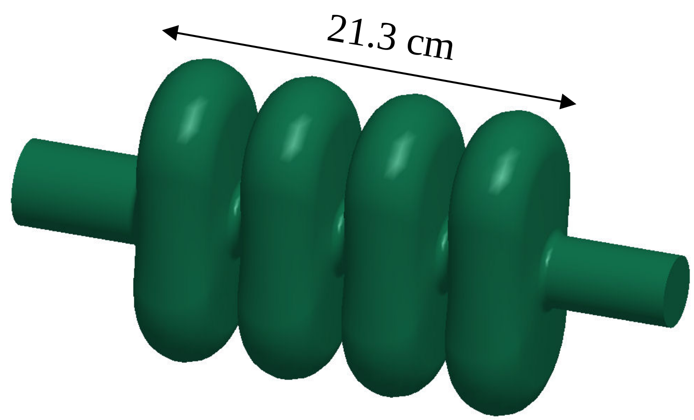
SC rf cavity study for APS *(G. Waldschmidt, G. Pile, D. Horan, R. Kustom, A. Nassiri, K. Harkay)*

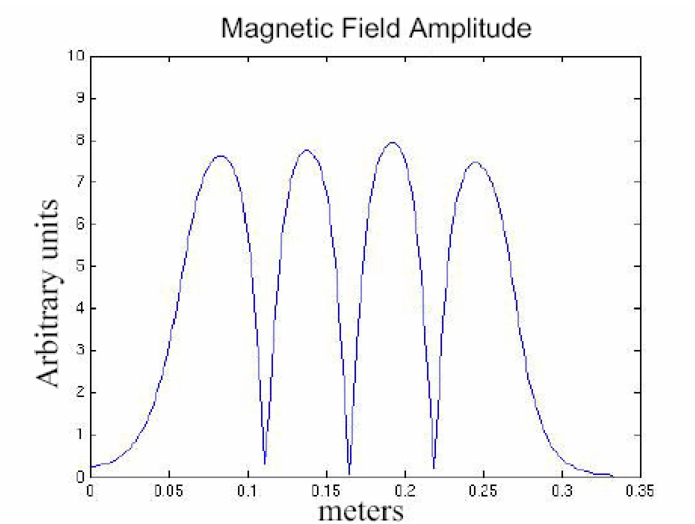
Frequency	2.81 GHz
Deflecting Voltage	4 MV
Deflecting Gradient	~ 5 MV/m
Q_o	3×10^9
B_{MAX}	< 100 mT
RF loss at 2 K	< 50 W
HOM: Rt at 100 mA	< 2.5 MΩ/m
HOM: Rs $*f_p$ at 100 mA	< 0.8 MΩ-GHz
Available length	2.5 m

Assuming CW operation, power and space reqt's favor SC:

- RF losses
  - RT, single cell cavity: on the order of 10 MW
  - SC cavity: on the order of 25 W (2 K)
- Single-cell vs. multiple-cell SC cavity configurations compared

Squashed rf crab cavity (based on KEK design)

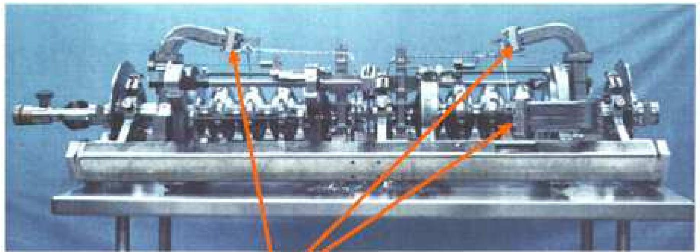




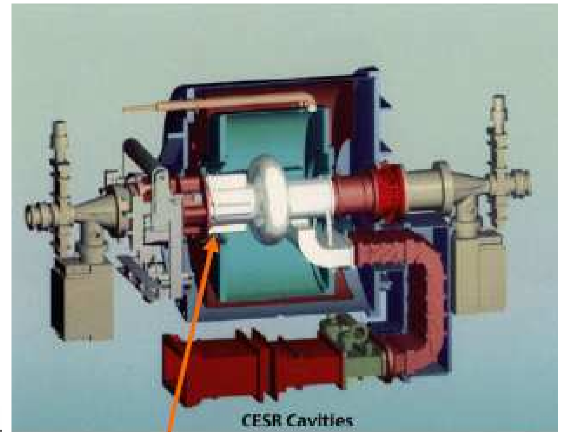
G. Waldschmidt, APS ps Workshop, May 2005

	1-cell	4-cell (π mode)	
Frequency	2.81	2.81	GHz
No. of cavities	7	3	
Phase advance	----	180	Deg
Cavity radius	7.8	7.8	cm
Iris radius	---	1.8	cm
Beam pipe radius	2.1 / 1.8	2.1 / 1.8	cm
Deflecting voltage	4	4	MV
Deflecting gradient	10.7	6.25	MV/m
Q_o	3×10^9	3×10^9	
R_T/Q	52 * 7	220 * 3	Ω
Active cavity length	5.3 * 7	21.3 * 3	cm
B_{MAX}	95	80	mT
P_{beam}, 1mm offset	~25	~25	kW
RF loss at 2 K	15	10	W

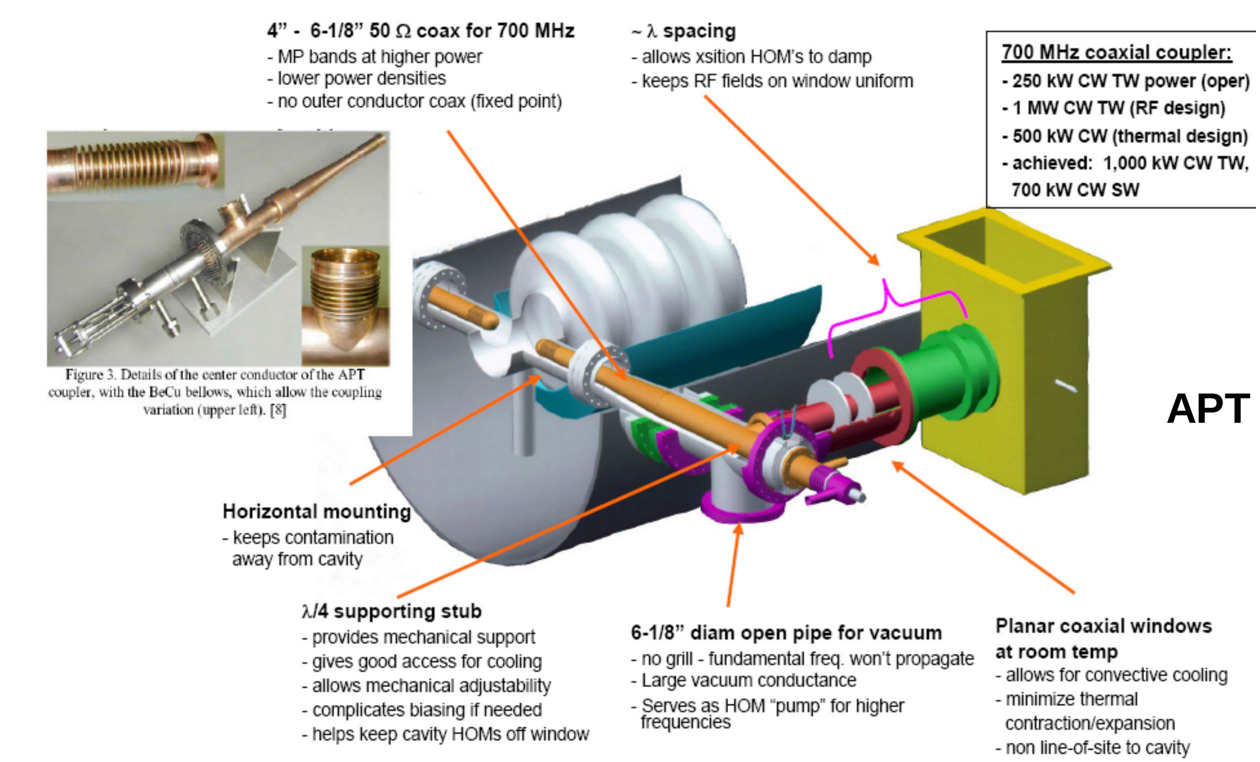
RF coupling and mode damping



waveguide HOM couplers with
dissipative loads on a JLab cavity



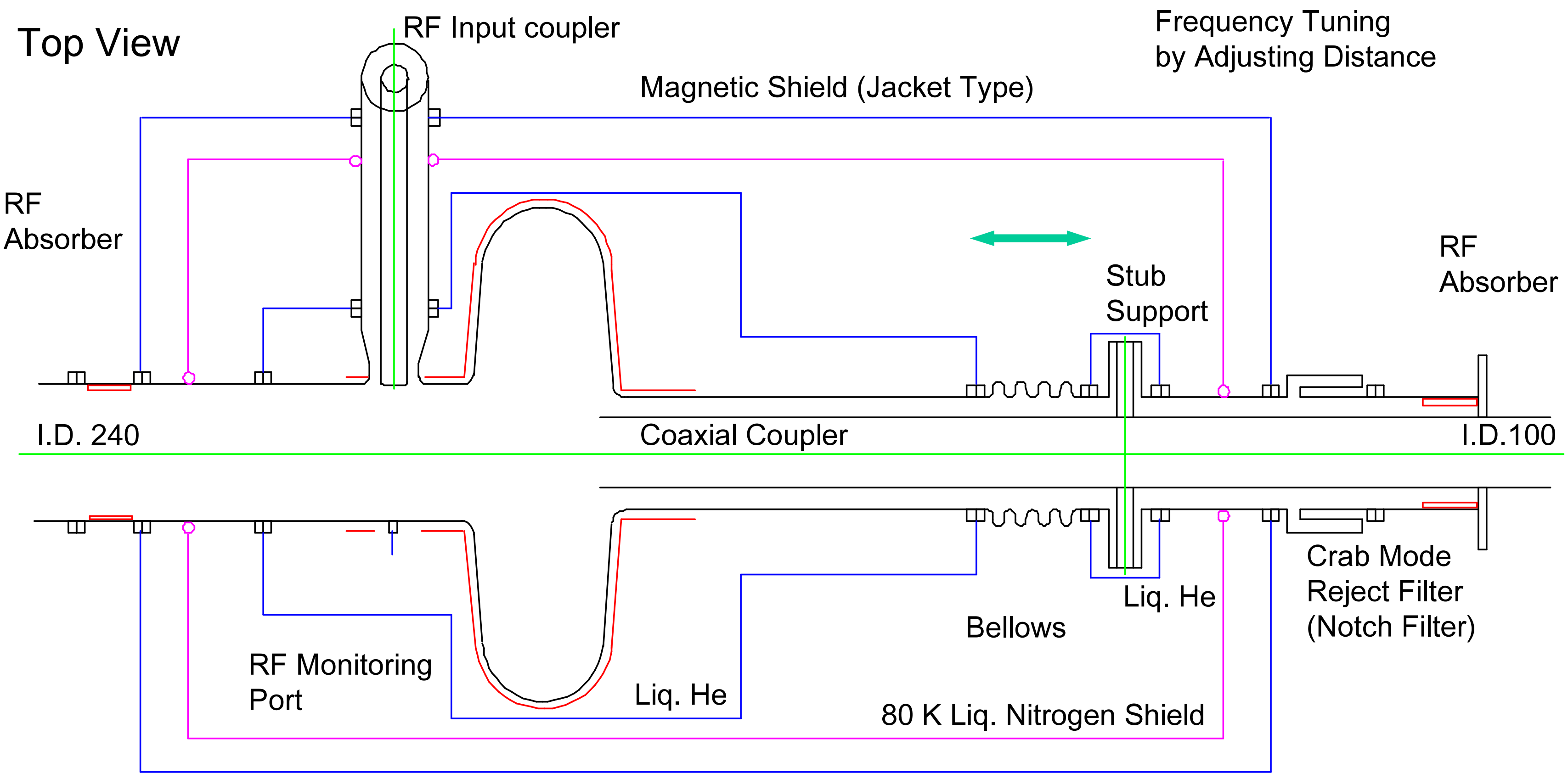
fluted beam tube leading to ferrite
dissipative loads on a CESR cavity



APT @LANL

Courtesy A. Nassiri

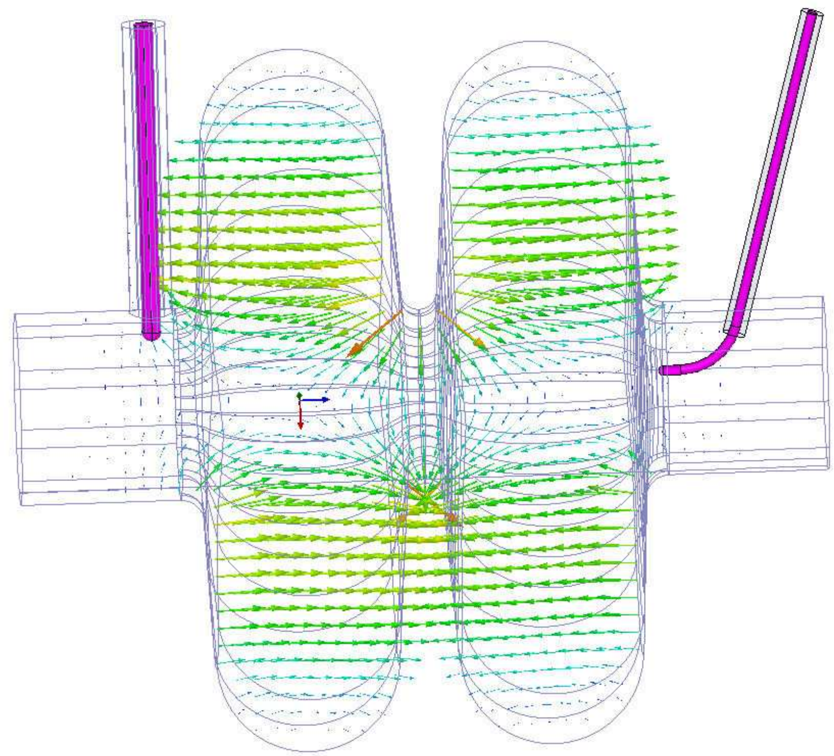
RF coupling and mode damping



Courtesy KEK

Two-Cell Deflecting Cavity

- Two-cell cavity
  - Requires less space than single-cell
  - Fewer parasitic modes than many-cell cavity
  - Less opportunity for trapped mode
- Coaxial input coupler supplies power for 4 MV deflecting voltage at 2.81 GHz.
- Various damping scenarios investigated.
- Note: Maximum B-field will be easily reduced by enlarging center iris
- Estimate no more than (5) 2-cell cavities required.

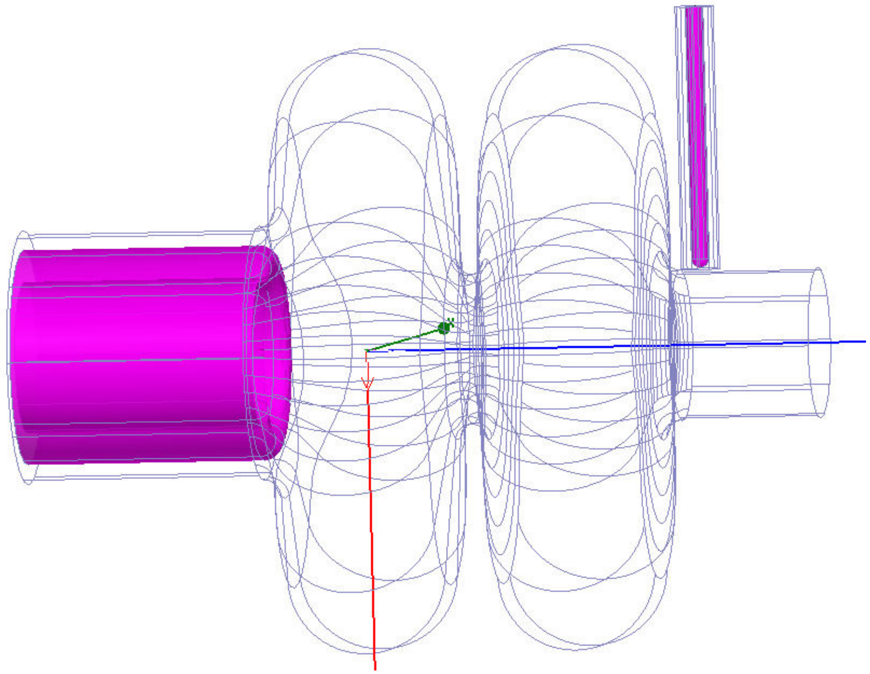


Frequency	2.81 GHz
V_T	4 MV
R_T/Q	100.6 Ω/m
Q	1.0 x 10^9
P_L	159 W
B_{MAX}	712 mT

Courtesy Waldschmidt, Nassiri

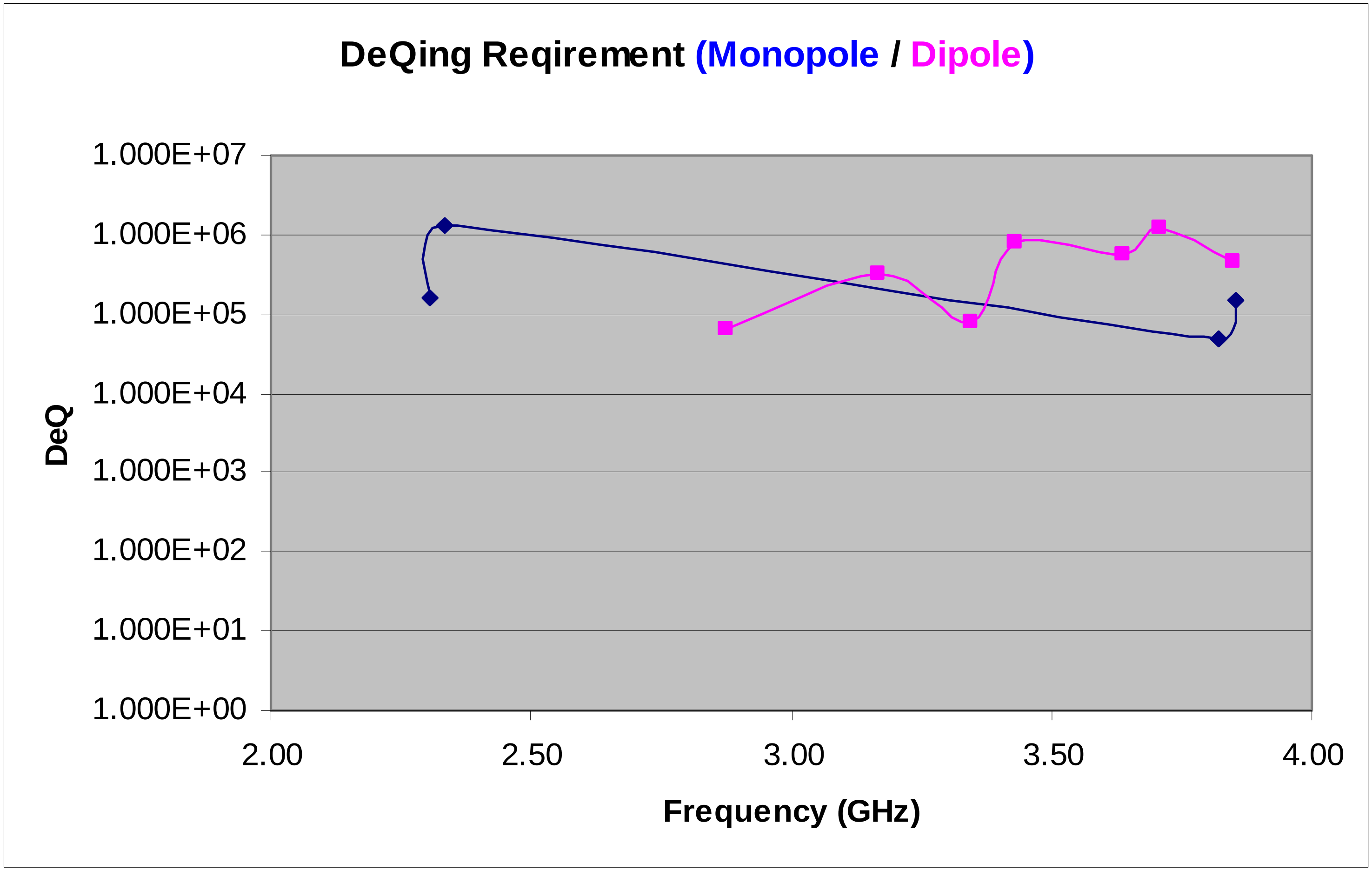
Coaxial Damper

- Beam pipe enlarged from 19 mm to 32 mm radius.
  - 19 mm aperture for beam.
  - 8 mm thick beam pipe damper for Nb and cooling channel
  - 5 mm gap between inner and outer conductors
- Substantial deQing of LOM ~10^4
- Deflecting mode rejection filter not yet implemented
- Removal of LOM from beam pipe damper will likely be done using coaxial transmission line



Waldschmidt

Recent efforts re. damping parasitic modes (APS, 2-cell)



Slide courtesy G. Waldschmidt

Issues to be resolved

- Effective damping of HOM and LOM
  - coaxial line in beam pipe
  - radial line
  - loop
- Deflecting mode input power coupling
  - coupler design
  - variable coupling
- Cavity optimization
  - deflecting gradient in available insertion length
  - shunt impedance
- Frequency
  - rf source availability
  - input power
  - fill-time

Issues to be resolved

- Extraction of LOM w/o disturbing deflecting mode excessively
- Accessing and eliminating the 0-mode in the TM11 passband - challenging task
- Proper deQing of all HOM’s
- Extraction of power from parasitic modes from coax beam pipe
  - Remove heat load outside of cryo-module.
  - Prevent heat loads too large for damping material
- Convert to waveguide input coupler for ease of cooling and construction – although possible added complexity for cryo system.
- Damping unwanted polarization of TM110 mode
  - Impedance threshold for stability in the APS dictates strong damping of these modes
  - HOM field profiles somewhat similar to the deflecting mode
  - Frequency separation of the nearest HOM is ~9 MHz. Damping this mode may cause significant deQing of the deflecting mode
  - Allowable deQing factor for the deflecting mode

Courtesy A. Nassiri

Advantages of KEK mode damper design

- Coaxial beam pipe on one side
- There is no cut-off frequency for TEM mode. All monopole modes in the cavity can couple to the coaxial beam pipe as a TEM mode and propagate
- In addition, all dipole modes can couple to the coaxial beam pipe as a dipole mode wave and propagate
- Designing cavity cell shape such that $f_{TE111} > f_{cutoff} > f_{TM110}$
- One dipole parasitic mode still left trapped in the cavity (unwanted polarity crab mode)

Courtesy A. Nassiri

CW RF Source (s)

- At what power?
  - ~100 kW (for 300 mA operation)
  - ~40 kW (for 100 mA operation)
- What frequency?
  - 2.8 GHz (8^{th} harmonic of the SR rf frequency)
  - 1.4 GHz (4^{th} harmonic of the SR rf frequency)

Manufacturer	Tube	Frequency (GHz)	Output Power (kW)	Voltage (kV)	Current (A)
THALES	**TH2110**	**2.856**	**50**	**26.5**	**3.3**
CPI	**VKS-7975A**	**2.45**	**120**	**34**	**6.3**
TOSHIBA	**E3724**	**2.45 (h=7)**	**100**	**42**	**4**
TOSHIBA	**E3778**	**1.76 (h=5)**	**1400**	**85**	**30**
TOSHIBA	**E3750**	**1.4**	**25**	**19**	**2.5**

Courtesy A. Nassiri

Outline

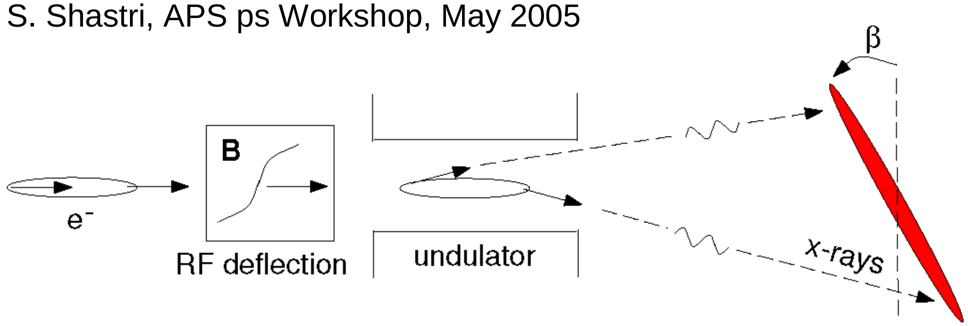
- Science case
- Introduction to rf deflection
- Rf deflecting cavities
  - RT vs SC
  - Challenges
- X-ray optics
- R&D plan
- Summary

X-ray compression optics design constraints

- Suite of beamlines to be determined
  - Some compressed, others not
  - Optimized for tuning range(s)
- Upgrades to existing ID beamline(s) include optics, modification of vertical apertures, etc
- Not trivial, but likely in line with typical new beamline commissioning timeframe of a few years
- Optimization:
  - Compression throughput
  - Pulse duration and spot size
  - Energy tunability (5-30 eV)
- Issues: geometric effect, mirror

RF Deflection Followed by Tilt - Rotation by Asymmetric Crystals

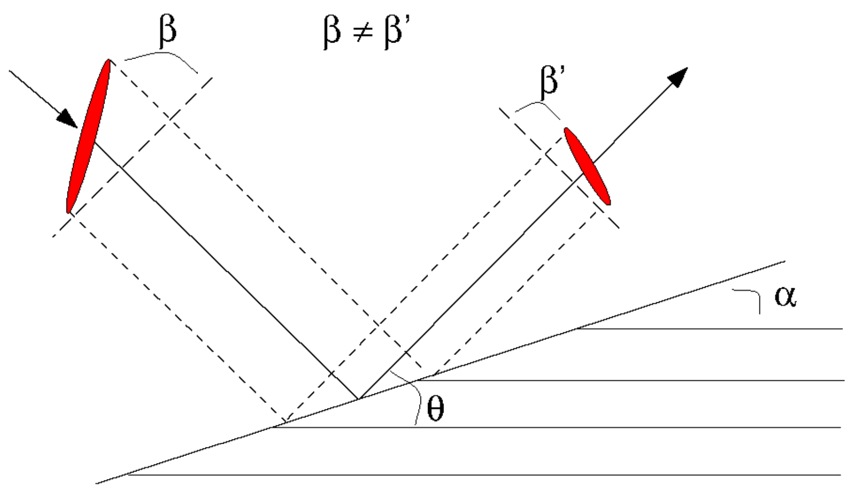
S. Shastri, APS ps Workshop, May 2005



RF voltage: 4 MV
RF freq: 8×352 MHz = 2.8 GHz

Gives deflection gradient $\pm$ 380 μrad / σ_t
where σ_t = 40 ps is r.m.s. bunch length

For x-rays at 30 m, $\beta = \pm 46°$,
1 σ_t vertically dispersed by 11.6 mm



Bragg geometry $-\theta < \alpha < \theta$

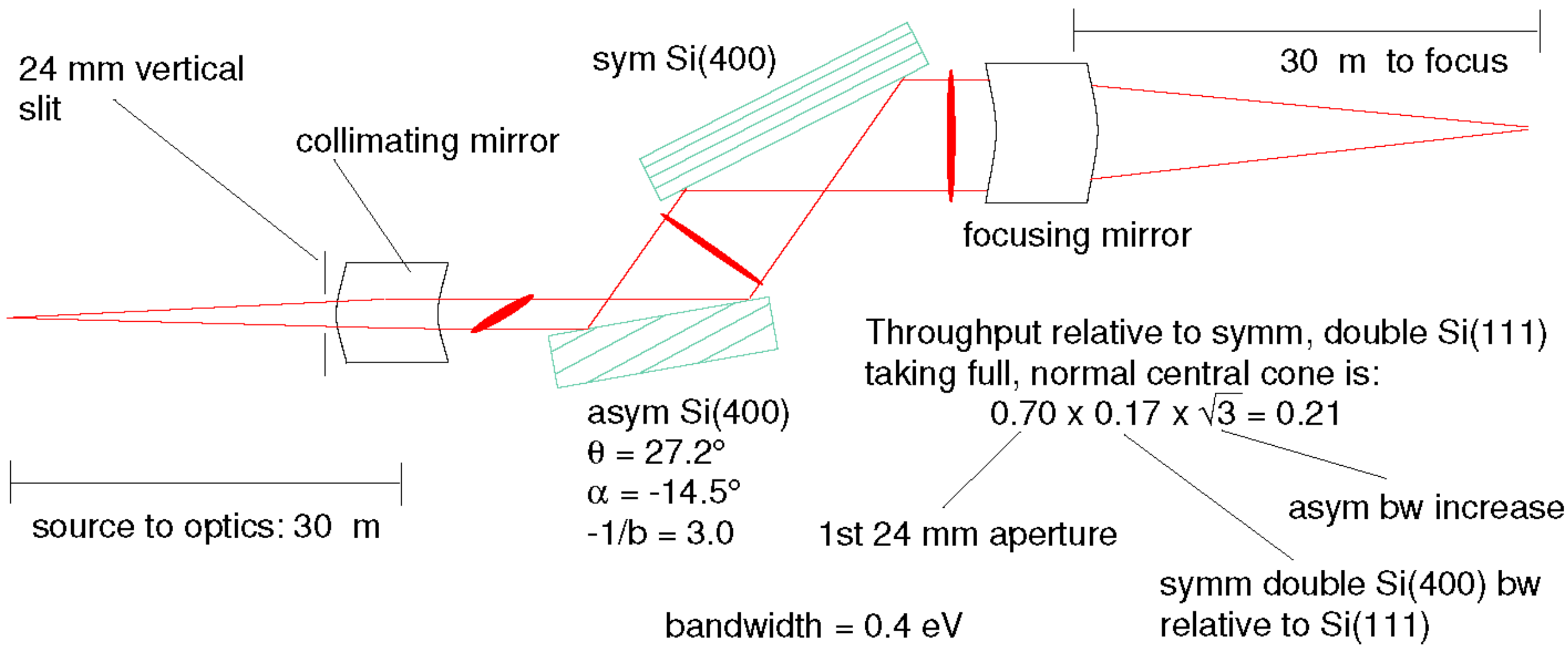
Laue geometry $\theta < \alpha < 180° - \theta$

Rotation $$\tan \beta' = \frac{\tan \beta \sin(\theta + \alpha) - 2 \sin \theta \sin \alpha}{\sin(\theta - \alpha)}$$

Beam size magnification $1 / |b|$ $$b = \frac{\sin(\theta + \alpha)}{\sin(\alpha - \theta)}$$

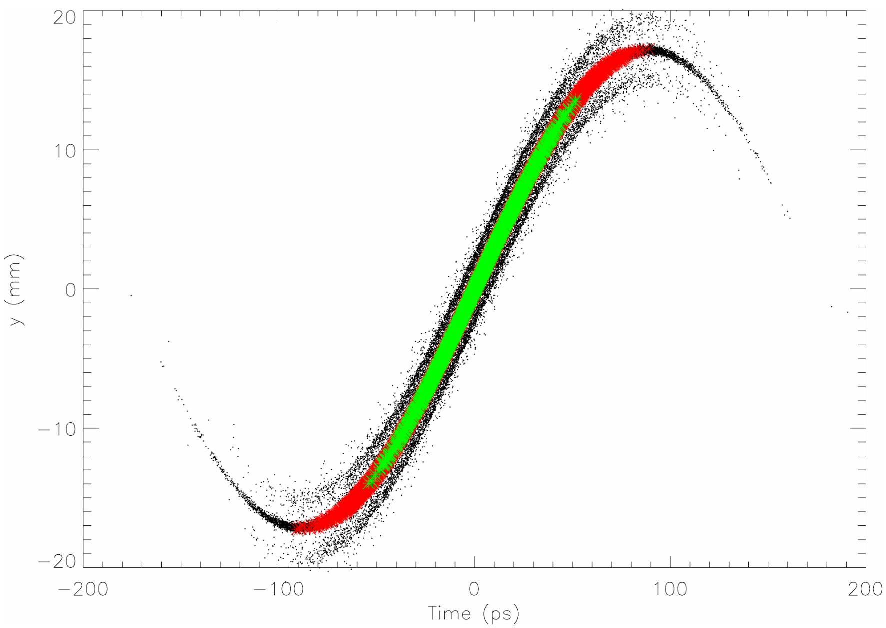
Angular divergence change $\Delta\theta \longrightarrow -b\,\Delta\theta$

X-ray compression optics
(S. Shastri, R. Dejus, L. Assoufid)

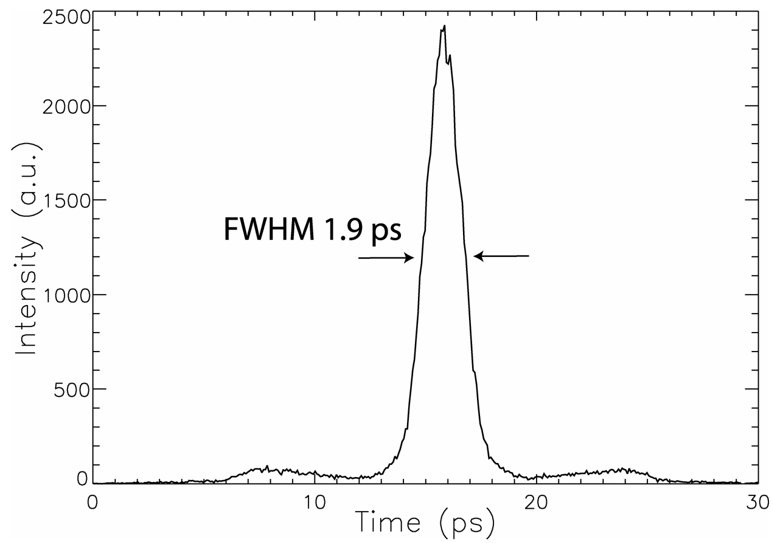


X-ray compression optics simulation

(R. Dejus)

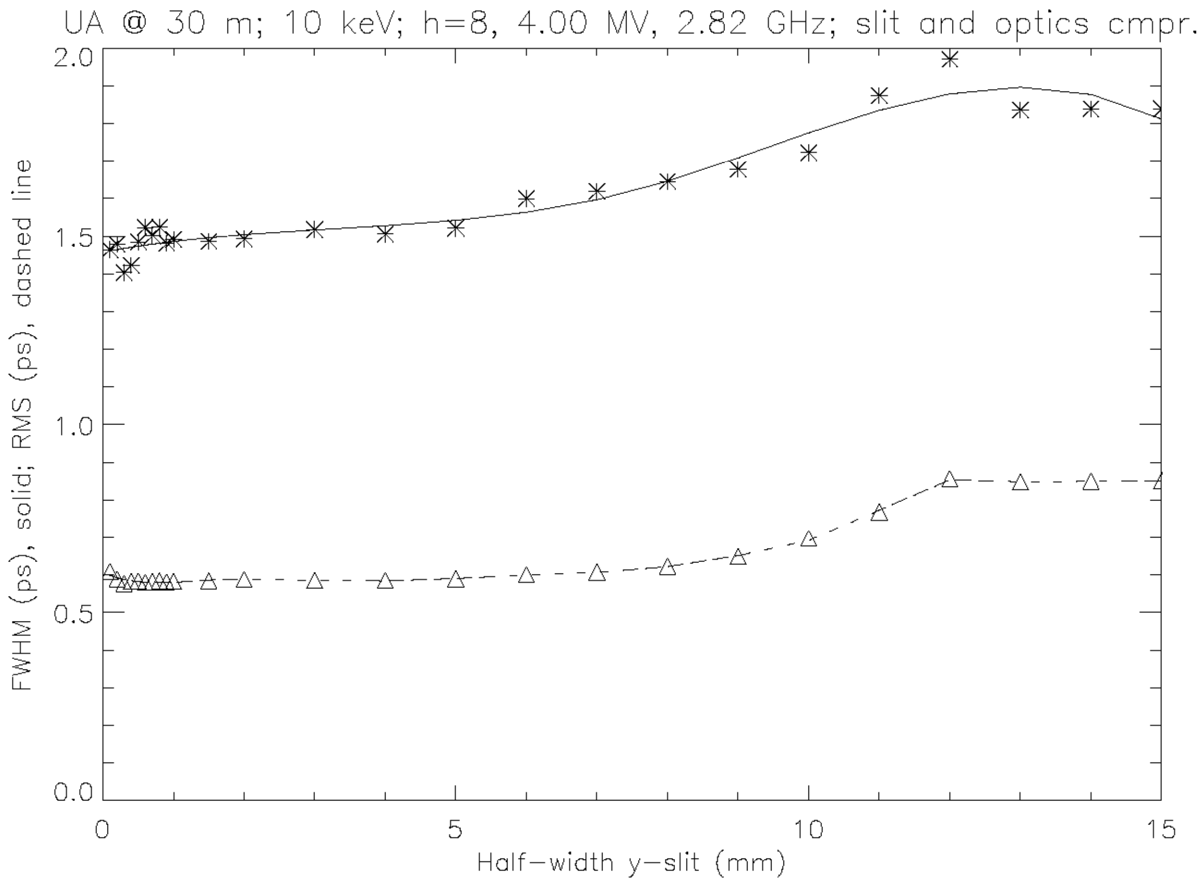


2D scatter plot, undulator A irradiance at 30 m, 10 keV. Red = 10% level, green = 37% (1/e).; ~ 20% are thrown away. The tilt angle β is ~ 55°.



Pulse histogram using optics compression and a slit of 8.0 mm (half-width). The rms width is 1.19 ps (FWHM ~ 2.8 ps), and the transmission is 62%.

Optics Compression Pulse Widths



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R&D Draft Plan

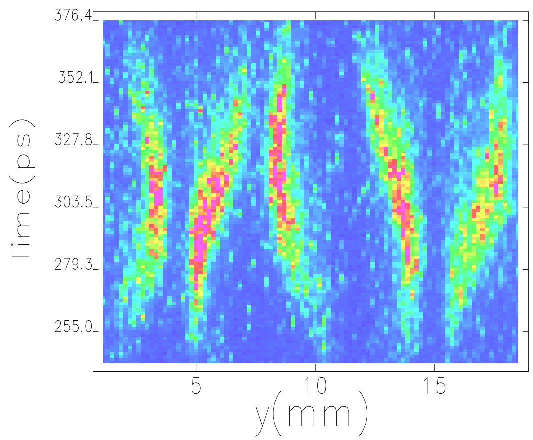
- Feasibility study completed
- SC rf technology chosen

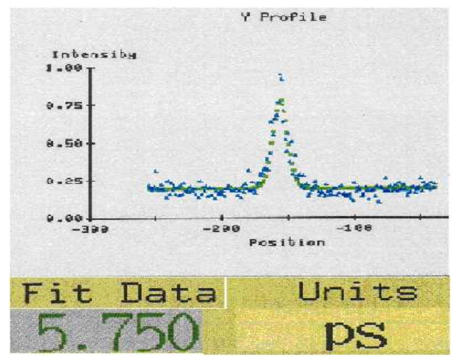
- Model impedance effects (parasitic modes, head-tail)
- Finalize RF system design, refine simulations
- Refine x-ray compression optics design, end-to-end ray tracing
- Conduct proof of principle tests (beam dynamics, x-ray optics)
  - Chirp beam using synchrobetatron coupling (transient) (W. Guo)
  - Install 1 MV RT S-band structure, quarter betatron tune (M. Borland, W. Guo)
  - Install warm model of SC rf cavity (passive), parasitic mode damping (K. Harkay)

- Green light: begin construction, order long-leads, fabrication, etc
- Deliver operational system in ≤ 3 yrs

Ultrashort x-ray pulse generation test 1

Transient, short pulses are generated using an alternate scheme based on synchrobetatron coupling (suitable for study, but not operation). At left, an image of the beam 0.3 ms after a vertical kick, using APS sector 35 optical streak camera. At right, a short pulse is observed using a 40 µm vertical slit (fit gives 5.8 ps rms, nominal bunch length 30 ps).





W. Guo, K. Harkay, B. Yang, M. Borland, V. Sajaev, Proc. 2005 PAC

Carry out a demonstration short-pulse x-ray experiment on APS beamline

Structural molecular reorganization following photoinduced isomerization/ dissociation can be studied on a finer timescale. Transient pulse requires acquisition of entire x-ray absorption spectrum in a single shot. (L. Young and colleagues)

Summary

- We believe x-ray pulse lengths ≤ 1 ps achievable at APS
- SC RF chosen as baseline after study of technology options
- Main rf challenges include parasitic mode damping and cavity optimization
- X-ray compression optics configurations studied
  - Slits only: 10^{13} ph/s avg (~1% of normal flux)
  - Compression: throughput 2-15x better than slits alone over energy range 30-5 eV, respectively
- Main optics challenges include very long focusing mirror if required
- Proof of principle R&D is underway: beam/photon dynamics, RT and SC rf
- Operational system possibly ≤ 3 yrs from project start

Select references

Deflecting cavity method

1. A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A 425, 385 (1999).

APS papers

1. K. Harkay et al., “Generation of Short X-Ray Pulses Using Crab Cavities at the Advanced Photon Source, ” Proc. 2005 PAC.
2. M. Borland, Phys. Rev. ST Accel. Beams, 074001 (2005).
3. M. Borland, V. Sajaev, “Simulations of X-ray Slicing and Compression Using Crab Cavities in the Advanced Photon Source,” Proc. 2005 PAC.
4. W. Guo et al., “Generating ps x-ray pulses with beam manipulation in synchrotron light sources, “ Proc. 2005 PAC.

Recent APS workshops (talks)

1. Future Scientific Directions for APS (http://www.aps.anl.gov/Future/Strategic_Planning_Meeting/home.htm)
2. 2005 APS Users Meeting: Workshop on Generation and Use of Short X-ray Pulses at APS (http://www.aps.anl.gov/Users/Meeting/)