The Accelerator-Science Test Accelerator (ASTA) facility at Fermilab: plans and opportunities

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CBP seminar,
October 25, 2011, LBNL

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The Advanced Science & Technology Accelerator (ASTA) facility at Fermilab: plans and opportunities

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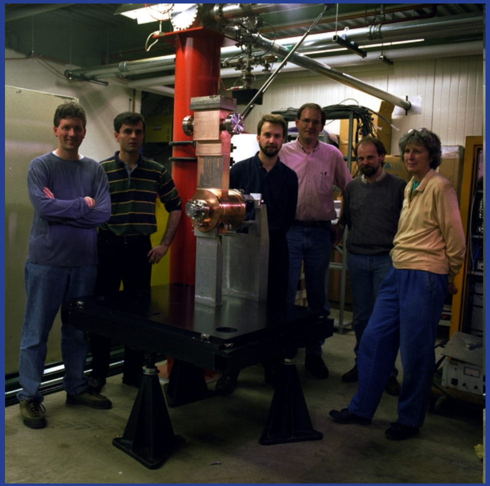
Outline

- Introduction,
- Accelerator science at the A0 photoinjector (A0PI): recent achievements,
- Near term plans:
  - Advanced Science & Technology Accelerator (ASTA)
  - High-brightness electron source Laboratory (HBSEL)
- Conclusion.

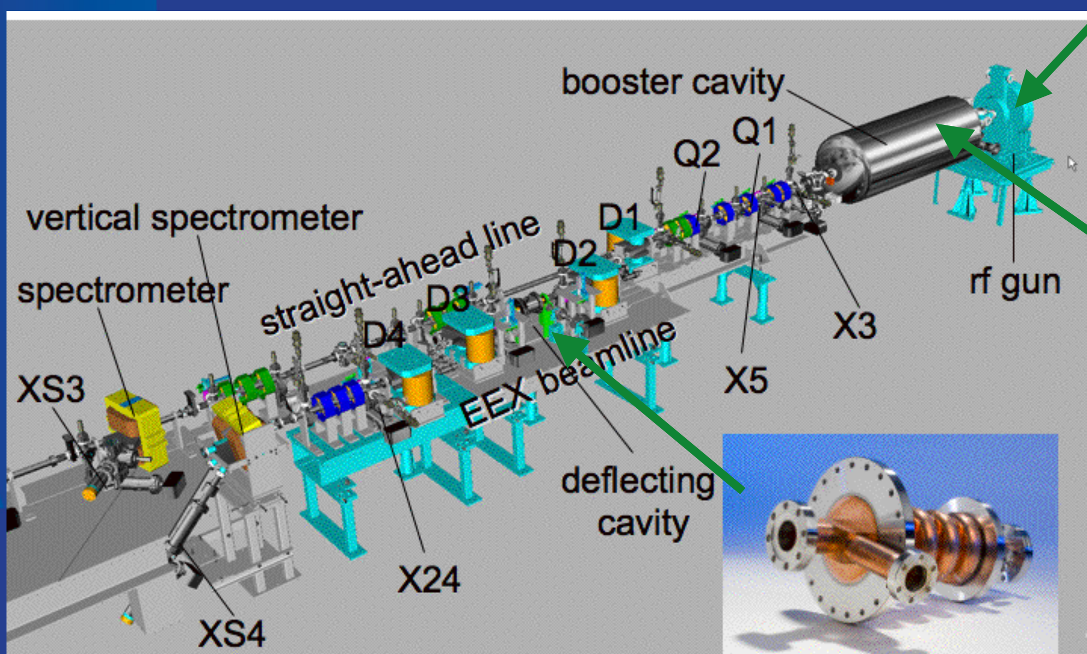
Introduction AARD at Fermilab

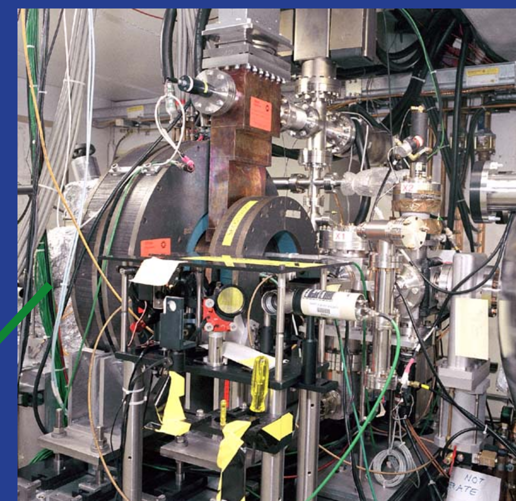


- **Technology:**
  - Designed, built, delivered an injector for the TESLA test facility (TTF-1) at DESY,
  - Laser capable of providing ILC-type macropulse.
- **Scientific Achievements:**
  - Characterization of a L-band gun over a wide range of operating parameter (1999), [Carneiro et al. PRSTAB 2005].
  - Channeling radiation at high charge (1999-2003) [Carrigan, PRA 2003],
  - Observation of wakefield via electro-optical imaging (2000). [Fitch, PRL 2001].
  - Generation of angular-momentum dominated beams (2002-2003), [Sun, PRSTAB 2004].
  - Flat beam production in a photoinjector (2000-2005), [D. A. Edwards, LINAC2000; Piot, PRSTAB 2006].
  - Plasma-wakefield acceleration and plasma lens in under-dense regime, (2003-2004), [Thompson, J. Plas. Phys. (2010)].
  - Emittance exchange between the horizontal and longitudinal degrees of freedom (2008-2010), [Koeth, PAC09; Ruan, PRL 2011].
  - Pulse shaping with emittance-exchanger beamline (2010-2011), [Sun, PRL 2010; Piot, PRSTAB 2011].

A0 photoinjector (A0PI): introduction

- Electron accelerator based on 1.3 GHz rf-gun with Cs_2Te photocathode → Q< 10 nC
- TESLA SCRF cavity → E=16 MeV
- Emittance exchange beamline $(\varepsilon_x, \varepsilon_z) \rightarrow (\varepsilon_z, \varepsilon_x)$
- Round-to-flat-beam transformer → $\varepsilon_x/\varepsilon_y$~100
- Extensive diagnostics
- Two photocathode lasers (Nd:YLF + Ti:Sp)



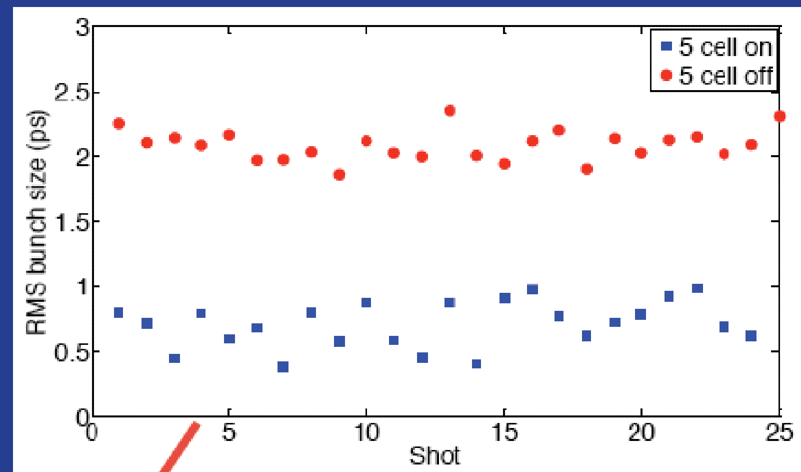


Phase space manipulations at the A0PI

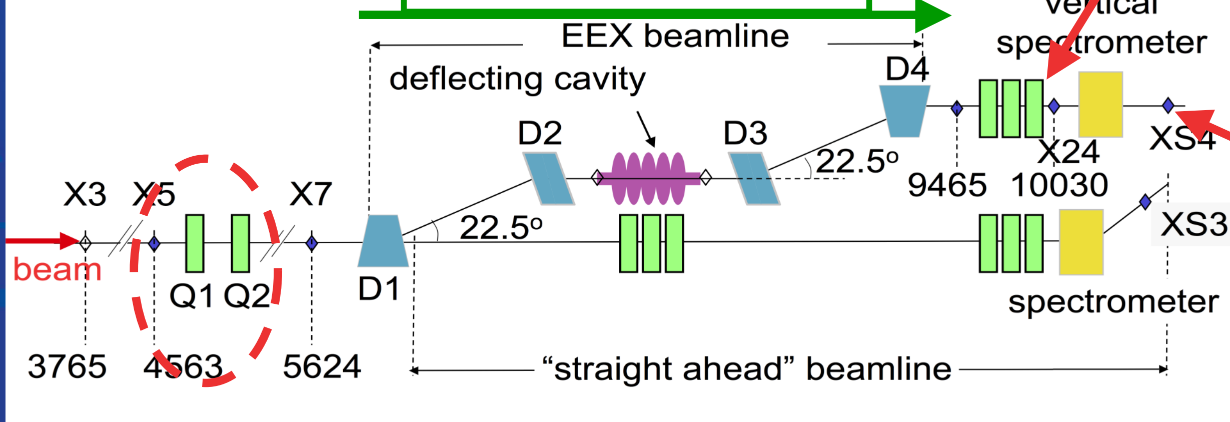
- Observed emittance exchange between the horizontal and the longitudinal phase spaces

	Simulated		Measured	
	In	Out	In	Out
ε_x^n	2.9	13.2	2.9 ± 0.1	11.3 ± 1.1
ε_y^n	2.4	2.4	2.4 ± 0.1	2.9 ± 0.5
ε_z^n	13.1	3.2	13.1 ± 1.3	3.1 ± 0.3

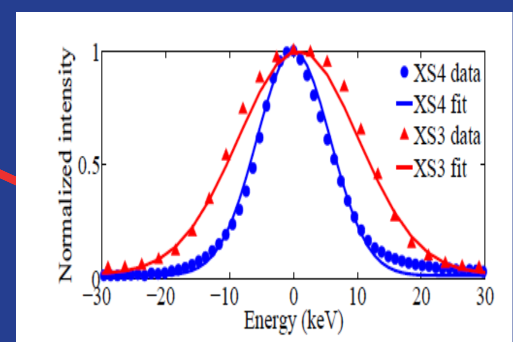
Bunch duration measurement with streak camera



$$\begin{cases} z = & -\frac{\xi}{\eta} x_0 - \frac{L\xi - \eta^2}{\eta} x_0' \\ \delta = & -\frac{1}{\eta} x_0 - \frac{L}{\eta} x_0', \end{cases}$$



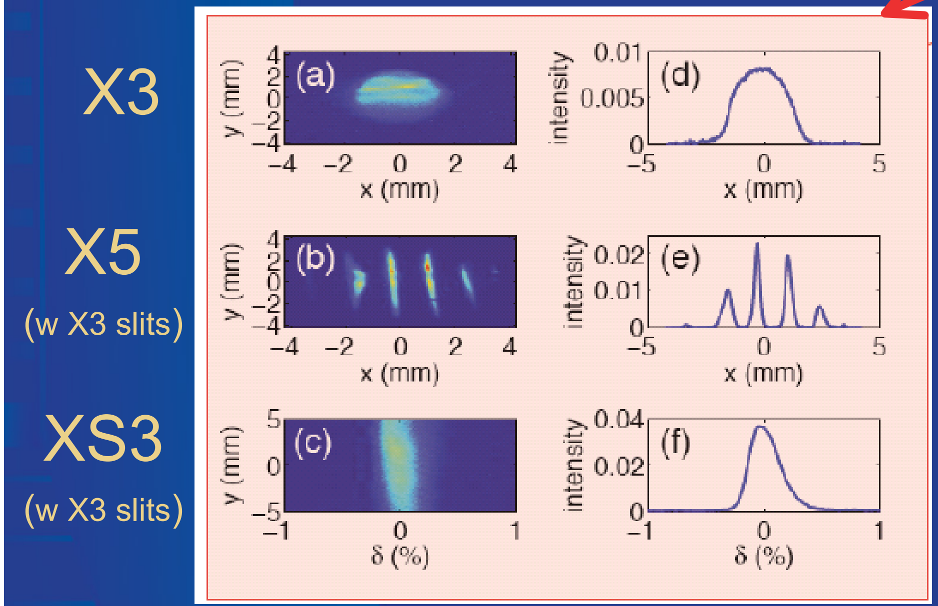
Energy spread

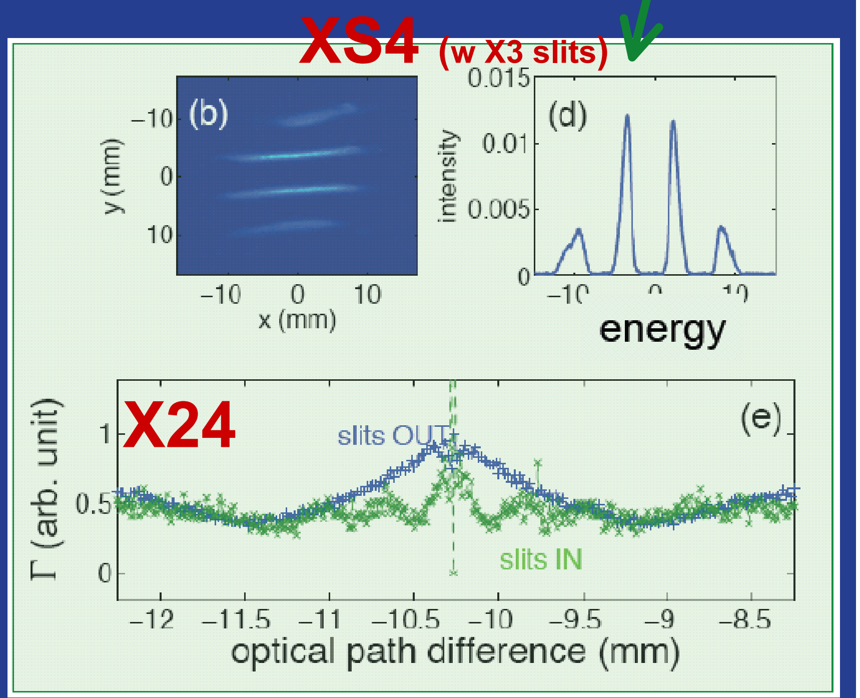


[J. Ruan et al., PRL 106 244801 (2011)]

Current-profile shaping at the A0PI

- Generated a **train of micro-bunches with sub-ps separation** using slits

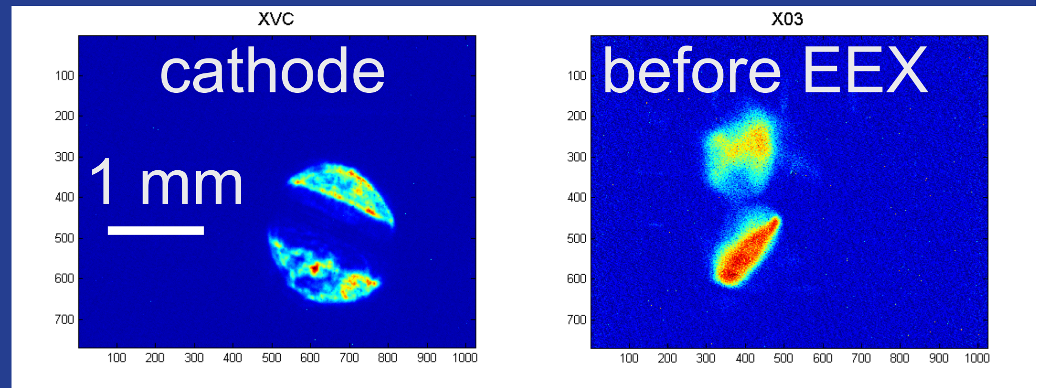


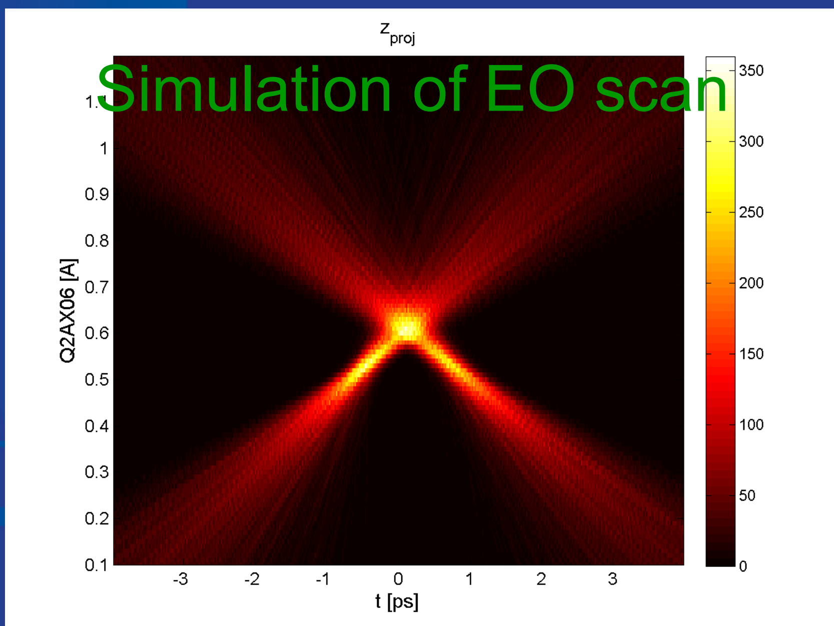


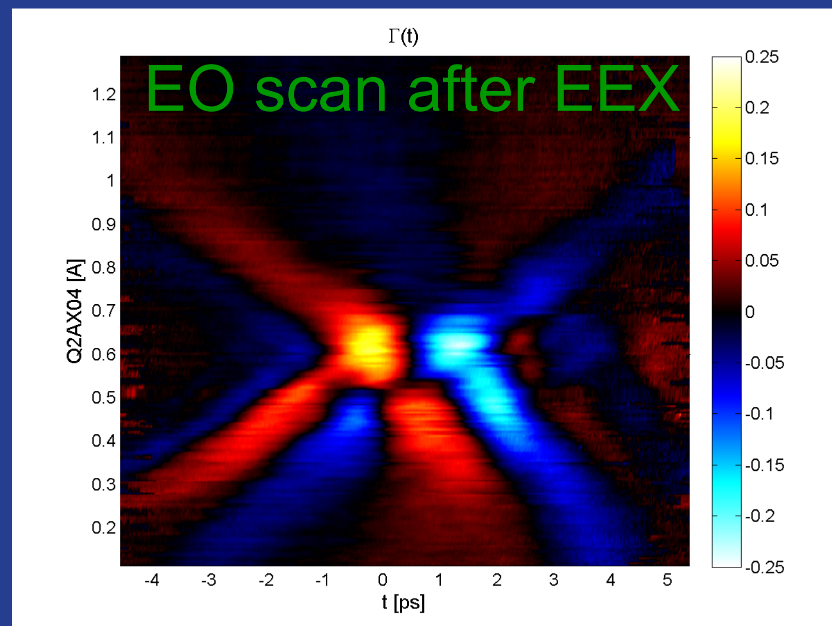
- Applications:
  - generation of narrow-band coherent radiation (next slide),
  - Resonant excitation of wakefields + transformer ratio enhancement in PWFA and DWFA. [Y.-E. Sun et al., PRL 105, 234801 (2010)
P. Piot et al., PRSTAB 14, 022801 (2011)]

Current-profile shaping at the A0PI (2)

- Demonstrated production of a double-bunch beam starting from a transverse modulation of cathode laser



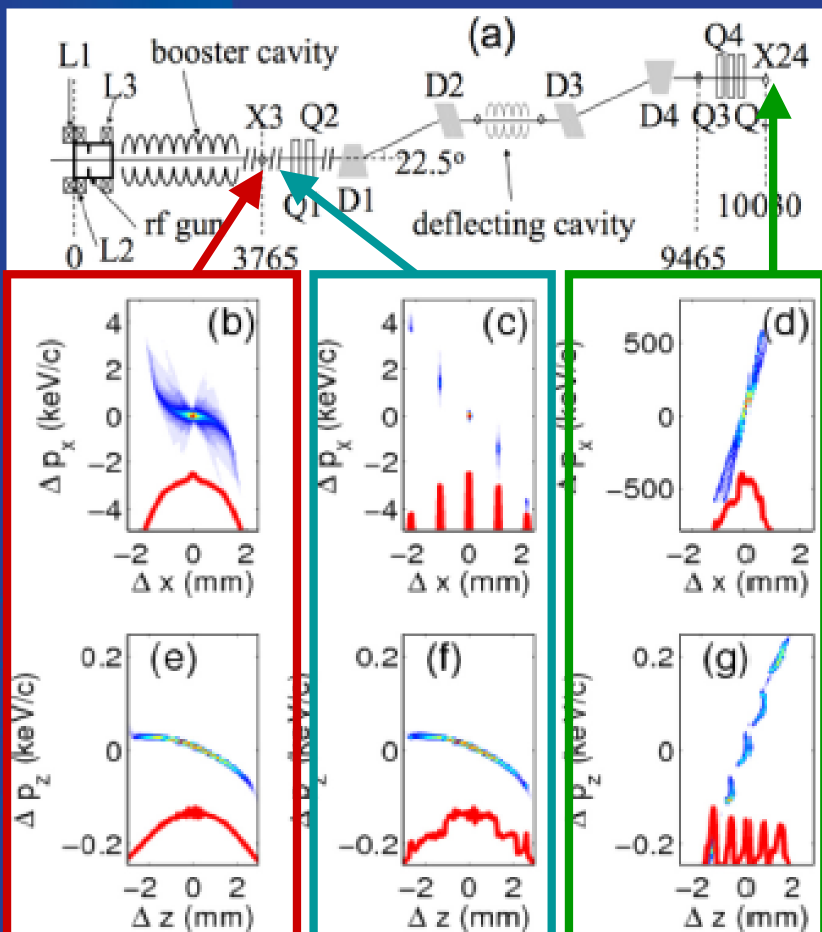


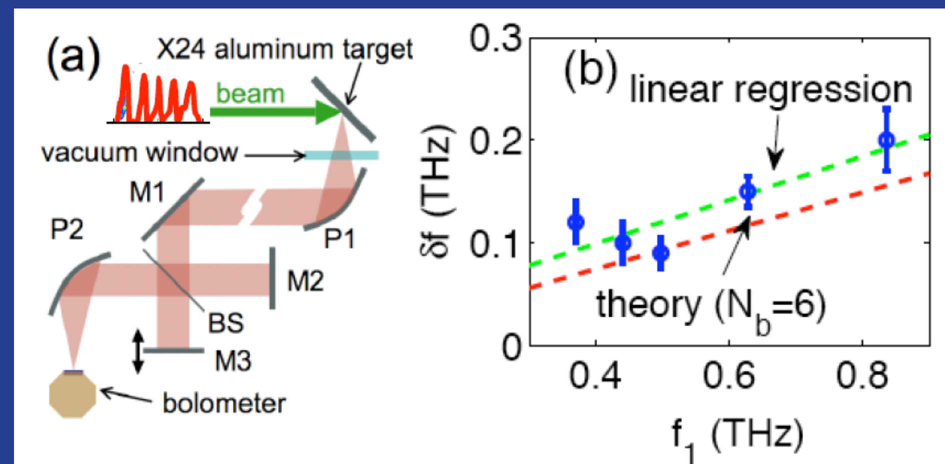


[T. Maxwell et al., (2011)]

Narrow-band Terahertz radiation

- Important application of sub-ps bunch train generation: production of tunable narrow band THz radiation,



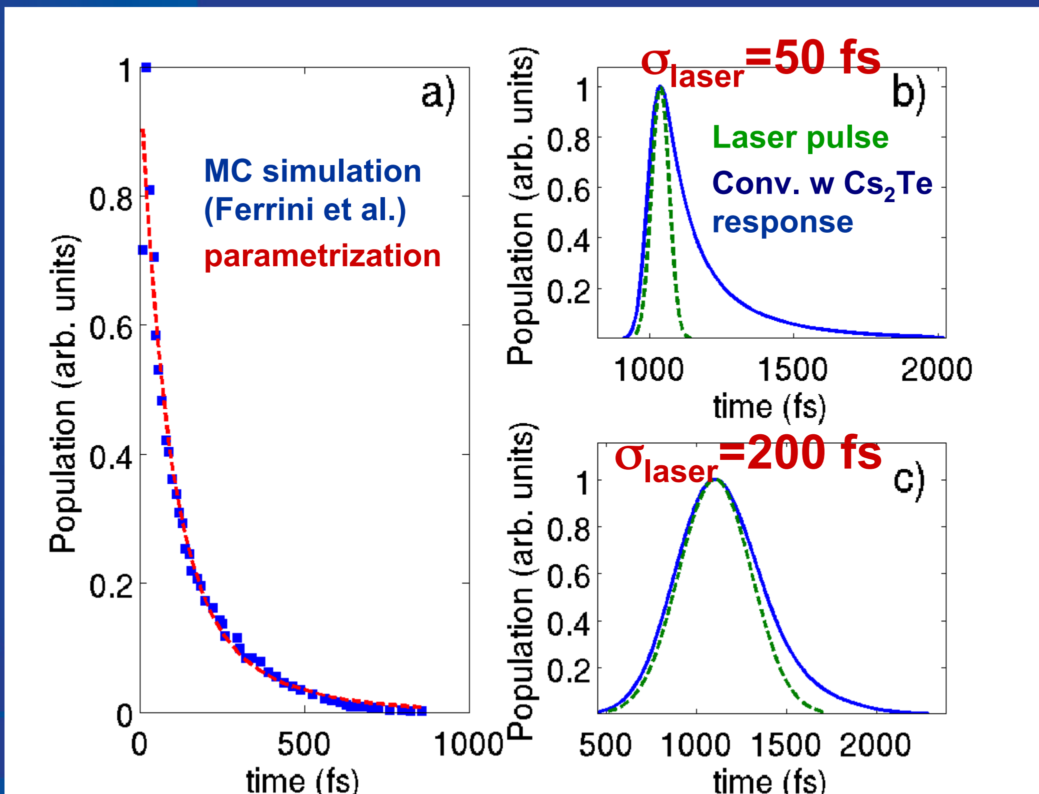


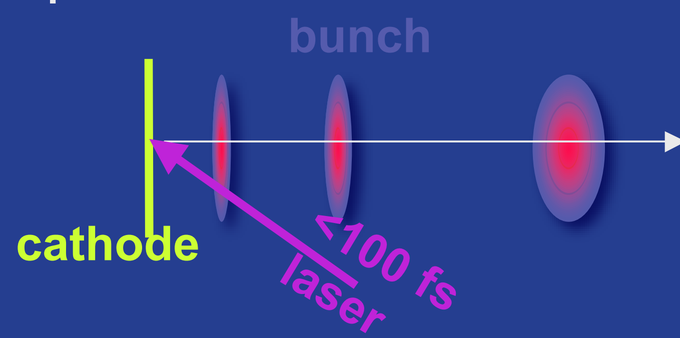
- At A0 demonstrated the generation of narrow-band THz transition radiation

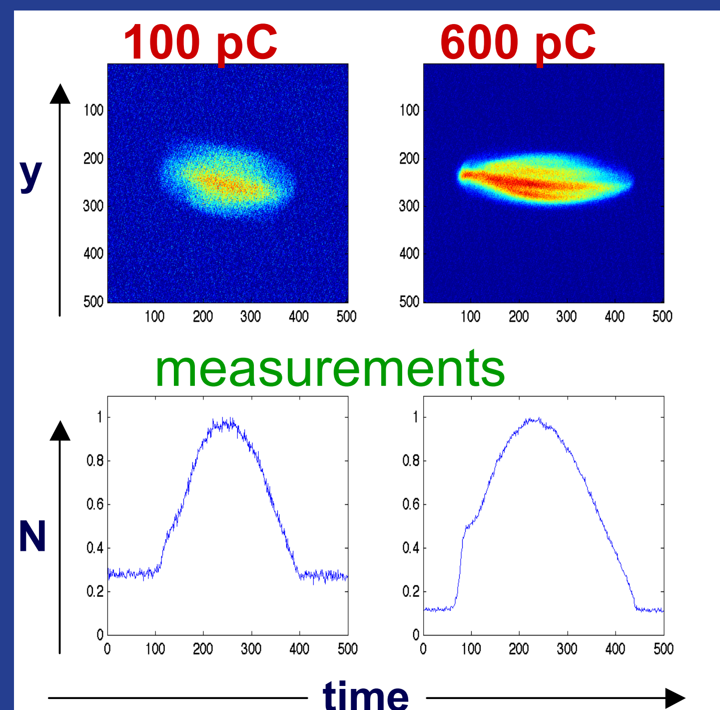
[P. Piot et al., APL 98, 261501 (2011)]

Ellipsoidal bunch from Cs_2Te photocathode

- Generation of uniformly-filled 3D ellipsoidal bunch from Cs_2Te photocathode:







- Preliminary experiment completed.

  [P. Piot et al., FEL11 (2011)]

A0 photoinjector decommissioned 09/31/2011…

- Operated from 1999 to 2011
- Next steps:
  - High-Brightness Electron Source Laboratory (HBESL)
    - RF gun,
    - Concentrate on new cathodes (especially field emitters)
  - The Advanced Science & Technology Accelerator (ASTA):
    - Eventually 900-MeV beams,
    - User-driven facility

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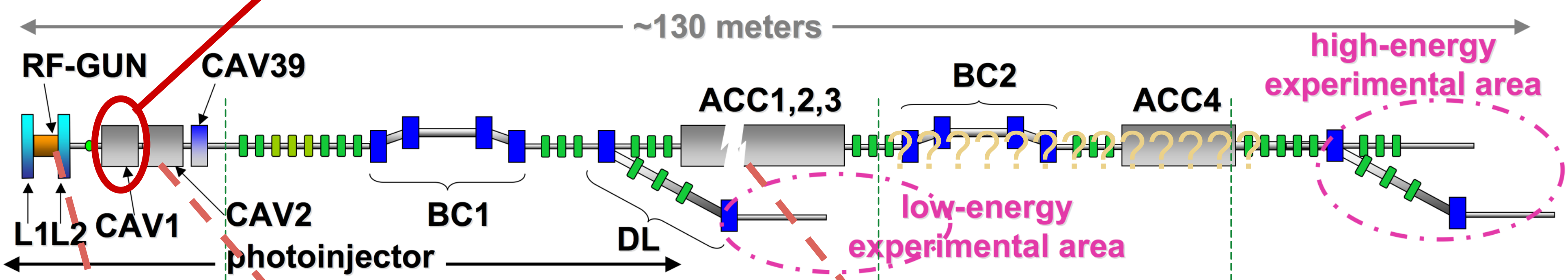
Advanced Science & Technology Accelerator

This cavity is currently at A0

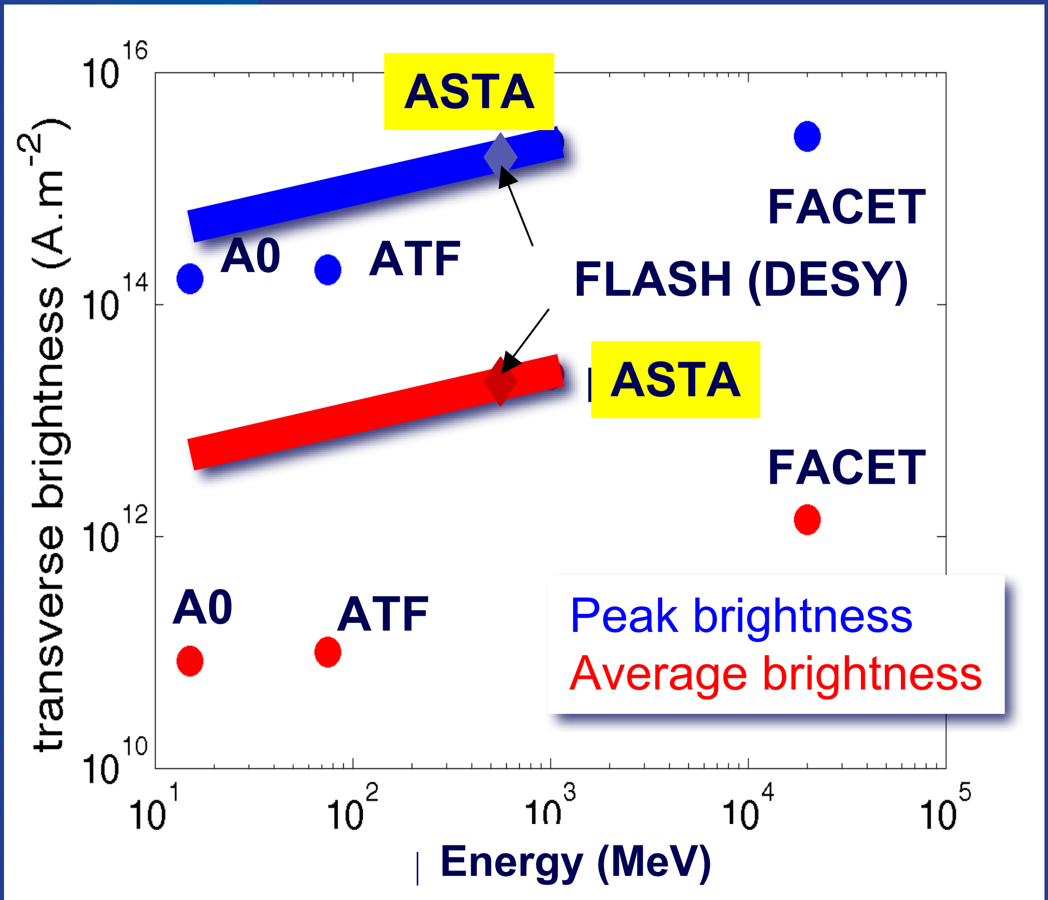


<40 MeV

< 750 MeV

< 1 GeV

ASTA promise…

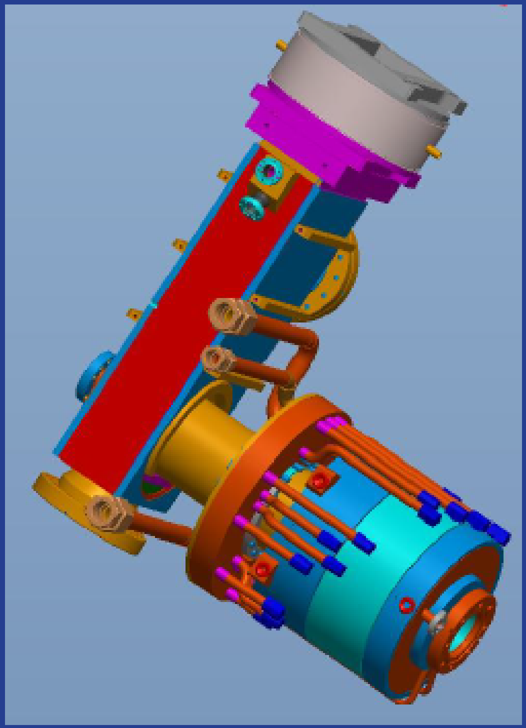


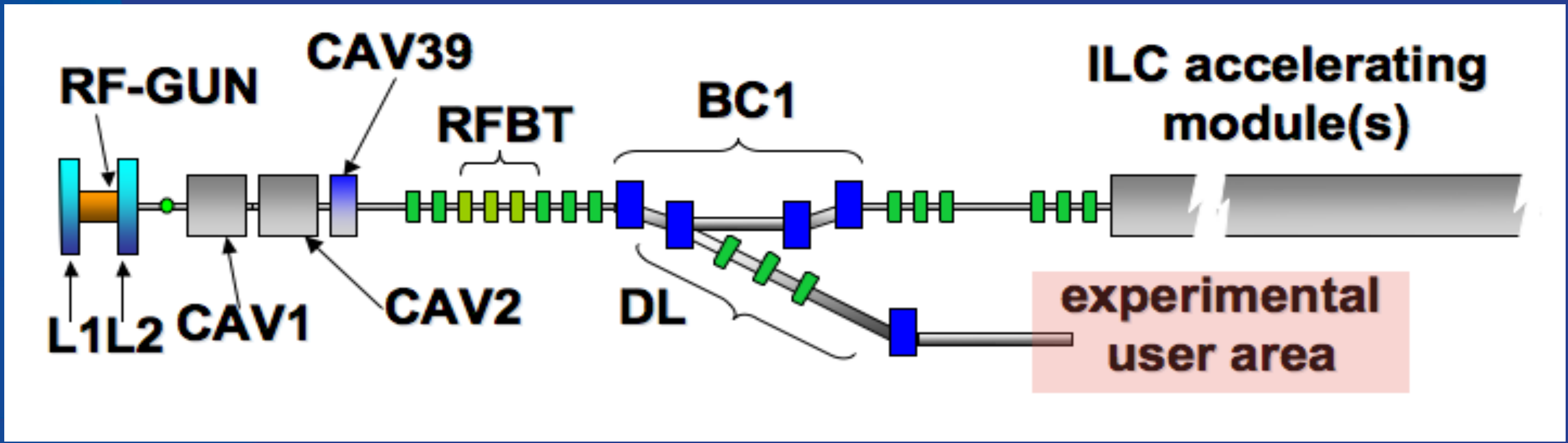
(extrapolated performances from the injector simulations)

- Variable energy from ~40 to ~1 GeV,
- High-repetition rate (1-ms trains):
  - Exploration of dynamical effects in beam-driven acceleration methods.
- L-band SCRF linac:
  - Well suited for beam-driven acceleration,
- Photoinjector source:
  - Provides low-emittance beam,
- Arbitrary emittance partition:
  - repartition of phase spaces to match final applications,
  - Tailored current profiles.

Photoinjector design

- Uses FLASH-type L-band rf gun (~40 MV/m),
- Nominal laser is 3-ps possibility to have flat-top distribution (stacking with α-BBO crystals),
- Variable transverse emittance ratio (magnetized beam + round-to-flat flat beam RFTB transform)
- 40-MeV off-axis user area

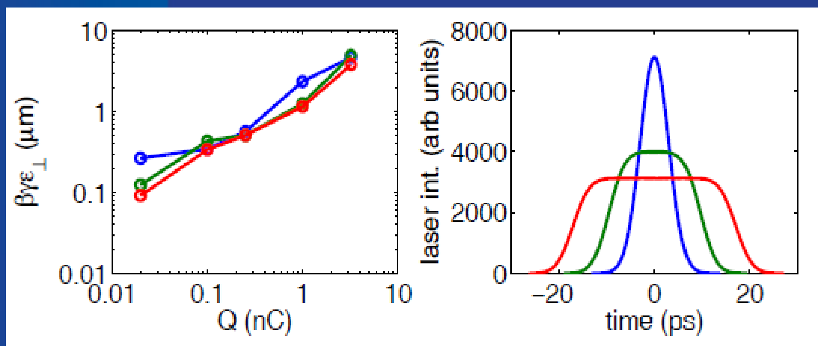




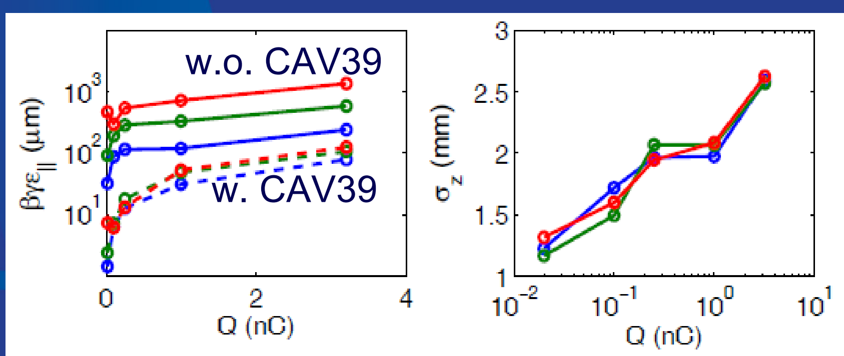
Photoinjector performances (simulations)

- Beam quality comparable to FLASH (uncompressed beam),

Transverse emittance

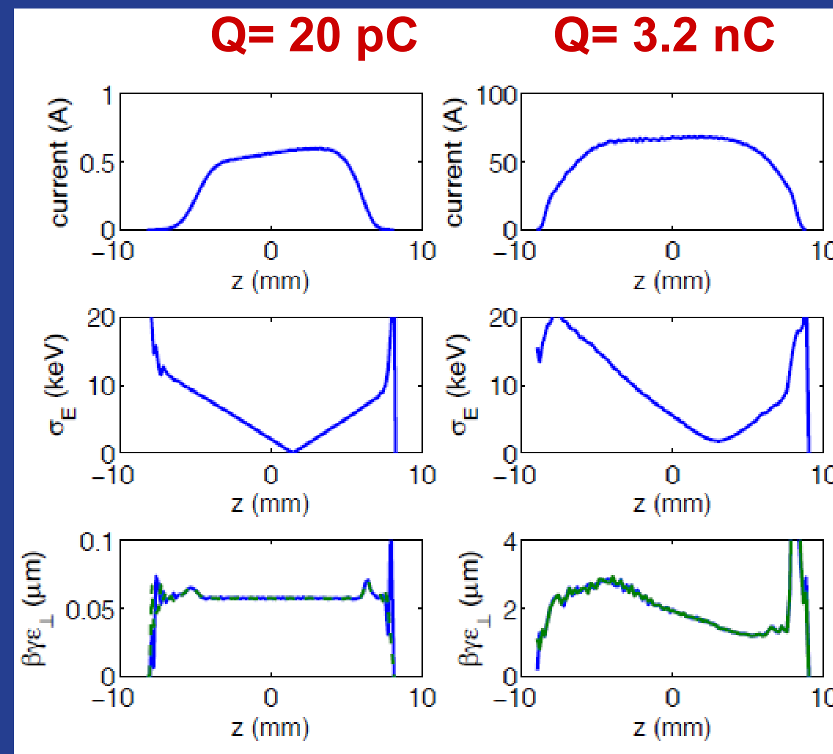


Longitudinal emittance & bunch length



[P. Piot, et al., IPAC10 (2010)]

Slice parameters



Photoinjector configuration for 1st beam

- No 3rd harmonic cavity
  $\Rightarrow$ nonlinear compression,
- Satisfies the ILC requirements: ~1.2 kA peak current (corresponds to a 3.2-nC 300-μm Gaussian bunch in a cryomodule).

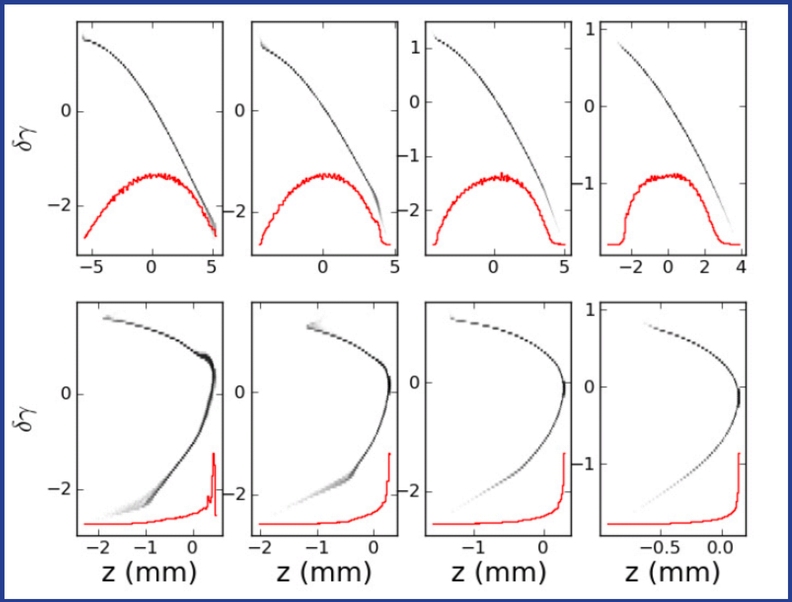
Q (nC)	ϵ_{nxi} (μm)	ϵ_{nxf} (μm)	ϵ_{nyi} (μm)	ϵ_{nyf} (μm)	σ_{zi} (mm)	σ_{zf} (mm)
3.2	4.62	13.40	4.61	8.099	2.60	0.53
1.0	2.33	3.393	2.32	2.472	1.97	0.33
0.25	0.598	1.25	0.598	1.392	1.95	0.38
0.02	0.279	0.459	0.279	.366	1.27	0.15

Transverse emittance before and after BC1 as function of charge

(simulations with IMPACT-Z)

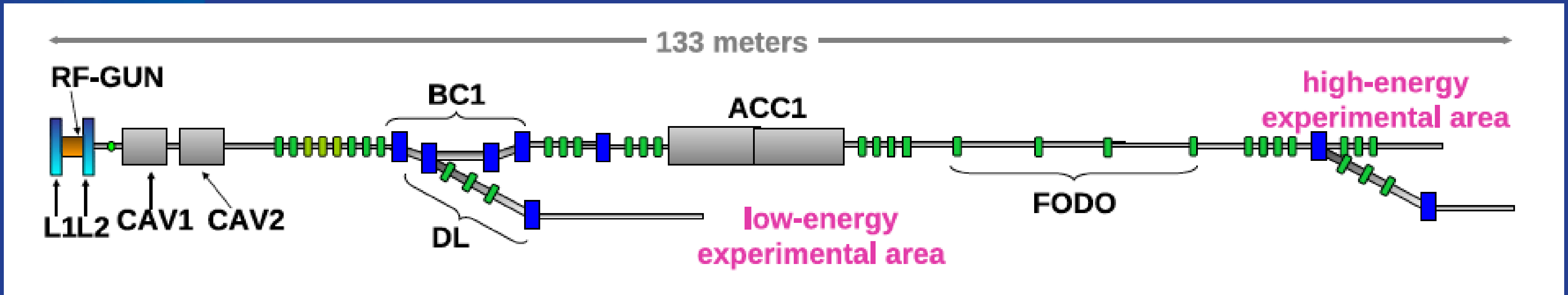
[C. Prokop, et al., (2011)]

Q= 3.2 1.0 0.2 0.02 nC



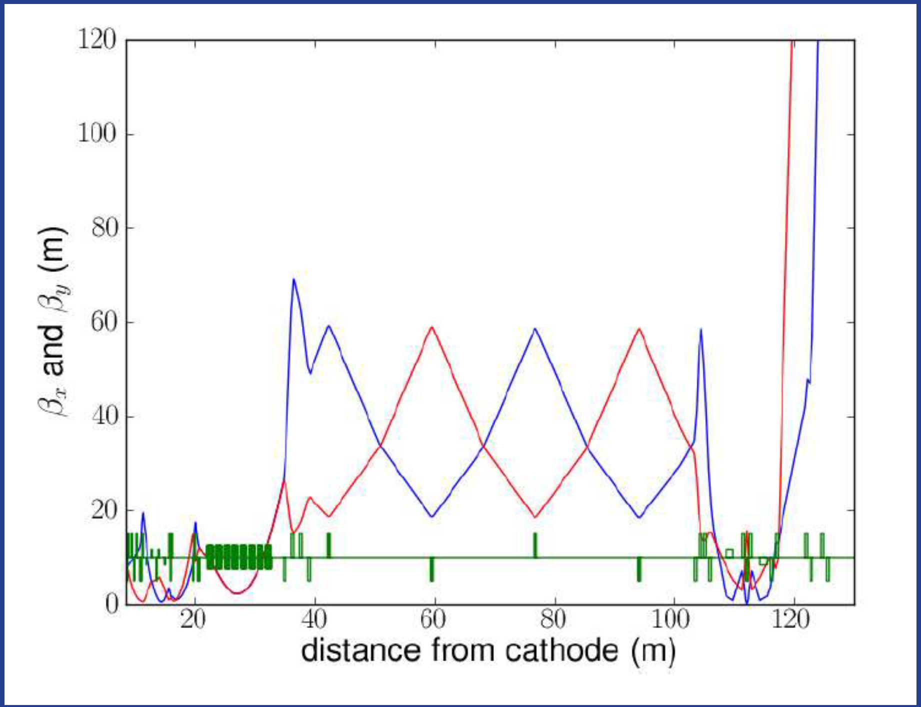
Longitudinal phase space upstream (top) and downstream (bottom) of BC1

Accelerator configuration for 1st beam



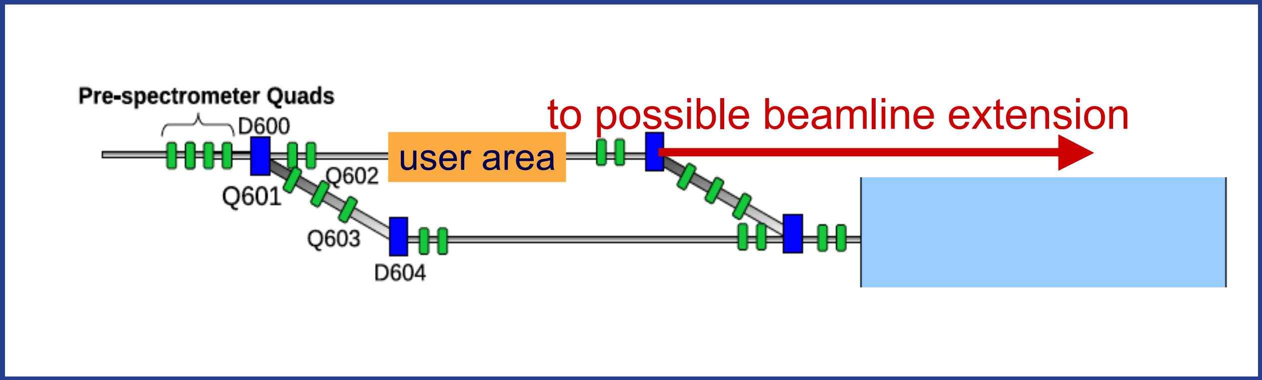
- Only one accelerating module available for first beam,
- Transport from cryomodule exit to spectrometer line with FODO
- High-energy spectrometer + user beamline(s)

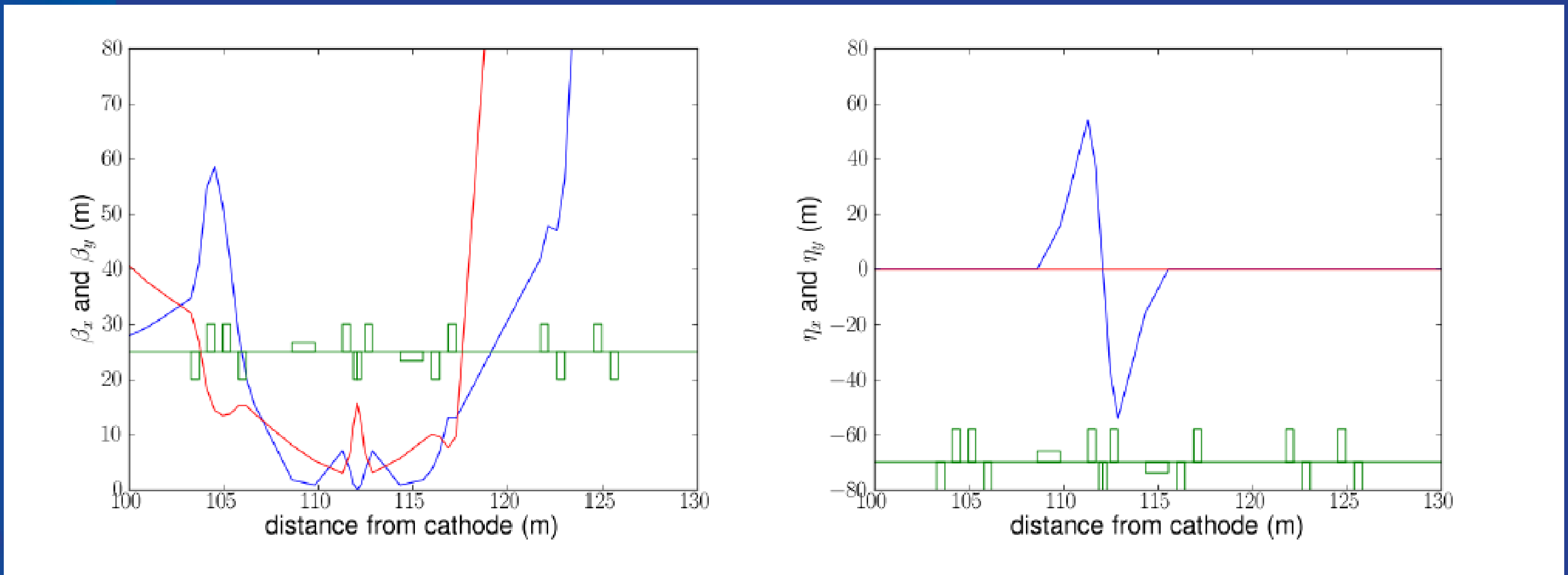
[C. Prokop, et al., (2011)]



Accelerator configuration for 1st beam

- High-energy user area + spectrometer





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Initial research themes (a biased view)

- Beam dynamics
  - Photoinjector characterization,
  - Low energy compression.
- Advanced phase space manipulations:
  - Flat beams and their compression,
  - Transverse-to-longitudinal phase space exchange (PEX),
  - Arbitrary repartitioning of emittances (flat beam + PEX)
- High-brightness electron beams
  - Channeling radiation (with Vanderbilt),
- Integrable-Optics Test Accelerator
  - Small diameter ring downtream of cryomodule to test integrable optics concept.

To be done after 1 accelerating module

Next generations phase-space exchange (PEX) experiment at ASTA

- Two stages:
  - Phase I: improve configuration in 40-MeV beamlline
  - Phase II: installation downstream of cryomodules
    $\Rightarrow$ usable for other applications (current shapers, microbuncher, etc…)
- Condition for phase space exchange

Dispersion vector downstream beamline

Transfer matrix of downstream beamline

$$\vec{\eta}_d = \begin{pmatrix} R_{11,d} & R_{12,d} \\ R_{21,d} & R_{22,d} \end{pmatrix} \vec{\eta}_u$$

Dispersion vector upstream beamline

$$\vec{\eta} \equiv (\eta, \eta' \equiv d\eta/ds)$$

$$\kappa = \frac{1}{\eta_u}$$

[R. Fliller, FNAL Beamdocs (2007)]

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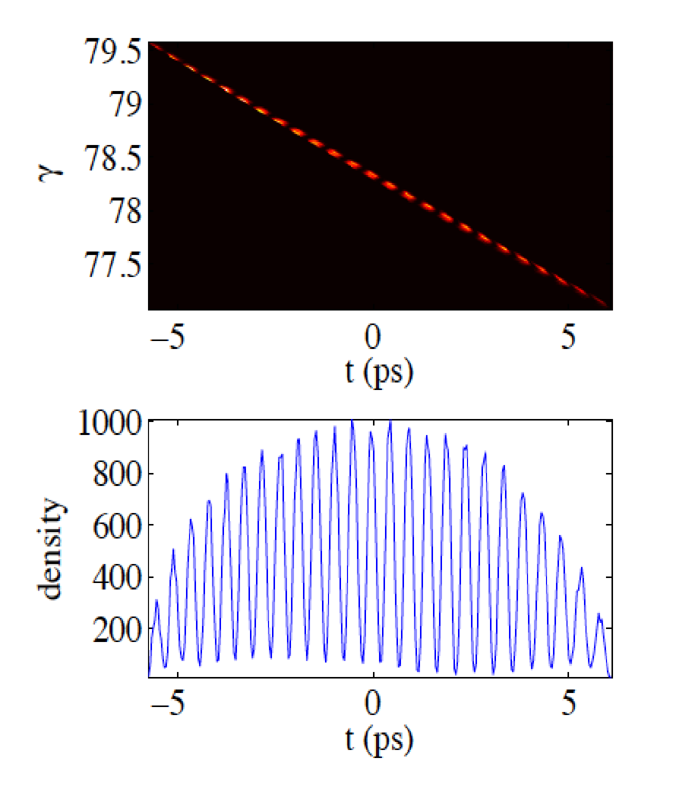
2nd-generation PEX experiments at ~40 MeV (1)

- Limitations of A0PI experiments:
  - No longitudinal phase space diagnostics downstream of PEX,
  - Imperfect exchange due to thick-lens deflecting mode cavity (still trying to understand this),
  - Limited in charge (15 MeV)

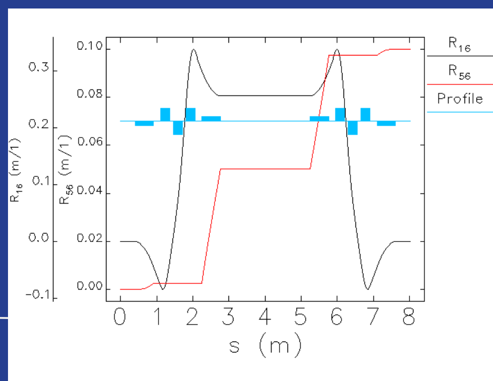
- PEX experiment will be resumed using an improved setup
  - Chicane-like PEX configuration,
  - Deflecting cavity downstream of PEX
  - Done in the 40-MeV user area (precludes injection in accelerating modules)

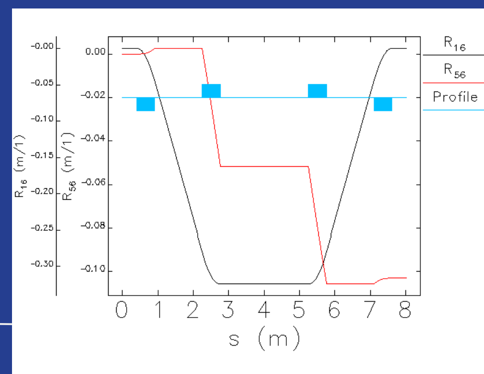


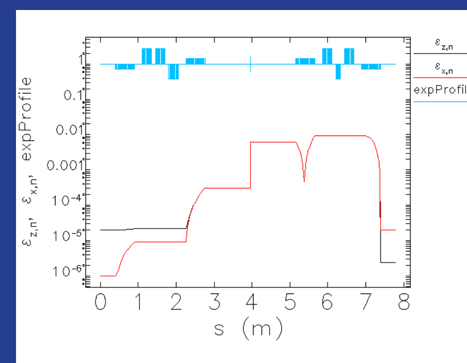
[Y.-E Sun, et al., (2011)]

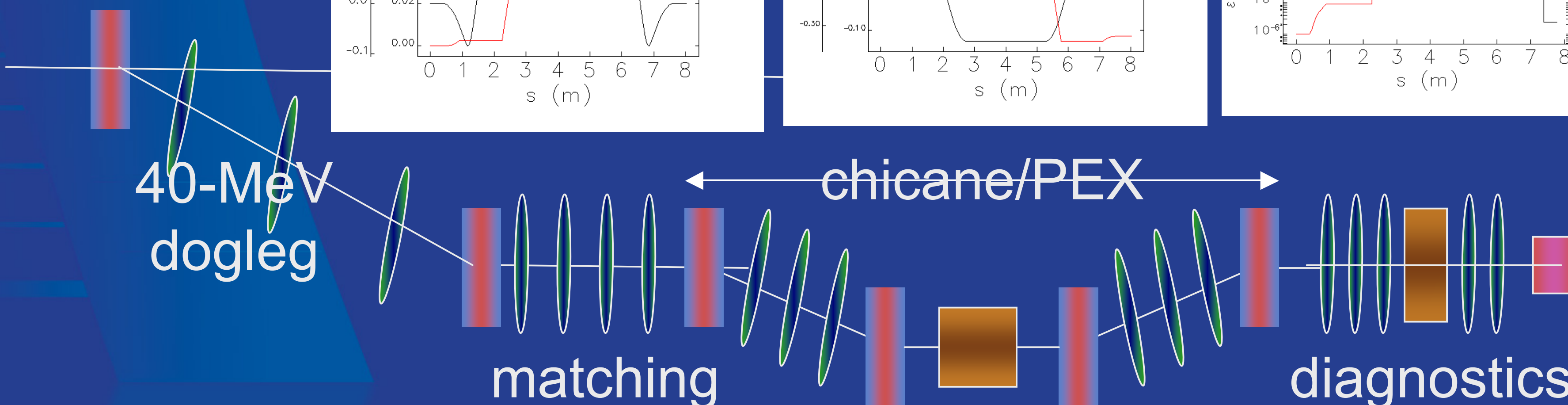
2nd-generation PEX experiments at ~40 MeV (2)

- Goals:
  - Arbitrary repartition of beam emittance within the 3 degrees of freedom (combined with round-to-flat beam transformer)
  - Generation of fs microbunches from patterned cathodes/lasers
  - Improved deflecting cavity following Zholents-Zolotorev’s suggestion (add TM_{110} mode to cancel thick-lens effect)



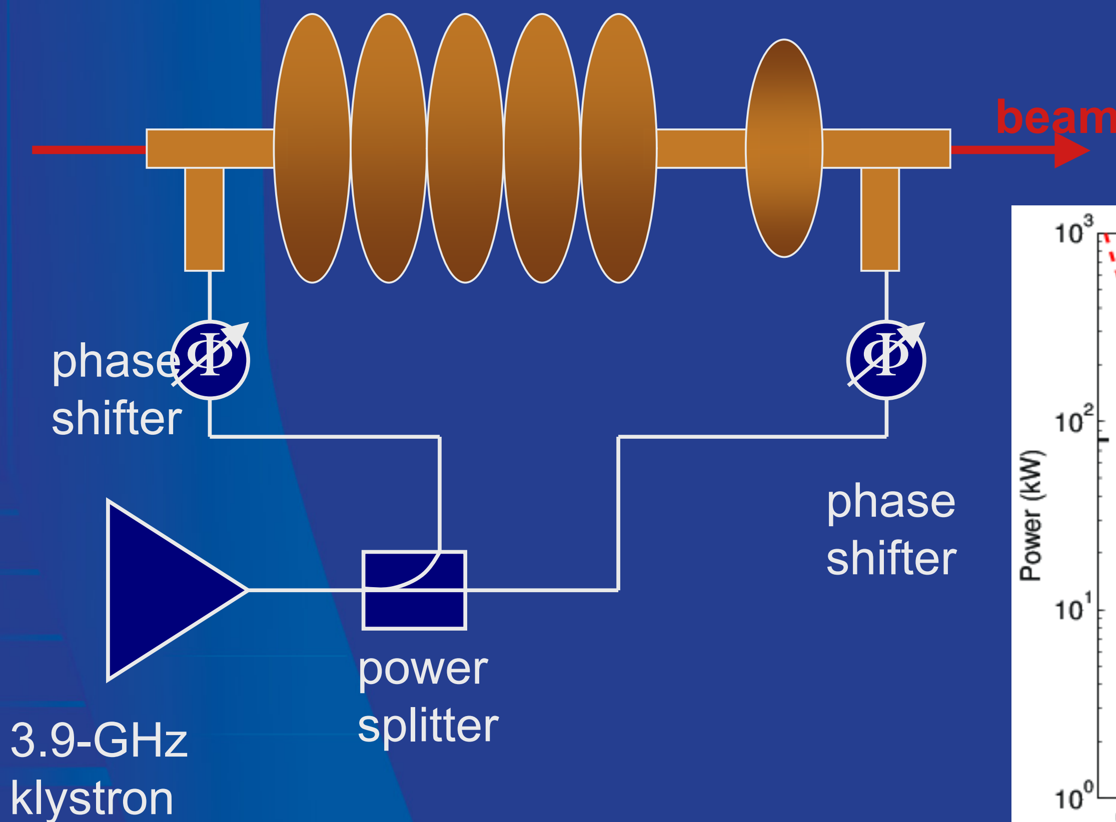


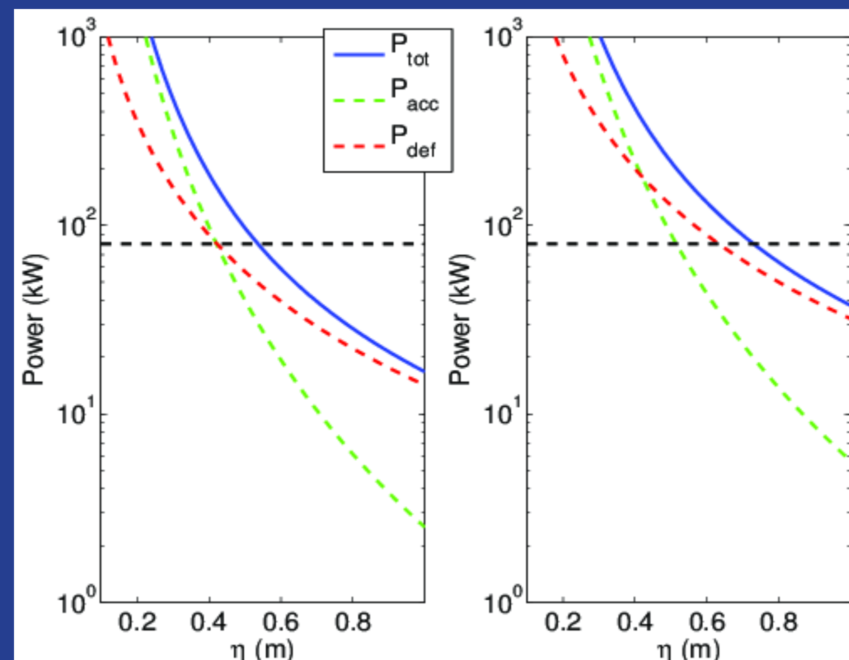




2nd-generation PEX experiments at ~40 MeV (3)

- TM_{010}+TM_{110} cavity (idea from Zholents and Zolotorev)
- At 40 MeV, we can still do this with a LN-cooled cavity





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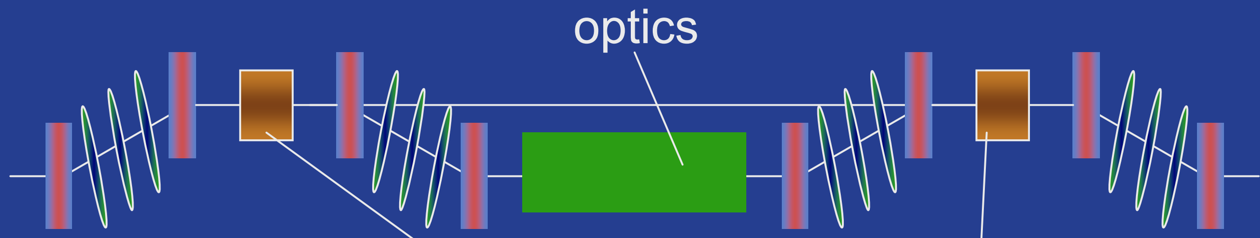
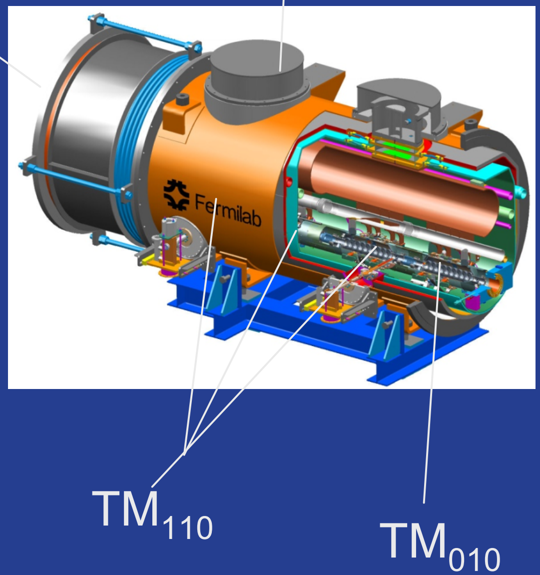
PEX at higher energies





- Requirement on deflecting cavity kick can be alleviated with a higher dispersion

$$\kappa = 1/\eta_x$$

- But beam size should satisfy

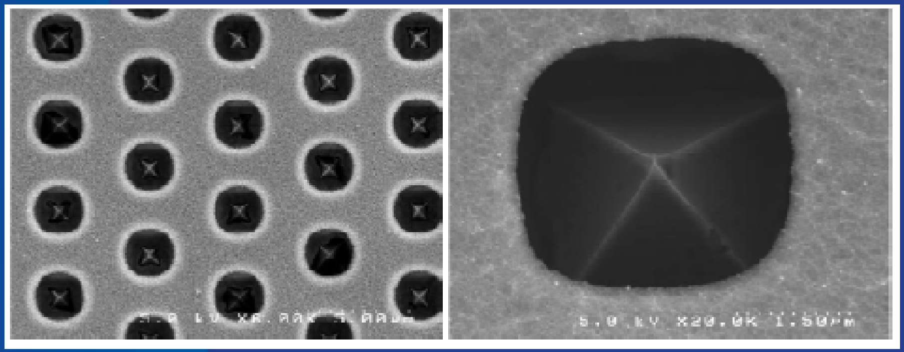
$$\sigma_x \leq \lambda/(12\pi)$$

- At 3.9 GHz, we will have to go with a SCRF system (advantage to also do full exchange over a bunch train)

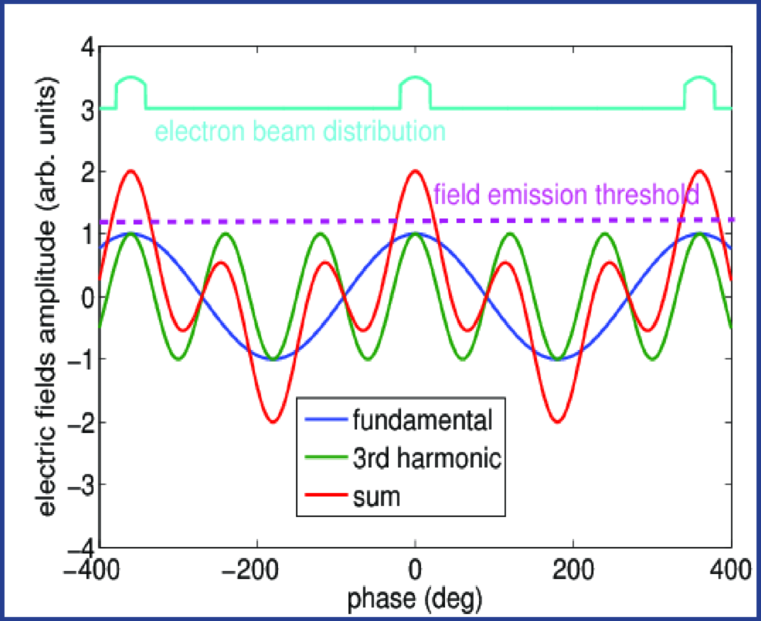
High-Brightness e- beams: possible production of field-emitted bunches

- During FY12-13, HBESL will support the development of a coaxial-line cathode holder
- Two-frequency gating of field emitters
- If successful this system will be and used at ASTA

[J. Lewellen, PRSTAB 2006]

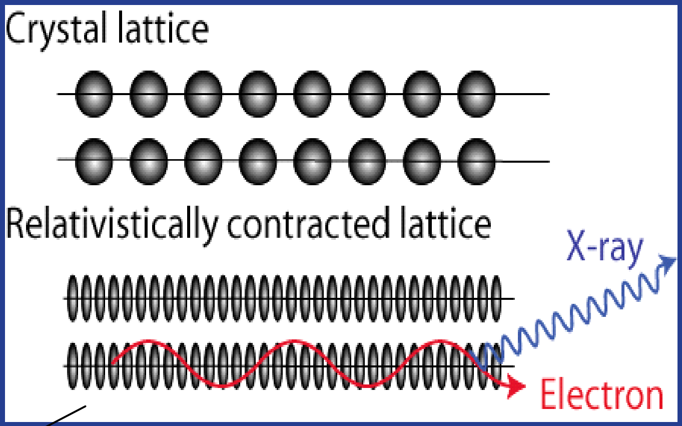


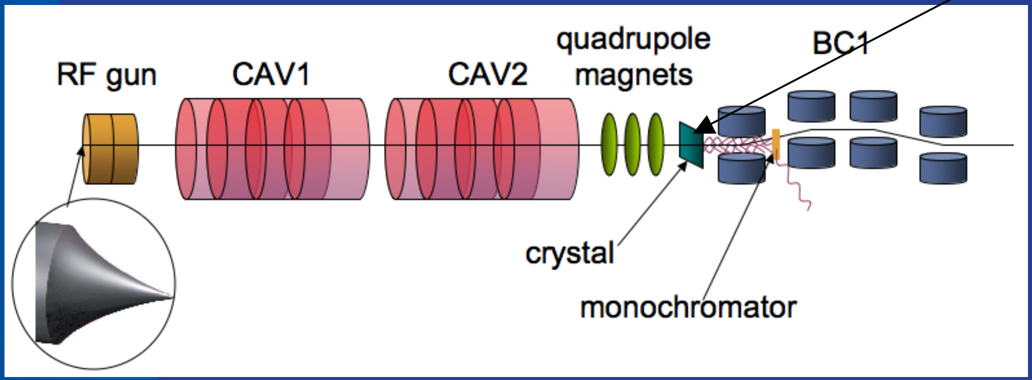
[collaboration with Vanderbilt and NIU (funded by DARPA)]



High-Brightness e- beam: applications to X-ray sources

- Bright electron beams from single-tip FE are planned to be used to produce X-rays via channeling radiation
- Expected brightness for 15 keV
  ~10^{12} photons/s-mm^2-mrad^2-0.1% BW
- Need 40 nm e- beam on the diamond crystal with ~1000 e-



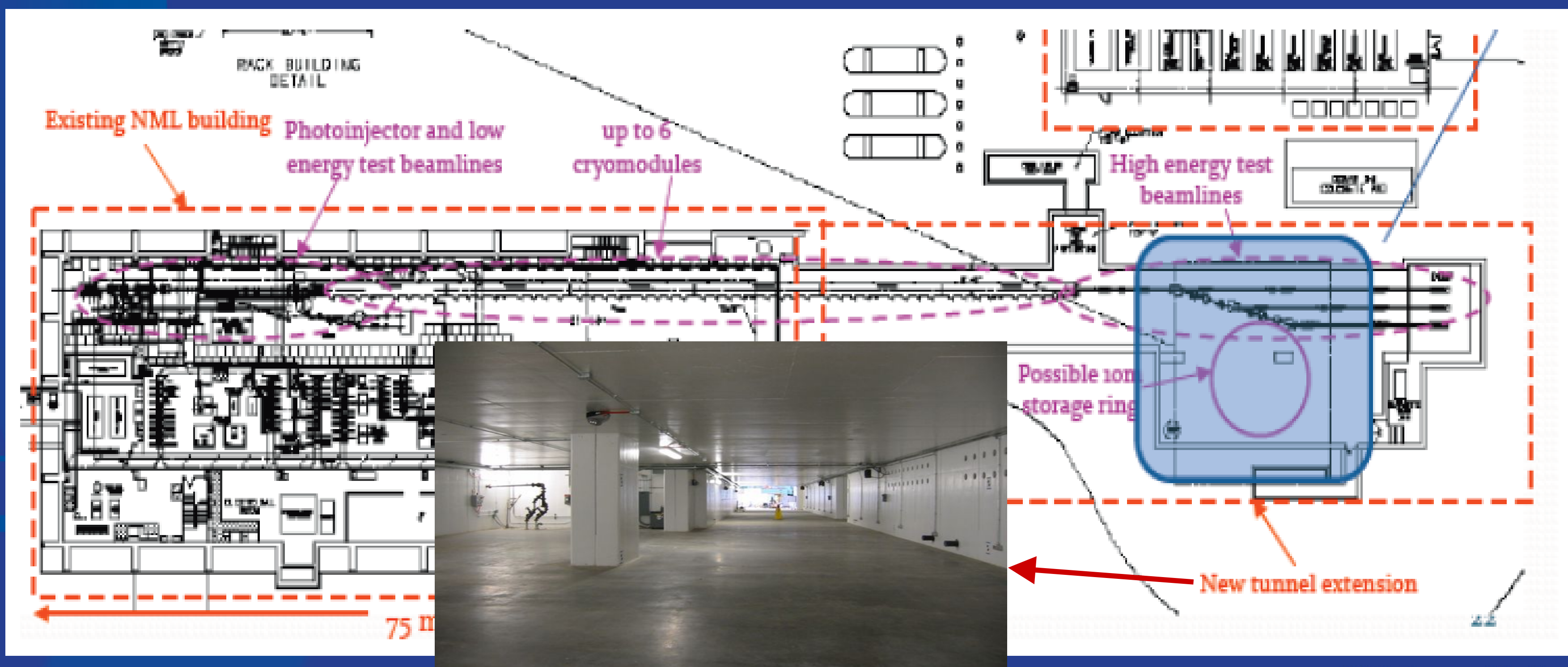


[C. Brau et al, to appear in Sync. Rad. News (2012)]

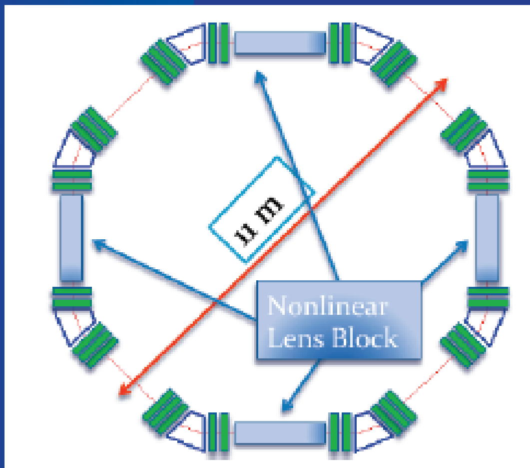
- FE array cathodes could also be used to increase charge/bunch or open new manipulation opportunities (combination with PEX)

Integrable-Optics Test Accelerator (1)

- ASTA facility provides the needed infrastructure to test other concepts,
- IOTA, a compact ring dedicated to test integrable optics, will use a 150-MeV beam from STF@NML,
- No stringent requirements on beam quality.

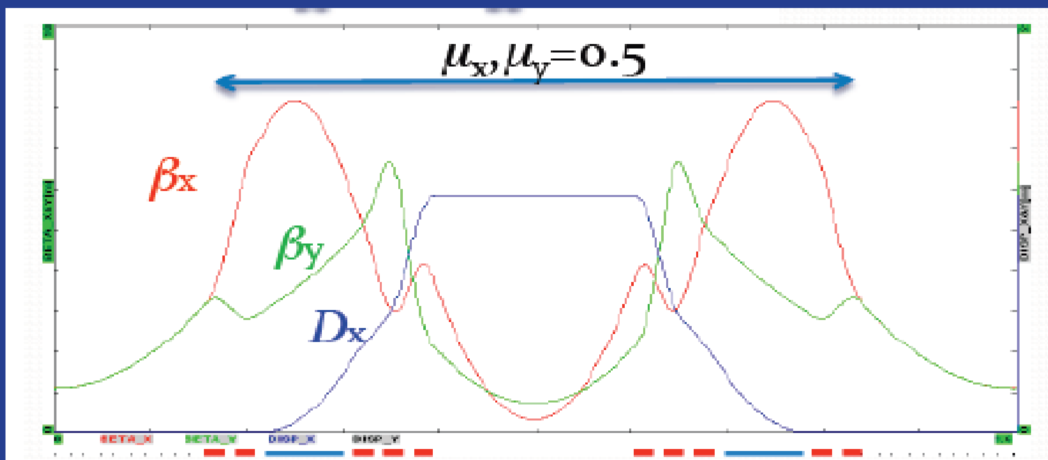


Integrable-Optics Test Accelerator (2)



e- Energy	150 MeV
Circumference	32 m
Dipole field	0.5 T
Betatron tunes	Qx=Qy=3.2 (2.4 to 3.6)
Radiation damping time	1-2 s (10^7 turns)
Equilibrium emittance, rms, non-norm	0.06 μm

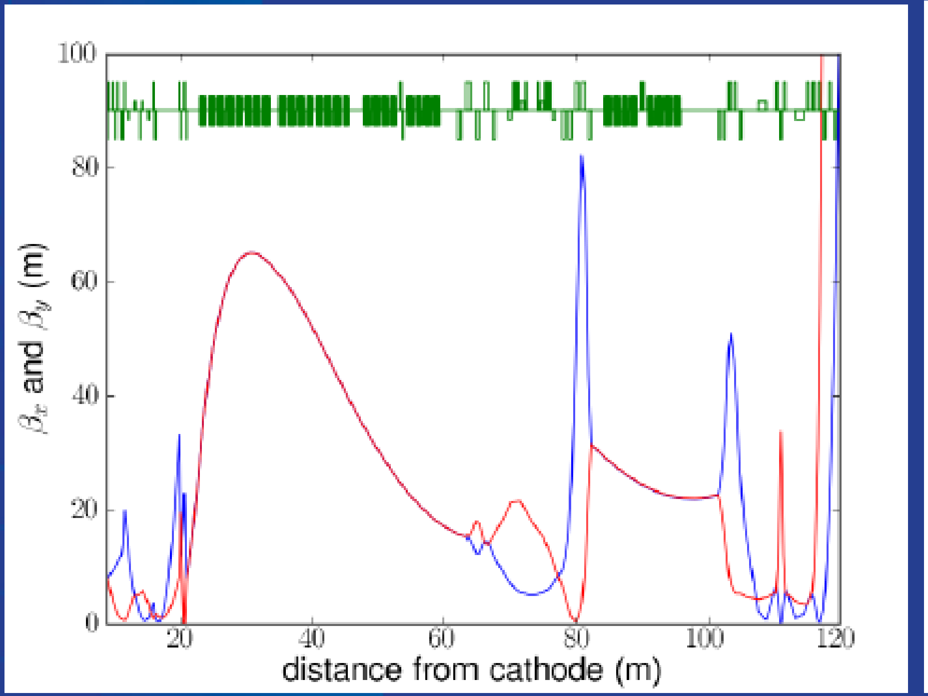
- Nonlinear integrable accelerator optics are being developed to enable stable operation of a completely nonlinear machine (tune spread up to 50%)
- Accelerators with very large tune spread will push the intensity limits of storage rings by suppressing collective instabilities through “better” Landau damping.

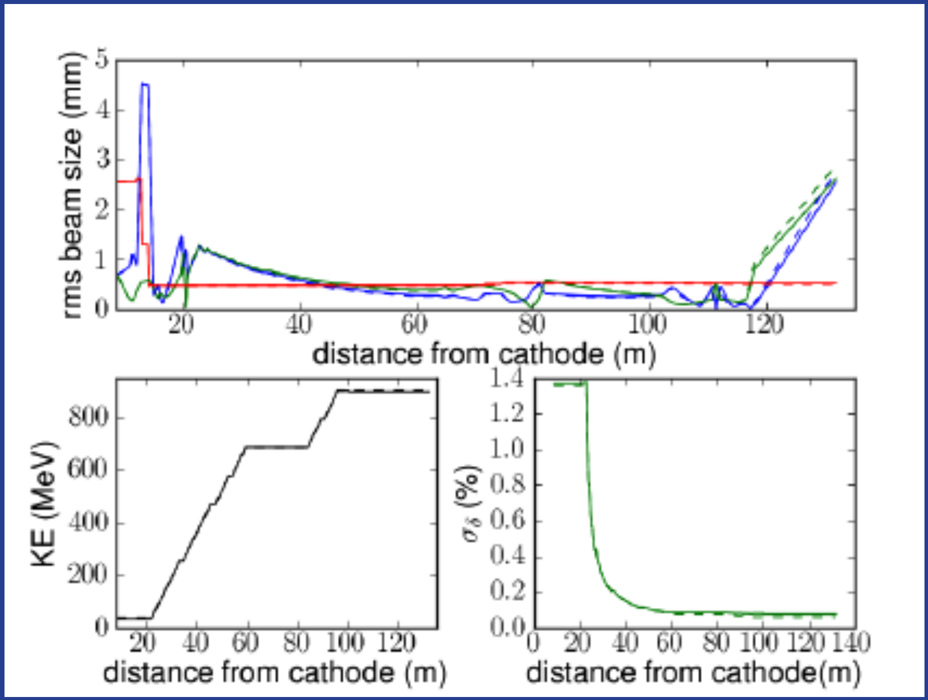


[Danilov, Nagaitsev, Valishev, 2011 see also PRSTAB 2010]

Further developments

- Two additional accelerating module will be installed
- At high-energy it is hope to have a PEX beamline or a magnetic chicane,

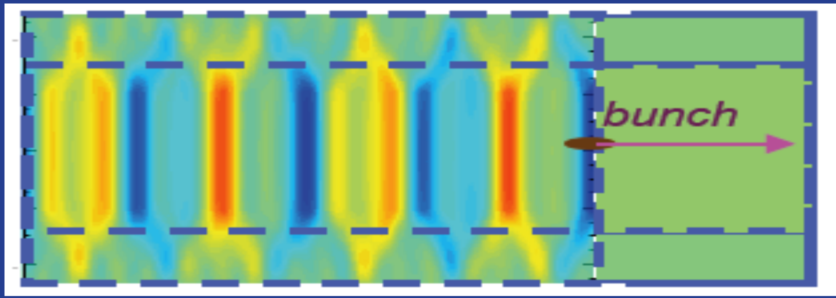




- Energy is currently limited to 900 MeV (safety envelope)

Other experiments currently being explored at ASTA

- Dielectric wakefield acceleration in slab structures with ramped current profile and flat beams
- Short-wavelength "seeded" FELs with emphasis on possible ap-plication of PEX techniques?
- Longitudinal space charge amplifier [idea from Schneimiller + Yurkov (DESY)]
- Positron beam production for ILC keep-alive e+ source,
- Narrowband gamma ray (muons Inc.)
- Many other possible applications discussed at a workshop in 2009.



http://apc.fnal.gov/ARDWS/index.html

Summary

- Over the last decade, Fermilab has been an active player in photoinjector R&D and applications to AARD:
  - e- source for linear collider + short-wavelength FELs,
  - novel phase space manipulations: flat beam, emittance exchange, current tailoring technique.
- Phase space manipulations pioneered at A0PI have many applications: beam-driven acceleration, light sources, …
- Formation of the *Illinois Accelerator Research Center* (IARC)
  - ASTA: will incorporate most of these manipulations $\Rightarrow$ flexible, powerful facility to foster an user-driven AARD program.
  - A0PI: will be transformed into a high-brightness electron source laboratory (HBSEL):
    - explore novel cathodes and acceleration concepts,
    - support gun R&D to improve the performances of ASTA.