Accelerator R&D at Fermilab

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FRA Physics Visiting Committee

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What is it?

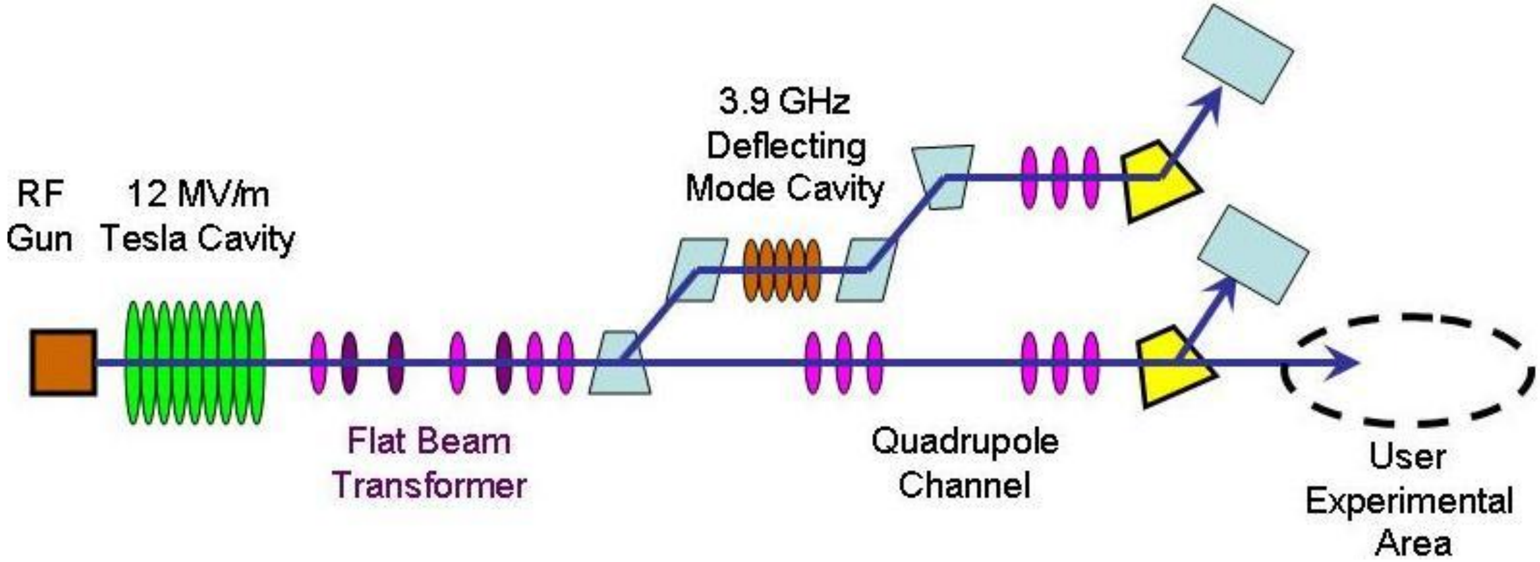
- DOE OHEP supports a vigorous nation-wide "Advanced Technologies R&D" program:
- The mission of the Advanced Technology R&D program is to foster world-leading research into the science of particle accelerators, as well as particle acceleration and detection techniques and instrumentation. These in turn provide enabling technologies and new research methods to advance scientific knowledge in a broad range of energy-related fields, including high energy physics, thereby advancing the DOE's strategic goals for science.

- Accelerator Sciences at National Labs (k$):
  - The Accelerator Science activity in this program focuses on the science underlying the technologies used in particle accelerators and storage rings, and the fundamental physics of charged particle beams. There is an emphasis on future-oriented, high-risk R&D, particularly in the development of new accelerating concepts, but essential infrastructure to support the HEP technology R&D programs is also addressed.
  - At Fermilab, the FY 2009 budget will support experimental studies of electron beam physics in a high-brightness photo-injector, research on muon acceleration, and research by the Accelerator Physics Center in beam theory and accelerator simulation. R&D in support of the international muon cooling collaboration with Rutherford Appleton Laboratory in the UK will continue.
- This talk is about the Fermilab Photo-Injector (aka AØ) Program
  - History, Present status, Future plans

Fermilab Photo-injector

- Started as a vision (by a small group of people) ~12 years ago to get FNAL involved in the TESLA collaboration.
- Hardware contributions from Cornell, DESY, INFN, Orsay, UCLA, U. of Rochester, Saclay,…
- Main goals:
  - **Scientific**: novel beam optimizations and manipulations, advanced accelerator concepts, and beam diagnostics;
  - **Educational**: train future accelerator physicist (average of 1PhD/year);
  - **Technical**: rf-gun, photocathode, laser systems R&D, Superconducting rf R&D, LLRF R&D, polarized rf gun R&D, injector for SC cryomodule beam tests.
- Reviews:
  - FNPL has (had) its own program review committee chaired by Prof. K.-J. Kim (U. of Chicago & ANL); last review 2002. Need to restart this process.
  - FNPL is also ~yearly reviewed by the FNAL Accelerator Advisory Committee (AAC)

A0 Photoinjector



- 1.3 GHz 1.5 cell NC RF gun with Cs_2Te photocathode
  - 35 MV/m maximum cathode gradient
- 9-cell TESLA-type SC accelerating cavity
  - 12 MV/m accelerating gradient
- Round to Flat beam transformer
- Transverse to Longitudinal Emittance Exchange Beamline
  - Dipoles recycled from Bunch Compressor
- Quadrupole transport channel
- User experimental area
  - Prototype kicker for ILC DR (UIUC, Cornell)

Scientific high-lights

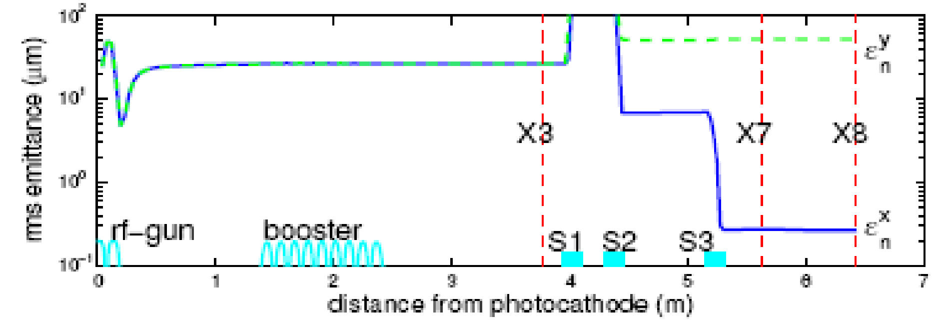
- Past and Present: Fermilab's forte: emittance exchange and phase-space manipulations
  - Traditional interest due to stochastic, electron, muon cooling expertise;
  - An important component of many proposed HE collider schemes;
  - Strong collaboration with ANL, NIU, DESY;
- Past: Plasma wake field acceleration
  - Demonstration of plasma wake-field acceleration with 130 MeV/m gradient (2001);
  - Collaboration with UCLA, ANL, NIU;
  - Strong competition from SLAC, LBL, BNL;
  - Plan to become competitive (again) when higher beam energy is available
- Future direction: A combination of emittance exchange schemes, higher beam energy and higher peak current
  - novel acceleration schemes, Å-wavelength photons, etc.

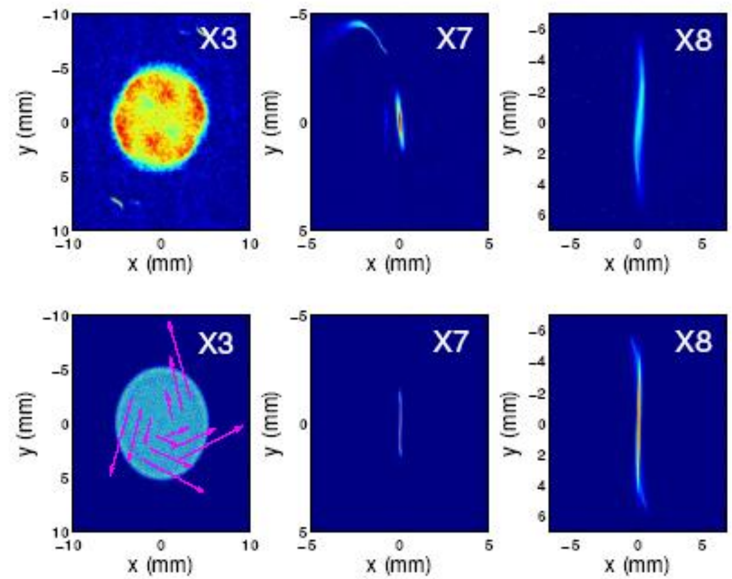
Publications (mostly PRSTA and NIMA)

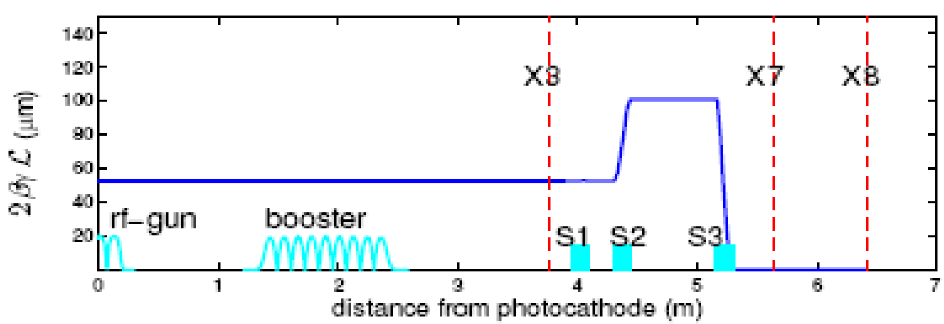
- Jang-Hui Han, Klaus Flöttmann, and Walter Hartung. " Single-side electron multipacting at the photocathode in rf guns" Phys. Rev. ST Accel. Beams 11, 013501 (2008)
- D. Mihalcea, C. L. Bohn, U. Happek, and P. Piot. " Longitudinal electron bunch diagnostics using coherent transition radiation " Phys. Rev. ST Accel. Beams 9, 082801 (2006)
- P. Piot, R. Tikhoplav, D. Mihalcea, and N. Barov. "Experimental investigation of the longitudinal beam dynamics in a photoinjector using a two-macroparticle bunch " Phys. Rev. ST Accel. Beams 9, 053501 (2006).
- P. Piot, Y.-E Sun, and K.-J. Kim." Photoinjector generation of a flat electron beam with transverse emittance ratio of 100 ". Phys. Rev. ST Accel. Beams 9, 031001 (2006)
- Jianliang Li, Rodion Tikhoplav, Adrian C. Melissinos. "Performance of the upgraded laser system for the Fermilab-NIU photoinjector" NIM A, Volume 564, Issue 1, 1 August 2006, Pages 57-65
- J.-P. Carneiro, N. Barov, H. Edwards, M. Fitch, W. Harung, K. Floettmann, S. Schreiber, M. Ferrario, "Transverse and longitudinal beam dynamics studies at the Fermilab photoinjector," Phys. Rev. ST – Accel. Beams 8: 040101 (2005)
- Y.-E Sun, P. Piot, K.-J. Kim, N. Barov, S. Lidia, J. Santucci, R. Tikhoplav, J. Wennerberg, "Generation of angular-momentum-dominated electron beam from a photoinjector," Phys Rev ST – Accel. Beams 7: 123501 (2004)
- N. Barov, J.B. Rosenzweig, M.C. Thompson, and R Yoder," Energy loss of a high-charge bunched electron beam in plasma: Analysis," Phys Rev ST – Accel. Beams 7: 061301 (2004)
- M. J. Fitch, A. C. Melissinos, P. L. Colestock, J.-P. Carneiro, H. T. Edwards, W. H. Hartung, "Electro-optic Measurement of the Wake Fields of a Relativistic Electron Beam," Phys Rev Lett 87, 034801 (July 2001)
- A. R. Fry, M. J. Fitch, A. C. Melissinos, B. D. Taylor, "Laser system for a high duty cycle photoinjector," NIM A 430, p. 180-188 (July 1999).
- J. Rosenzweig, N. Barov, A. Murokh, E. Colby, P. Colestock, "Towards a Plasma-Based Wake-Field Acceleration-Based Linear Collider," NIM A 410, p. 532-543 (June 1998).
- Mark S. Champion, "RF Input Couplers and Windows: Performances, Limitations, and Recent Developments," Particle Accelerators 53, p. 269-300 (August 1996).

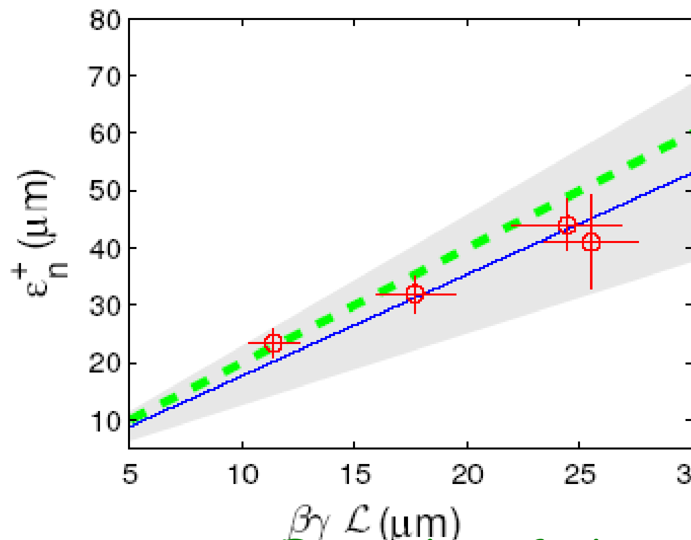
Flat beam transformation

- Demonstrated the transformation of a round magnetized beam into a flat beam
- Achieved a transverse emittance ratio of 100
- Experiment is resolution-limited





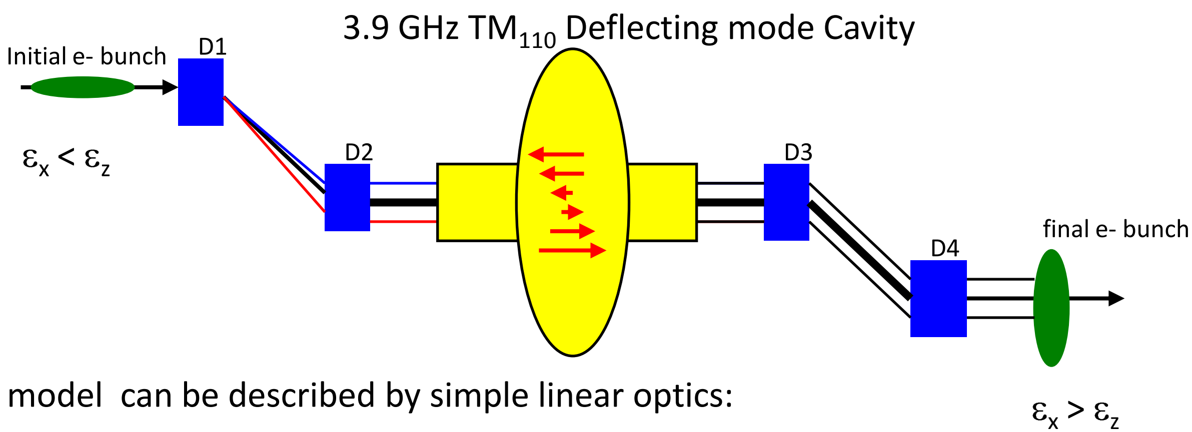




Y.-E Sun (U. of Chicago)

Emittance Exchange at the Photoinjector

We have built a beamline to exchange the horizontal and longitudinal emittance.



Thin lens cavity model can be described by simple linear optics:

$$R \equiv M_{ac} M_{cav} M_{bc} = \begin{pmatrix} 1 & L & 0 & D \\ 0 & 1 & 0 & 0 \\ 0 & D & 1 & \alpha D \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & L & 0 & D \\ 0 & 1 & 0 & 0 \\ 0 & D & 1 & \alpha D \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

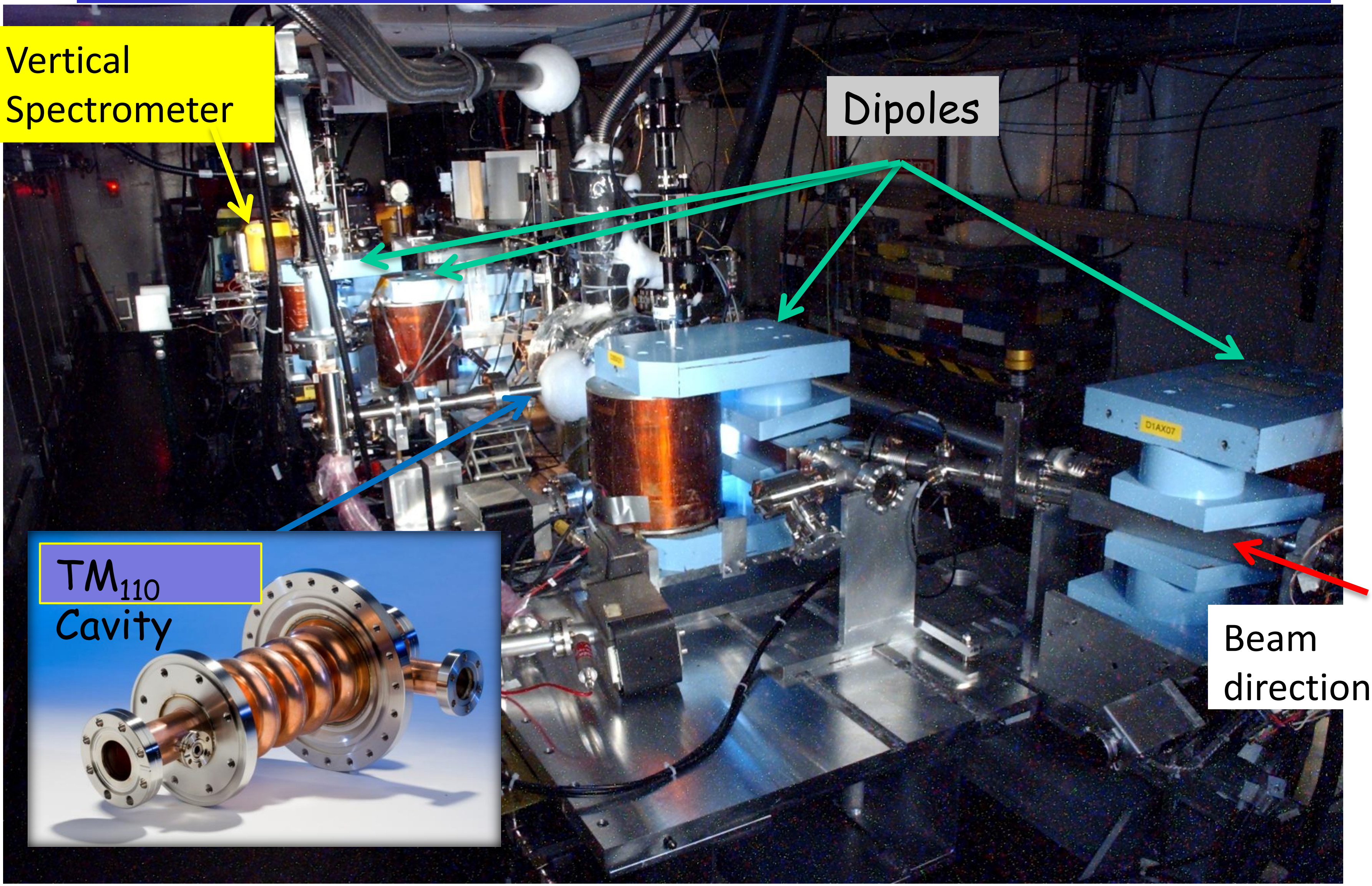
Choose TM110 cavity strength such that k=-1/D to get:

$$R = \begin{pmatrix} 0 & 0 & \frac{L}{D} & D - \alpha L \\ 0 & 0 & \frac{-1}{D} & -\alpha \\ -\alpha & D - \alpha L & 0 & 0 \\ \frac{-1}{D} & \frac{L}{D} & 0 & 0 \end{pmatrix}$$

Tim Koeth, Rutgers Univ.

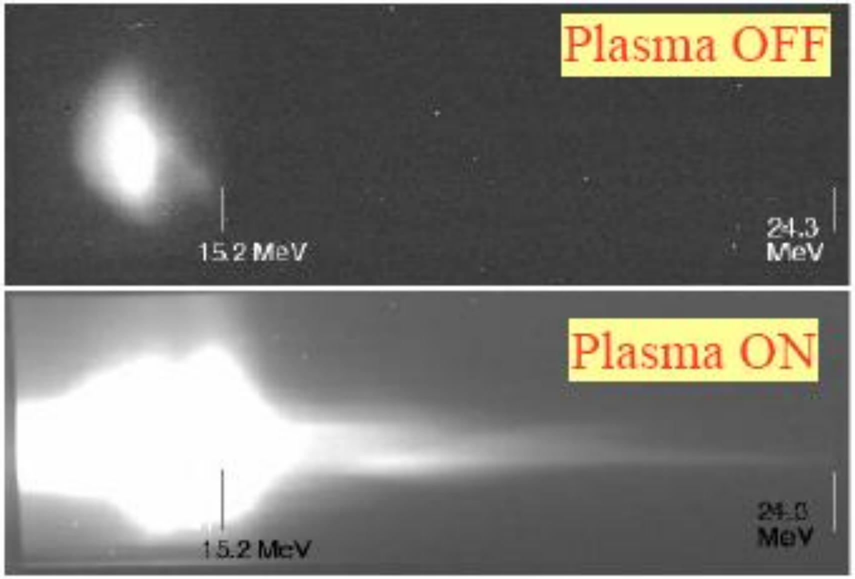
All of the X-X and Z-Z coupling elements are zero !

EEX Beam Line at the Photoinjector



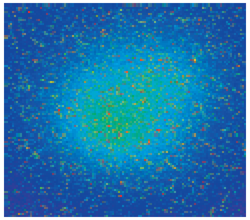
Plasma wakefield acceleration & focusing

- Achieved average accelerating gradient of 130 MeV/m

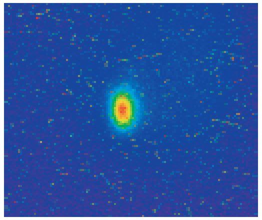


N. Barov (NIU/UCLA)

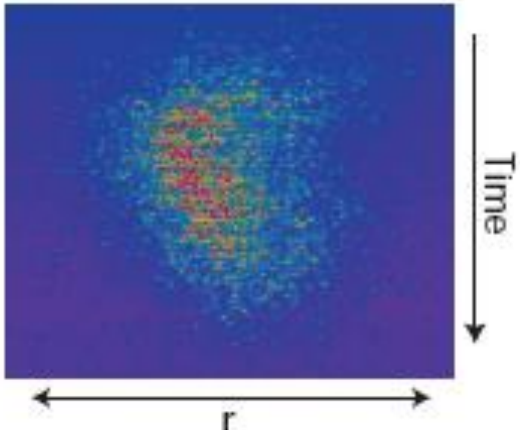
- Observed time-dependent focusing in a plasma lens operating in under-dense regime

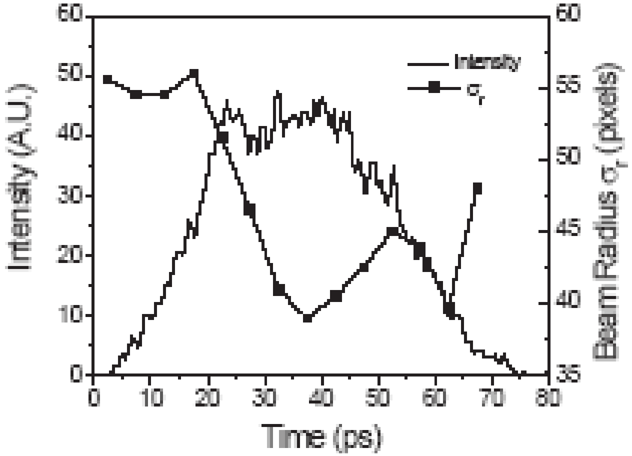


Unfocused - 5 electron pulses



Focused - 1 electron pulse

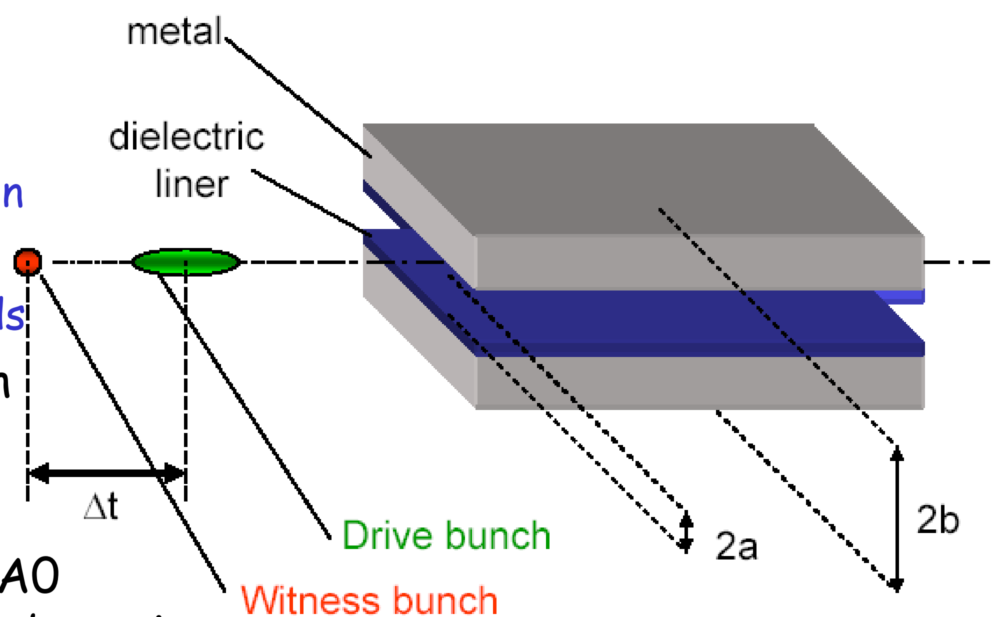




Matt Thompson (UCLA)

Future topic (a): THz dielectric wakefield acceleration in slab structures

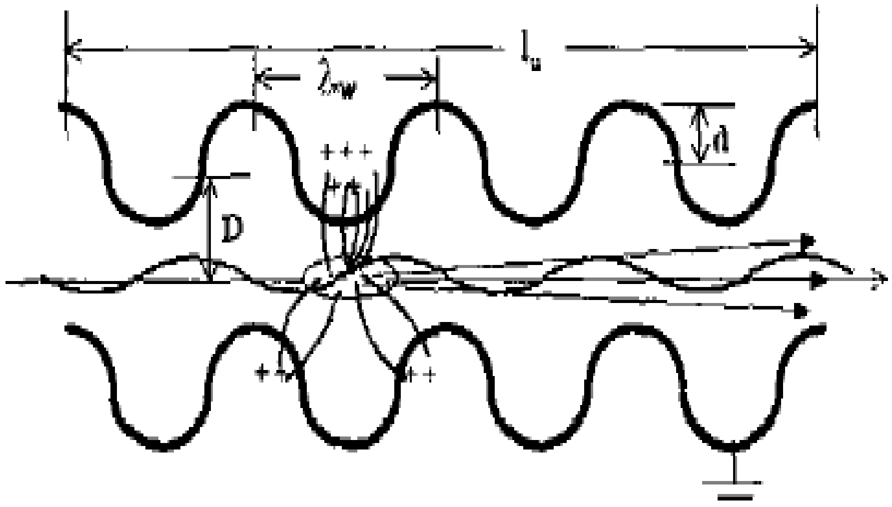
- Dielectric wakefield acceleration in cylindrical-symmetric structures was pioneered at ANL (AWA) in the GHz regime
- An extension to THz (sub-mm wavelength) regime provides a path to more compact accelerators and higher E-field
- Slab structures offer advantages
  - better tuning capability,
  - higher stored energy and reduction of beam loading, and
  - mitigation of transverse wakefields
- Need compressed flat beams with bunch length < 1 mm
- This could be an extension of the A0 program that would be done in collaboration with AWA personal



See e.g. A. Tremaine, et al., PRE 52, 7204 (1997)

Future topic (b): Image Charge Undulator

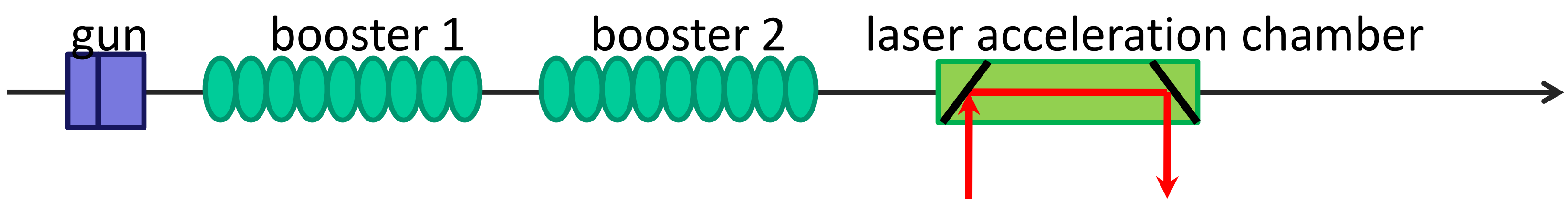
- Undulating motion of an electron bunch as it propagates between a pair of grating provide undulator-type radiation
- Simple estimate: the undulating motion of a 200MeV, 10 nC flat bunch with sizes (sx, sy, sz) = (4, 300, 100) mm in a ICU with period λ_w =30 μm would be equivalent to a magnetostatic undulator with 60 T peak field!
- Short wavelength possible at low energy: λ =1 Å for 200 MeV
- A proof-of-principle of a visible ICU-based free-electron laser at Fermilab is within reach!

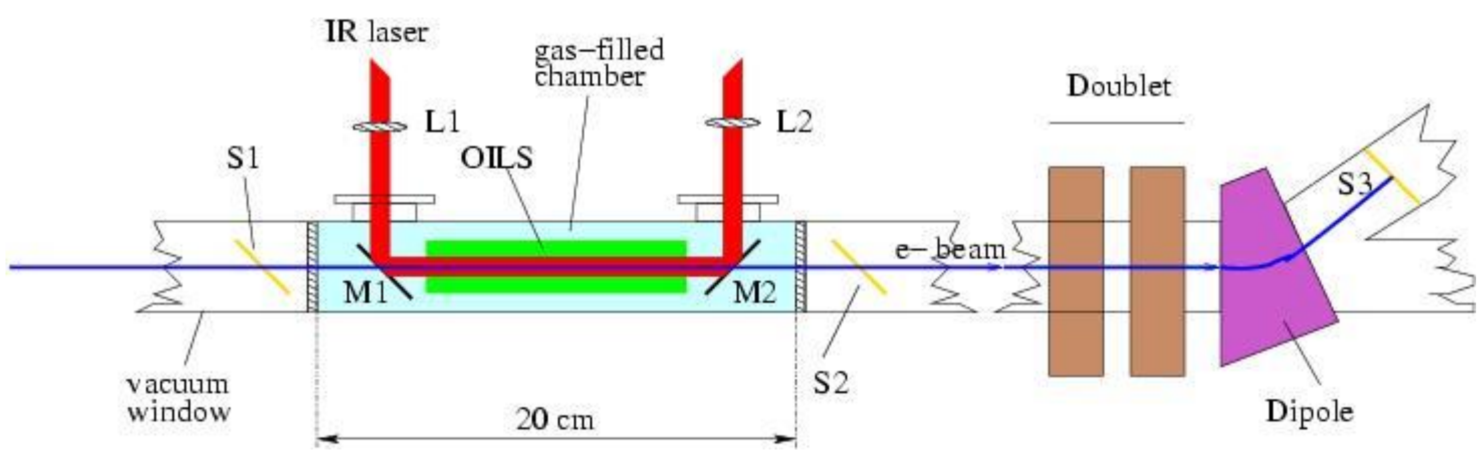


See Y. Zhang, Ya. Derbenev, R. Li, NIM A 507, 459 (2003)

Future topic (c): Laser acceleration

- Initially proposed by A. Melissinos (part of R. Tikhoplav's disseration), Rochester U.
- Need a >40 MeV beam





http://home.fnal.gov/~piot/laser_acceleration/laseracceloverview.jpeg

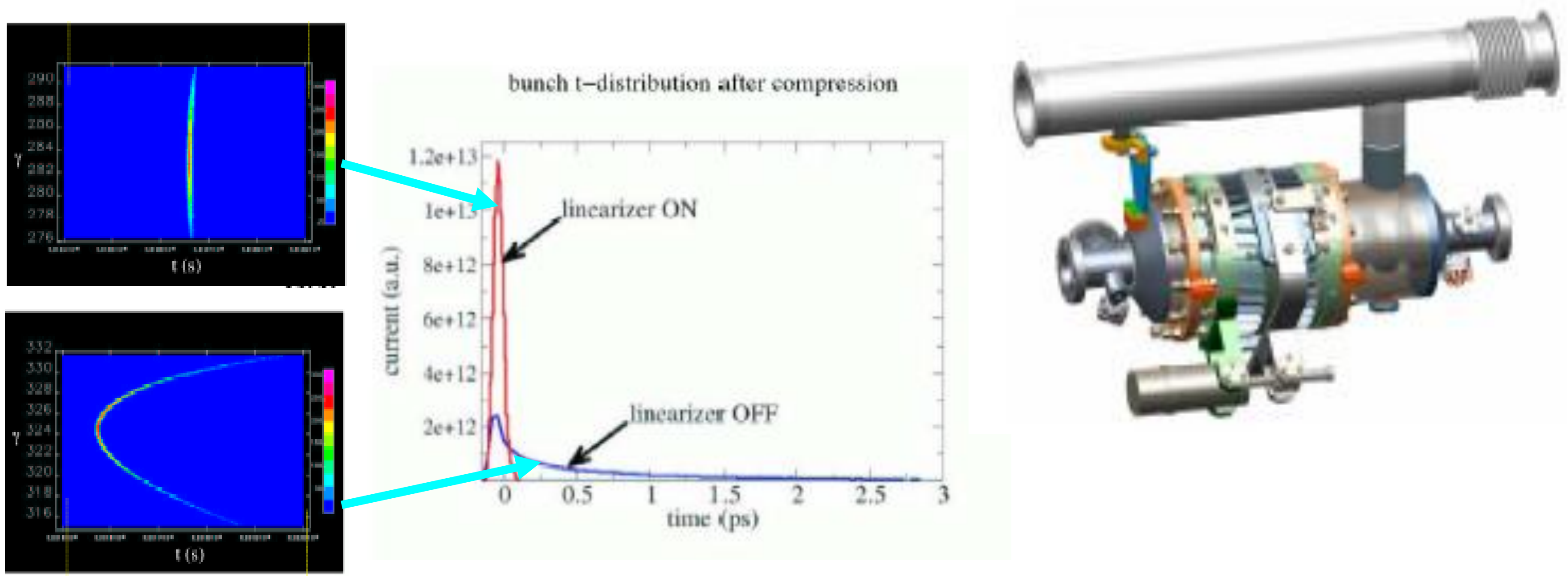
Future topic (d): Muon collider technology

- Parameteric Resonance Ionization Cooling (PIC)
  - One proposed cooling solution for the muon collider requires a transport channel operated at the ½ integer resonance. Absorbers are added to reduce the angles and make the transport stable. The current challenge is to design a lattice with the required angular and momentum acceptance and correct all chromatic aberrations to produce the required emittance.
  - Great PhD topic to implement it at A0!
- Emittance Exchange
  - Transverse to Longitudinal Emittance Exchange is needed for the final stages of Muon cooling. We are planning to implement a cooling channel “mock-up” at A0.
- Dielectric Wall Accelerator
  - The muon collider requires fast accelerator to get the beam to full energy prior to the muons decaying.
  - Dielectric Wall Accelerators are capable of high gradients and accelerations. A cavity designed for the muon collider could have initial beam testing done at the photoinjector. Expected gradient: 100 MeV/m

Technical high-lights

- Past, present and future: RF gun, UV laser, photo-cathode
  - Designed, built, delivered an rf-gun to DESY TESLA test facility (TTF-1); rf-gun was key element for 1st SASE FEL proof-of-principle in UV regime (108 nm);
  - Laser capable of providing ILC-type beam macropulse format;
  - Strong collaboration with DESY, U. of Rochester, NIU, ANL, INFN
- Present and future: SCRF R&D
  - Without the A0 photoinjector we would not have had any SCRF at Fermilab!
  - R&D on a 3.9-GHz cavity and CM for the DESY FLASH facility;
- Present and future: Advanced beam instrumentation

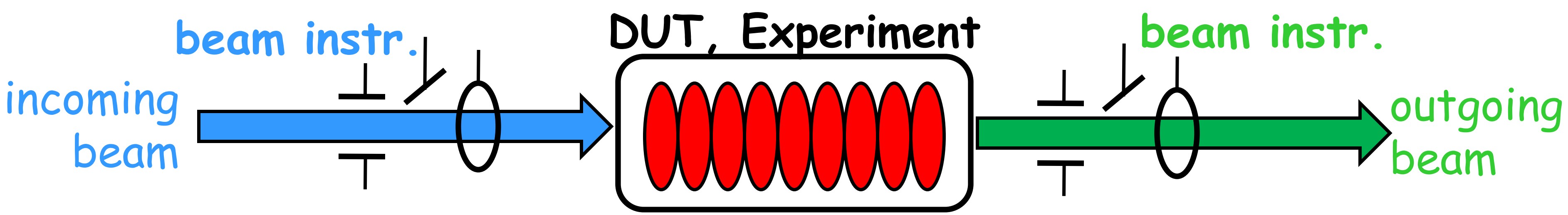
Phase-space manipulation: 3.9-GHz cavity



- A 3rd harmonic accelerating rf cavity corrects the nonlinear contribution of the 1.3 GHz cavity
- Gives a factor of 5 higher peak current
- A CM with four cavities soon to be delivered to DESY

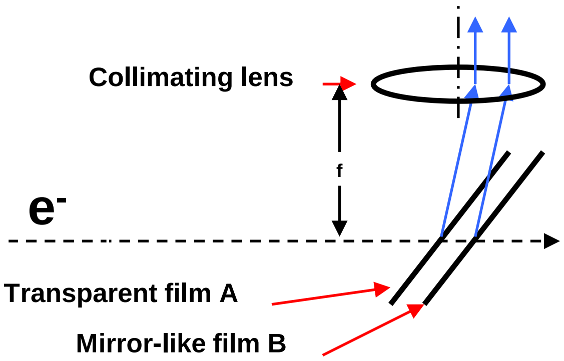
Advanced Beam Instrumentation

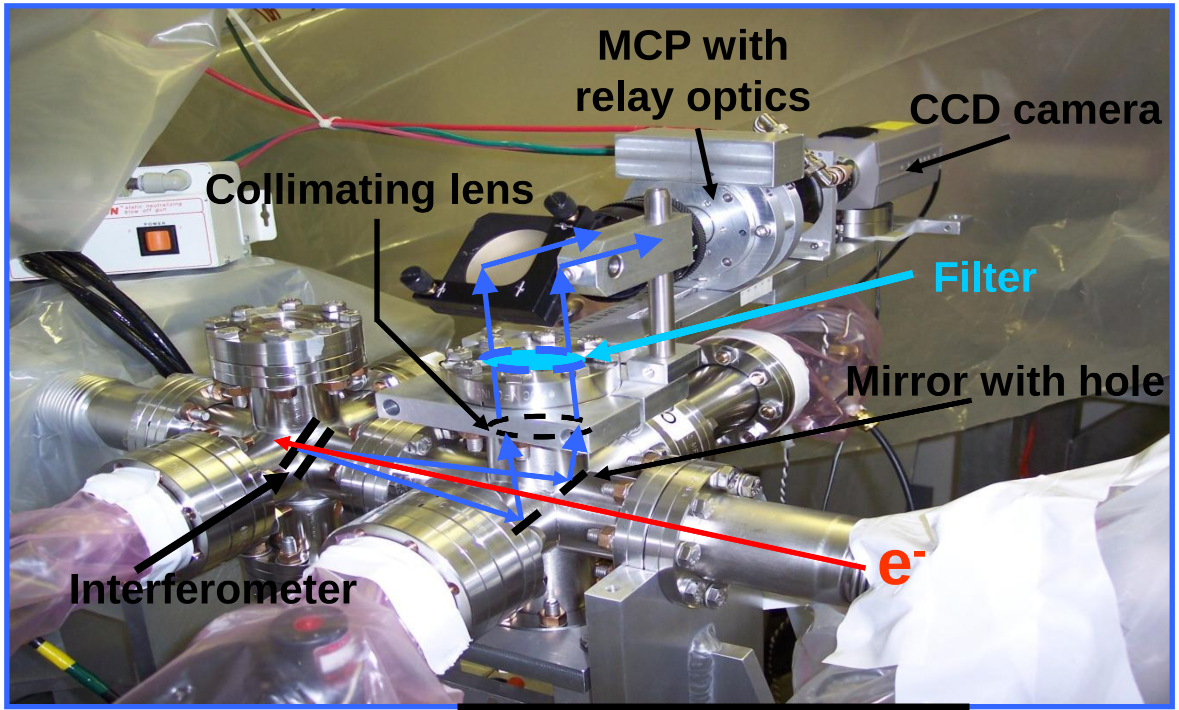
- AARD requires state-of-the-art beam instruments for a precise analysis of mission critical beam parameters.
- Some advanced beam instruments are scientific enterprise projects in itself, e.g.
  - Laser wire scanner for bunch-by-bunch beam profile / emittance measurements.
  - Deflecting mode cavity for long. bunch profile / bunch length monitoring.
  - Fiber-laser based, electro-optical beam instruments in the fs regime (time-of-flight / bunch phase, long. bunch profile).
  - Beam parameter characterization based on transition / diffraction radiation (OTR, OTRI, ODR).

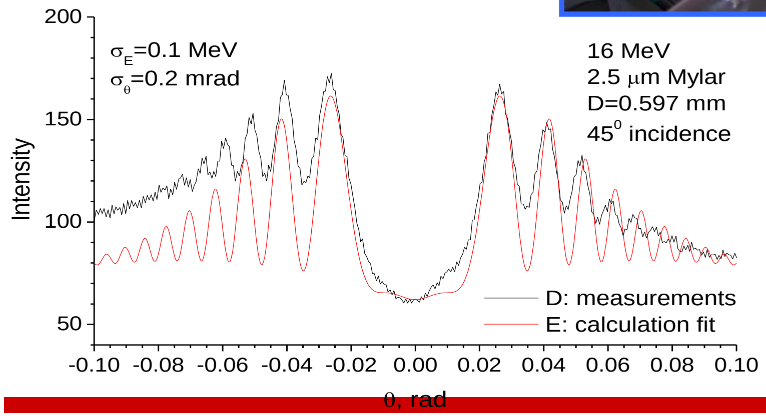


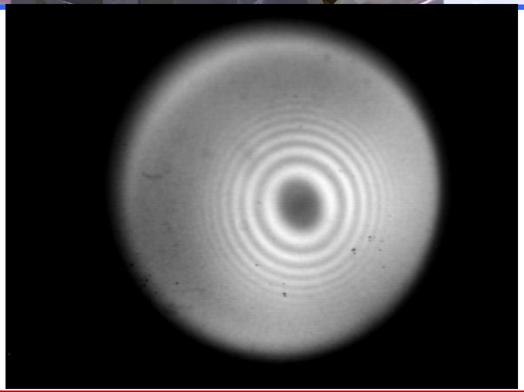
Example of Advanced Beam Instrumentation: OTRI

OTRI experimental setup at A0









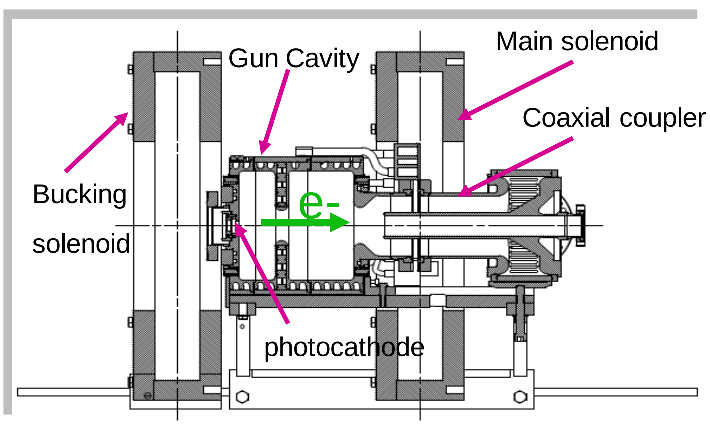
Education

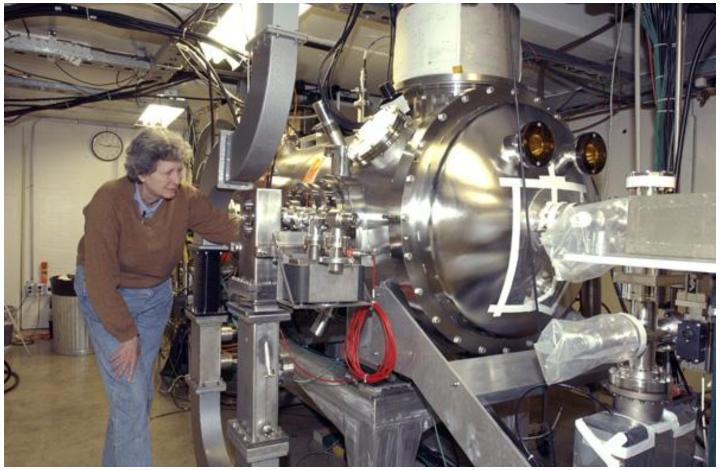
- **Graduated**:
  1. Eric Colby, PhD, UCLA, 1997 (J. Rosenzweig)
  2. Alan Fry, PhD, U. of Rochester, 1998 (A. Melissinos)
  3. Michael Fitch, PhD, U. of Rochester, 2000 (A. Melissinos)
  4. Jean-Paul Carneiro, PhD, U. Paris XI France, 2001 (J. Le Duff)
  5. Matt Thompson, PhD, UCLA, 2004 (J. Rosenzweig)
  6. Dan Bollinger, MS, Northern Illinois University, 2005 (C. Bohn)
  7. Yin-E Sun, PhD, U. of Chicago, 2005 (K.-J. Kim)
  8. Rodion Tikhoplav, U. of Rochester, 2006 (A. Melissinos)
- **Present:**
  1. Timothy Koeth, Rutgers University
  2. Arthur Paytyan, U. of Yerevan, Armenia
  3. Justin Keung, U. of Penn.
- **Peoples Fellows:**
  1. Markus Huening, (from DESY)
  2. Philippe Piot, (from DESY)
  3. Yin-E Sun, (from ANL)
- **Undergraduates:** UIUC + summer students

* Sponsored by the Fermilab/universities PhD program in accelerator physics

What is the plan?

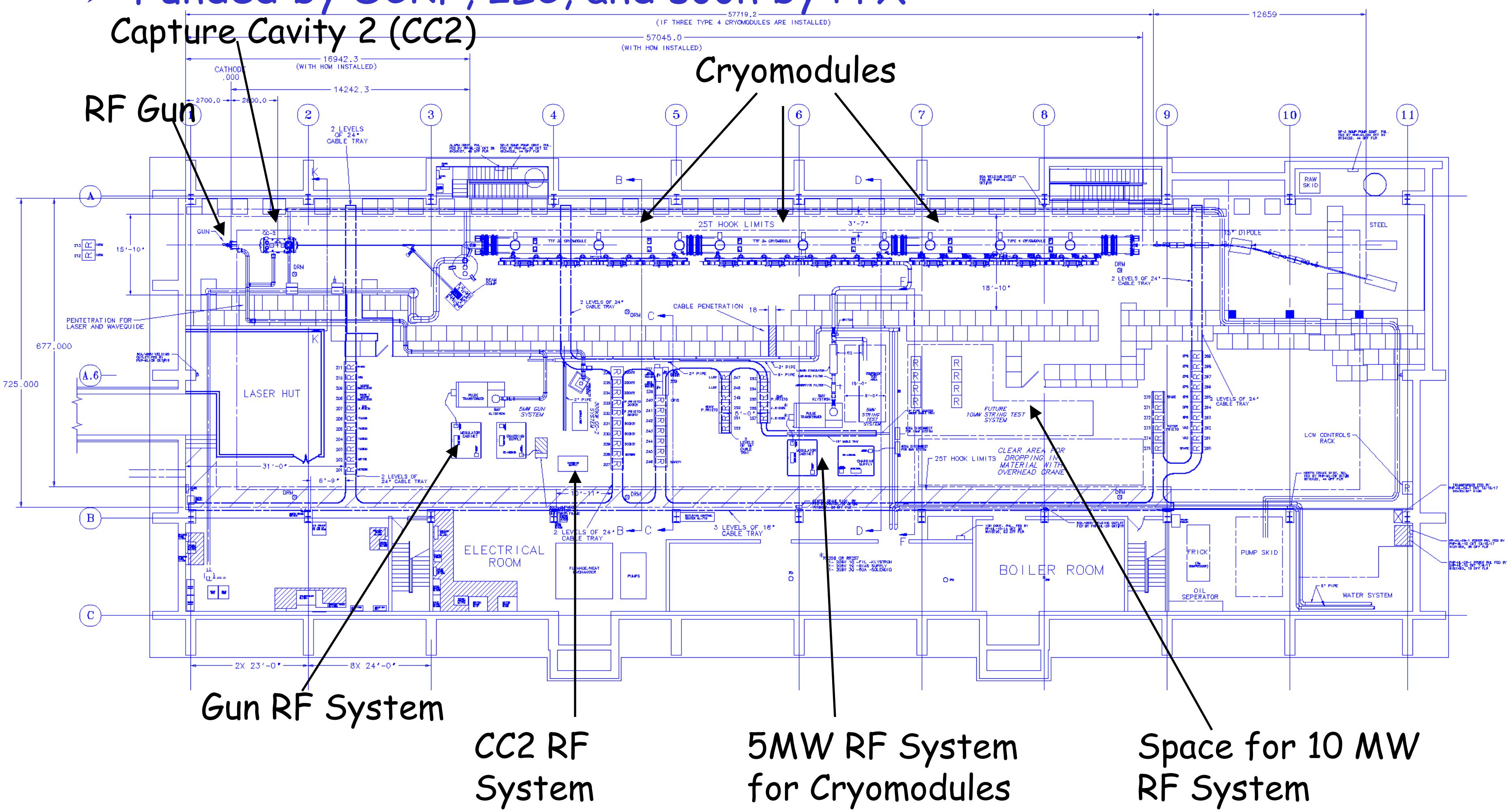
- Upgrade A0 photoinjector:
  - New rf gun: higher brightness, lower dark current
  - Higher energy (40 MeV) by changing SCRF cavity
  - Better laser, upgrade to ILC parameters
- Continue experimental program thru 2011
- Move to a new facility (NML) in 2012

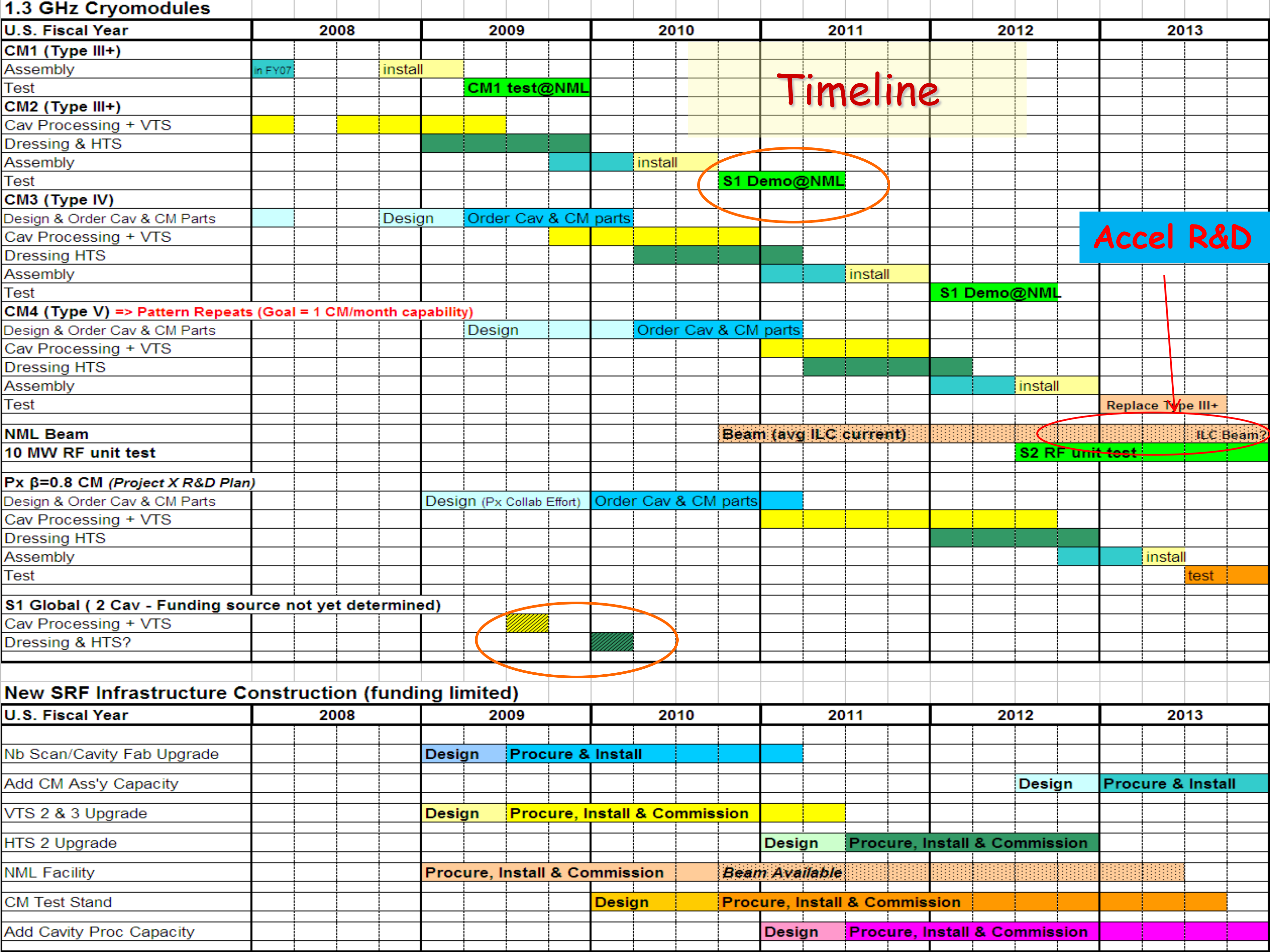




What's the plan?

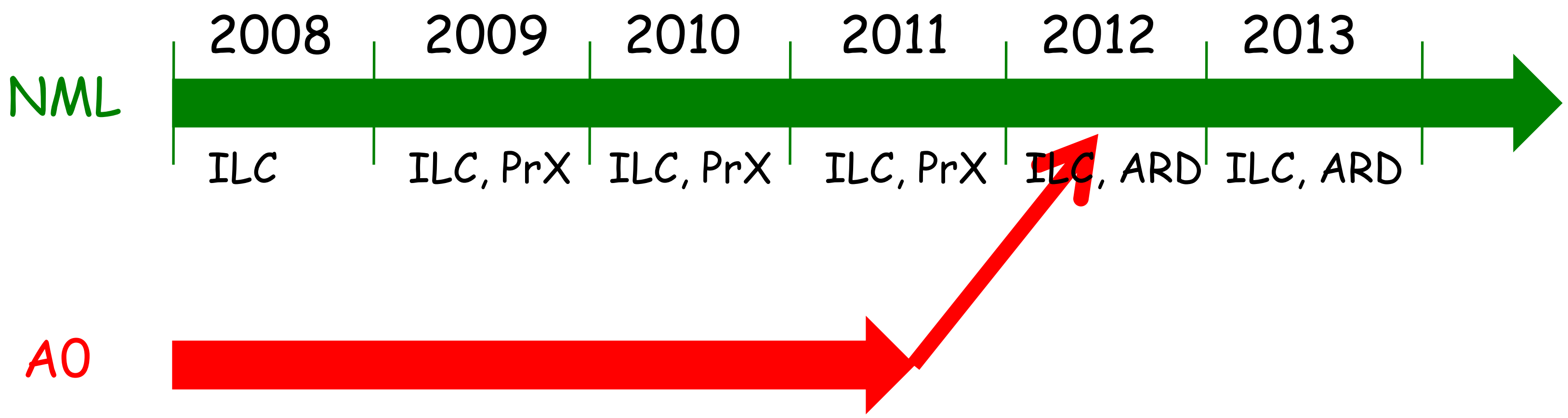
- We are presently constructing a cryomodule test facility at NML:
  - Funded by SCRF, ILC, and soon by PrX





1.3 GHz Cryomodules
U.S. Fiscal Year
2008
2009
2010
2011
2012
2013
CM1 (Type III+)
Assembly
in FY07
install
Test
CM1 test@NML
Timeline
CM2 (Type III+)
Cav Processing + VTS
Dressing & HTS
Assembly
install
Test
S1 Demo@NML
CM3 (Type IV)
Design & Order Cav & CM Parts
Design
Order Cav & CM parts
Accel R&D
Cav Processing + VTS
Dressing HTS
Assembly
install
Test
S1 Demo@NML
CM4 (Type V) => Pattern Repeats (Goal = 1 CM/month capability)
Design & Order Cav & CM Parts
Design
Order Cav & CM parts
Cav Processing + VTS
Dressing HTS
Assembly
install
Test
Replace Type III+
NML Beam
Beam (avg ILC current)
ILC Beam?
10 MW RF unit test
S2 RF unit test
Px β=0.8 CM (Project X R&D Plan)
Design & Order Cav & CM Parts
Design (Px Collab Effort)
Order Cav & CM parts
Cav Processing + VTS
Dressing HTS
Assembly
install
Test
test
S1 Global (2 Cav - Funding source not yet determined)
Cav Processing + VTS
Dressing & HTS?
New SRF Infrastructure Construction (funding limited)
U.S. Fiscal Year
2008
2009
2010
2011
2012
2013
Nb Scan/Cavity Fab Upgrade
Design
Procure & Install
Add CM Ass'y Capacity
Design
Procure & Install
VTS 2 & 3 Upgrade
Design
Procure, Install & Commission
HTS 2 Upgrade
Design
Procure, Install & Commission
NML Facility
Procure, Install & Commission
Beam Available
CM Test Stand
Design
Procure, Install & Commission
Add Cavity Proc Capacity
Design
Procure, Install & Commission

Summary



- A0 has a great research and education program
  - Many technical assets: 1.3 GHz SCRF, laser, 3rd harmonic
- Implement upgrades to A0 photoinjector to continue research through 2012
- Recruit more PhD students
- Move A0 to NML to use is as an injector
  - one can keep a single cryomodule and have enough room for experiments;