International Europhysics Conference on High Energy Physics
Grenoble, Rhône-Alpes France July 21-27 2011

European Physical Society
HEP 2011

Accelerator R&D for Future Colliders

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SLAC National Accelerator Laboratory

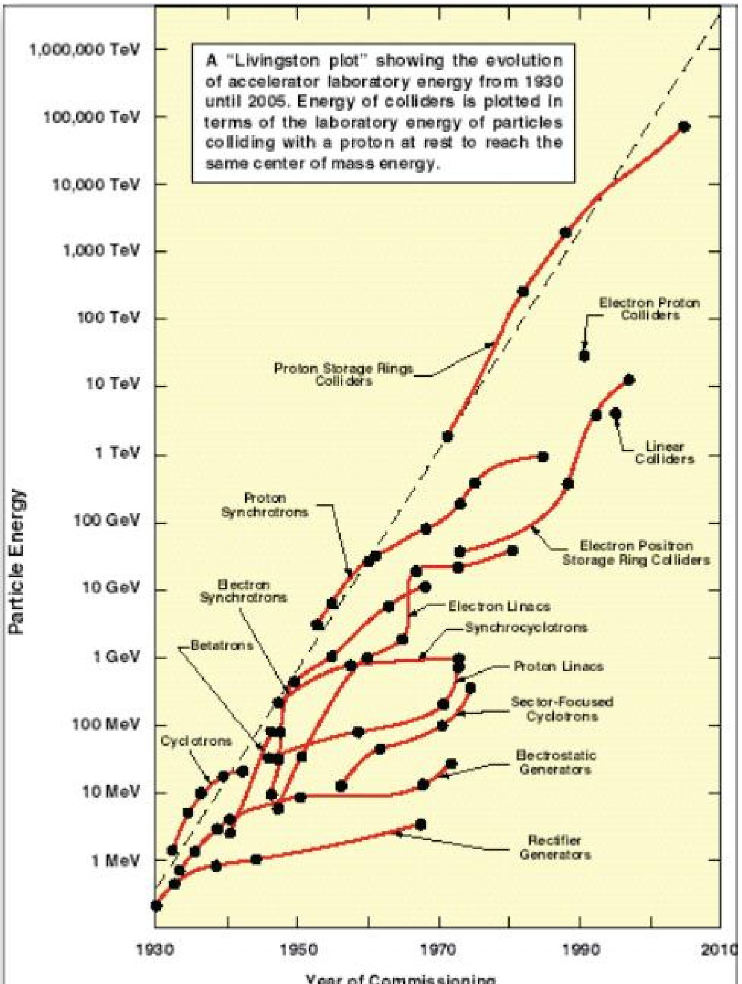
European Physical Society HEP Meeting

Grenoble, France

July 26, 2011

Why New Acceleration Techniques?

- Accelerator have been primary tool to advance HEP frontiers
  - But accelerators have continued to increase in size and cost and appear to be approaching the limit that can be supported



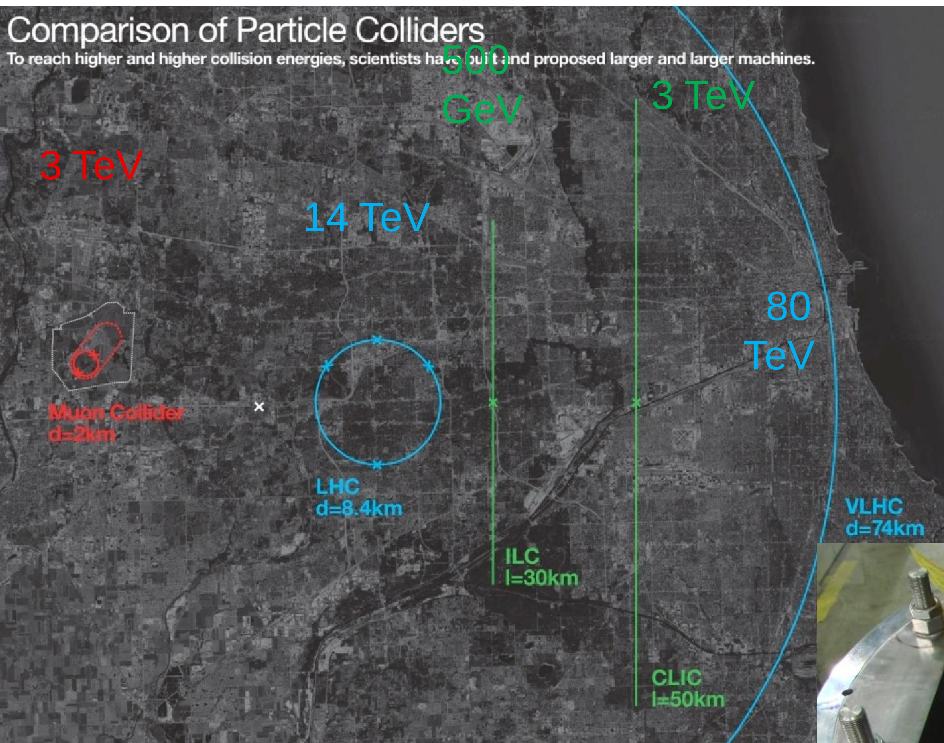
The Evolution of Particle Accelerators & Colliders
by W. K. H. Panofsky
2-017

- Need new technologies that are aimed at cost effective solutions

- Accelerator research very broad from materials to rf to nonlinear dynamics
  - Advances come from both fundamental research and focused R&D directed aimed at applications

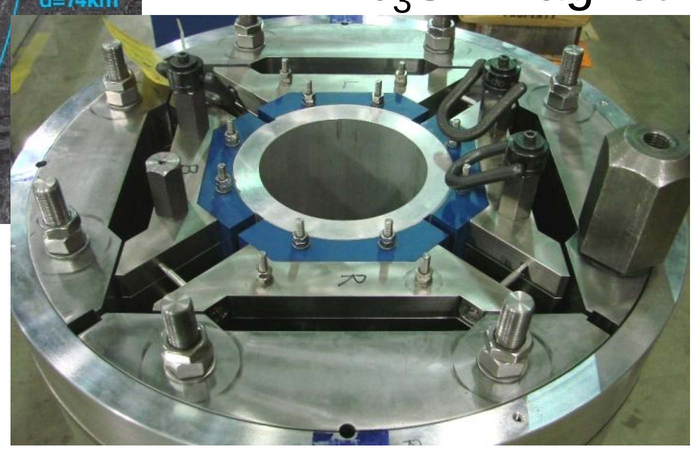
Energy Frontier Accelerators
Cost is a major limitation

- Size of the accelerator facilities is a large cost driver
  1. High field magnets
  2. High gradient acceleration
  3. Recirculating systems, e.g. Muon Collider vs. Linear Collider



- High field magnets
  - Examples abound: LHC, LEHC, MC
    - 20T for LeHC and 30~40T for MC
  - Improvement in magnetic fields relies on fundamental research and directed magnet R&D

LARP Nb_3Sn magnet



35T Bitter magnet

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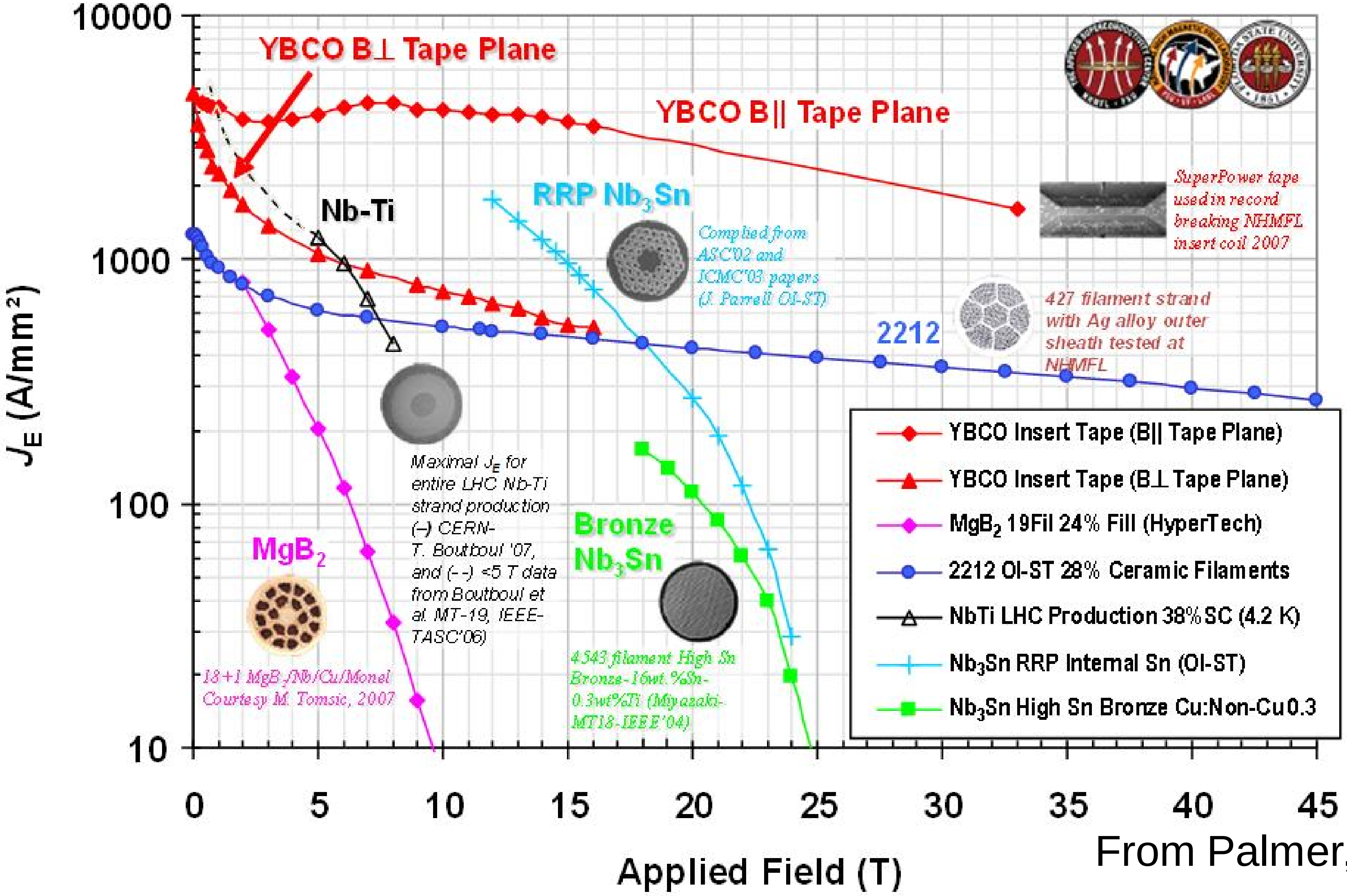
1. Superconducting Wire
High Field Magnets



From Palmer, AAC'2010

2. High Gradient Acceleration

- High gradient acceleration requires high peak power and structures that can sustain high fields
  - Beams and lasers can be generated with high peak power
  - Dielectrics and plasmas can withstand high fields

- Many paths towards high gradient acceleration
  - RF source driven superconducting structures
    - ~40 MV/m
  - RF source driven metallic structures
  - Beam-driven metallic structures
    - ~100 MV/m
  - Laser-driven dielectric structures
  - Beam-driven dielectric structures
    - ~1 GV/m
  - Laser-driven plasmas
  - Beam-driven plasmas
    - ~10 GV/m

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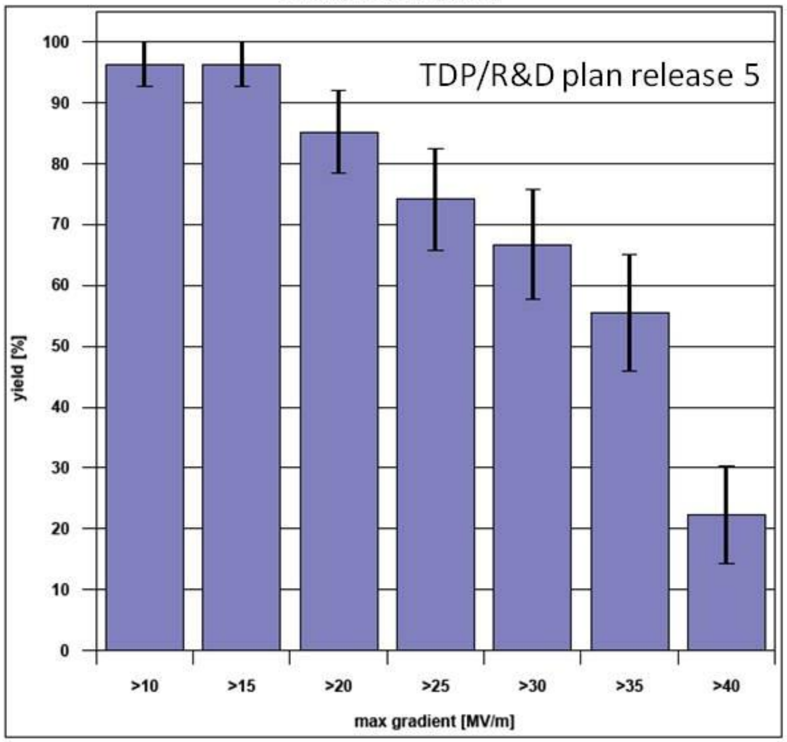
Superconducting Rf Cavities

- ILC based on high gradient superconducting rf cavities
  - Potential for still higher gradients from geometry or new materials

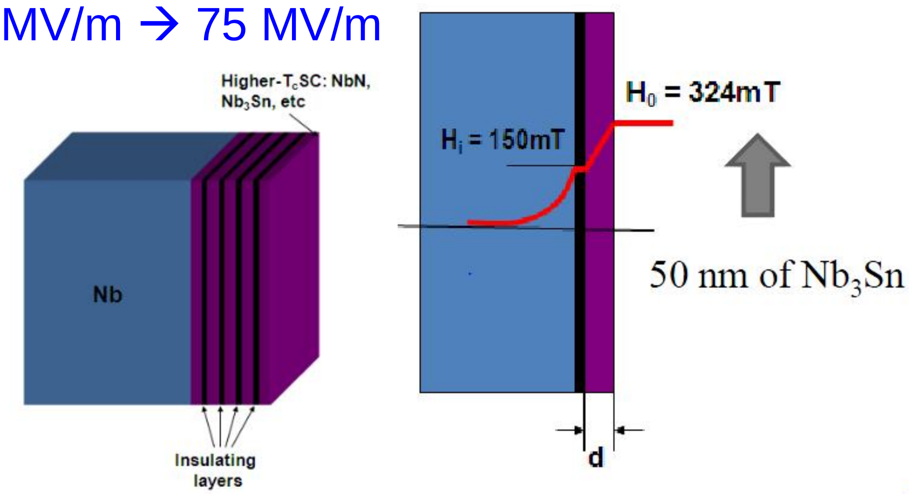
ILC cavities reaching 35 MV/m routinely
~75% of magnetic field limit

Yield of ILC 1.3 GHz cavities



- R&D towards new materials and geometries for higher gradients
  - Materials with higher H_c and lower Rs: MgB_2, NbN, Nb_3Sn, …
  - Multi-layer materials to reduce fields in bulk material

50 MV/m → 75 MV/m

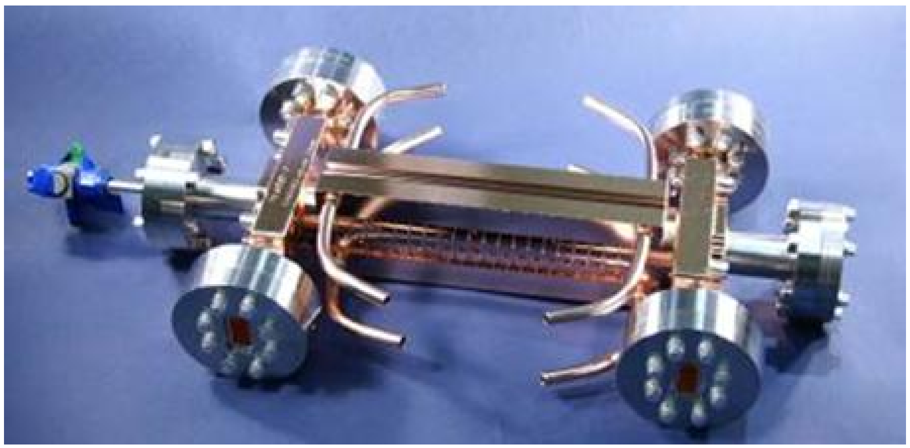


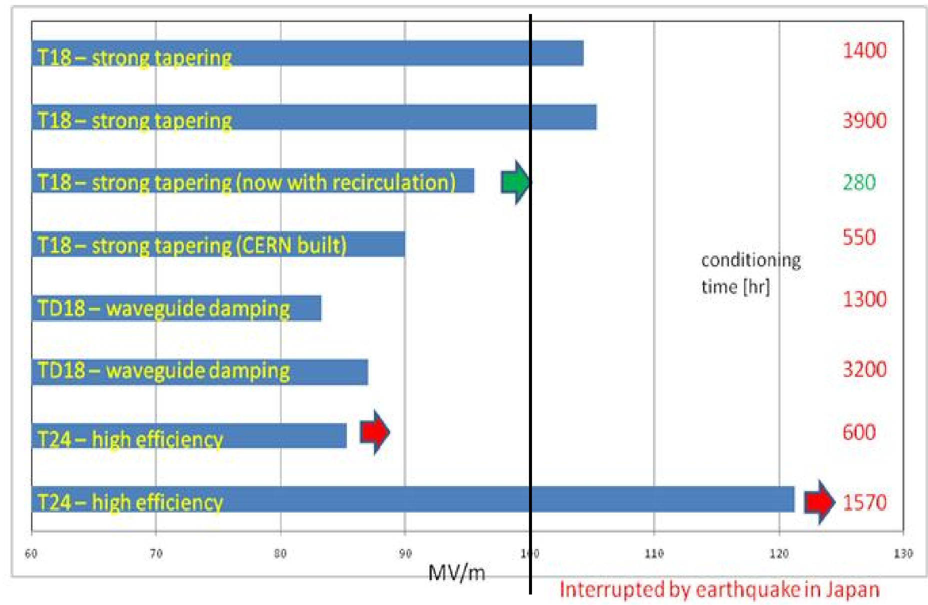
From *Grigory Eremeev SFR'09*

Normal Conducting RF Cavities

- Extensive R&D on breakdown limitations in normal conducting microwave structures
  - Most focus has been on geometry to understand breakdown limits

CERN CLIC Study



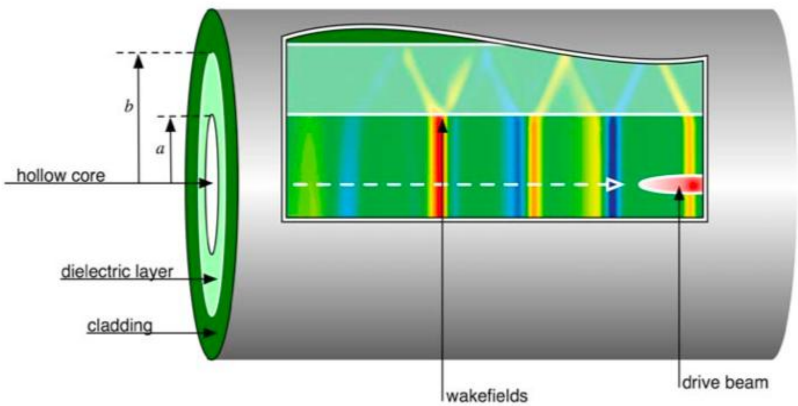


100 MV/m

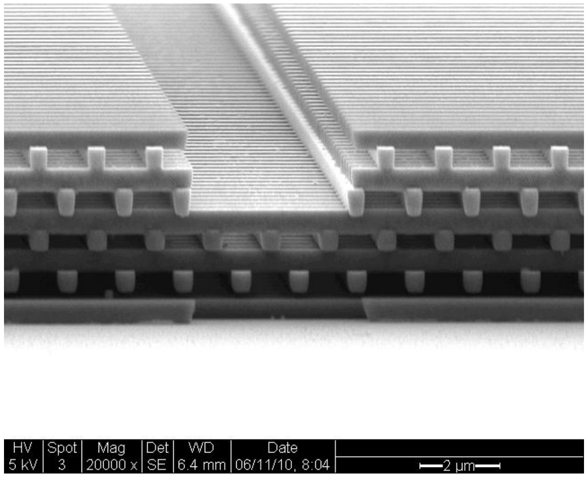
- In the last few years:
  - X-band gradients have gone from ~50 MV/m loaded to demonstrations of ~150 MV/m loaded with ~100 MV/m expected
  - C-band rf unit is operating at 35 MV/m; 8 GeV XFEL operating

Dielectric Accelerator Structures

- Unlike Copper, dielectric structures have higher breakdown limits approaching 1 GV/m at THz frequencies
  - Extensive damage measurements to characterize materials
  - Structures can be either laser driven or beam driven (wakefield)
- Beam-driven structures
  - Frequencies are in GHz regime and dimensions are cm-level
  - Higher gradients than metallic structures but more difficult wakes



- Laser-driven Photon Band-Gap structures
  - Use lasers to excite structures similar to microwave accelerators but with 10,000x smaller wavelengths!



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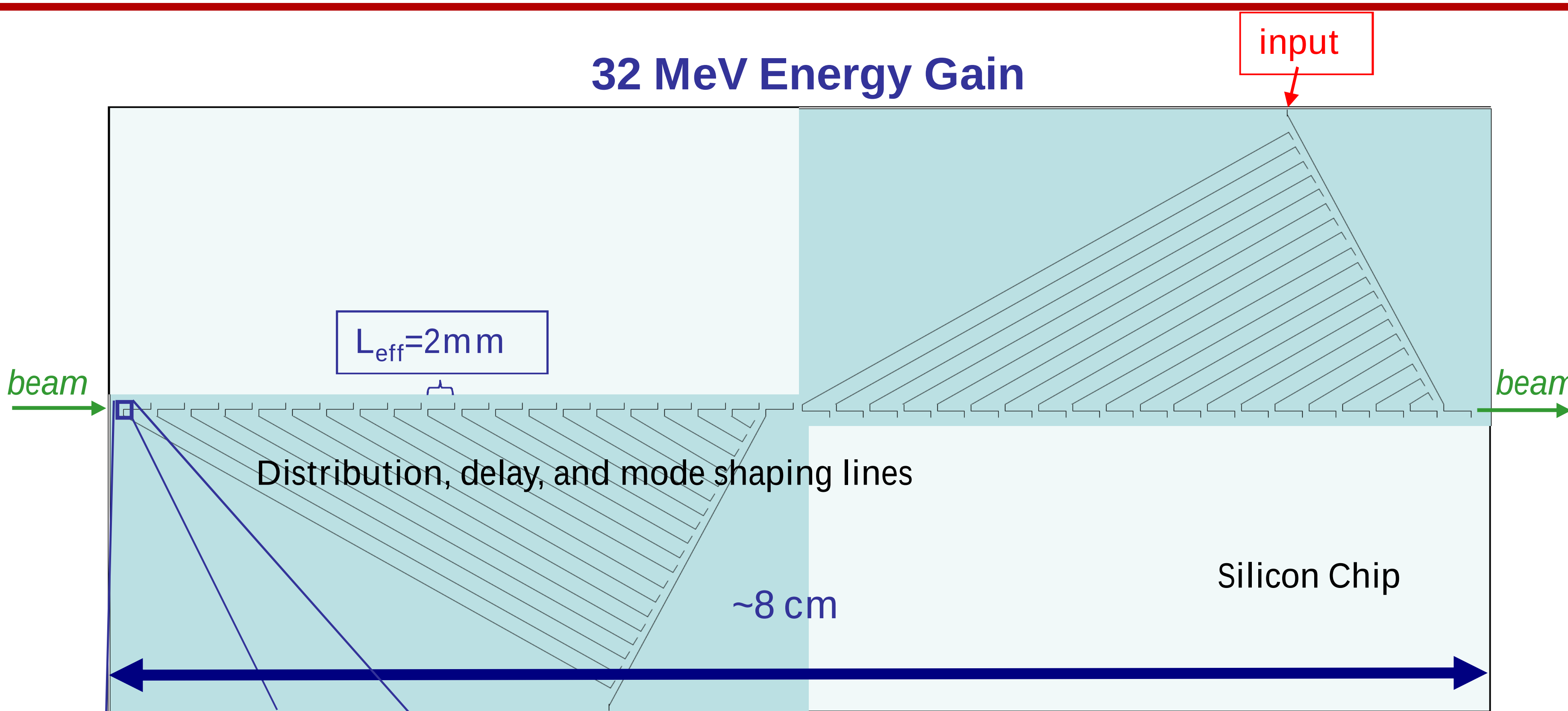
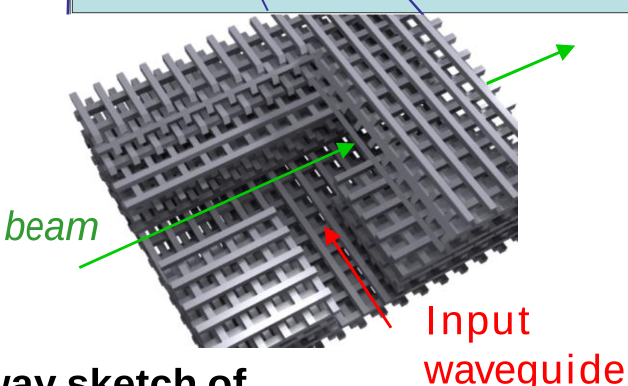
Laser-Driven Dielectric Accelerator
(Accelerator-on-a-chip)



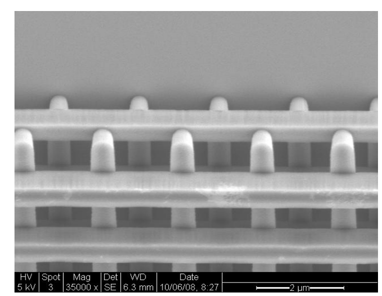
Fiber coupled input

λ=2 μm
20 μJ/pulse
1 ps laser pulse



Cutaway sketch of coupler region

Image courtesy of B. Cowan, Tech-X.

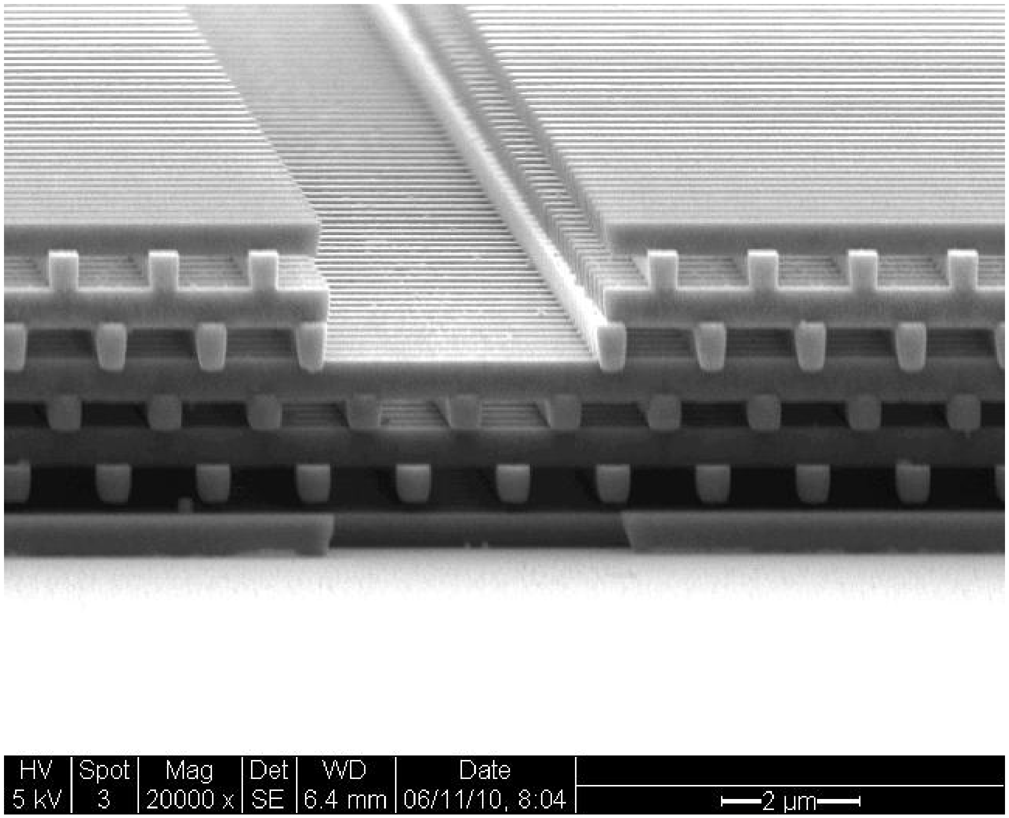


4-layer Structure Fabrication (completed at SNF)

Image courtesy of C. McGuinness, Stanford.

Fabrication of 3-D PBG Structure

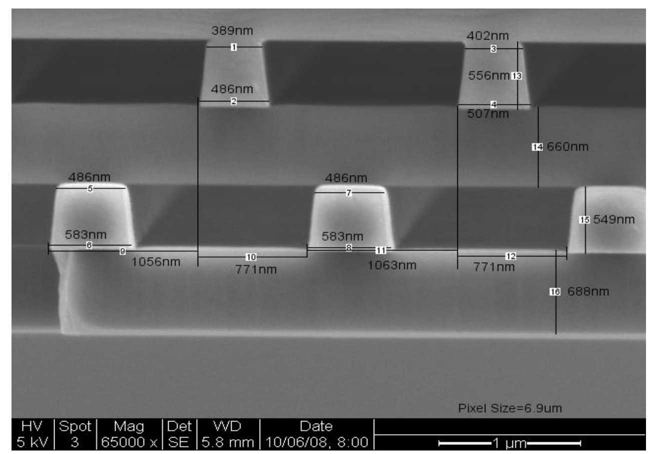
Silicon woodpile structure produced at the Stanford Nanofabrication Facility (SNF)



Fabricated by graduate students

Detailed Tolerance Studies of CDs

Process Version	Rod width base	Rod width top	Taper Angle	Layer Thickness	Alignment Offset	Period
3	389	486	9.89624641	556	142.5	1834
3	402	507	10.69429961	660	146	1827
3	486	583	10.01988665	549	161.5	1834
3	486	583	10.01988665	688	102.5	1808
3	311	441	9.575247964	516		2013
3	280	391	11.1759075	658		1721
3	379	509	11.04285784	559		
3	348	485	10.49147701	702		
2	438	556	13.12686302	506	412.5	1844
2	419	506	9.755861898	681	400	1838
2	469	525	5.75140209	556	522	1813
2	450	544	9.595956437	545	516	1857
2	384	455	7.092112957	643		1870
2	366	446	6.301068652	580		1832
2	446	527	5.850496153	527		
2	464	518	8.737992324			
1	434	529	10.43182293	542		1818
1	503	669	15.86761887	516		1789
1	483	649	15.86761887	584		
1	480	690	19.90374954	580		
average	420.85	529.95	10.55991867	586.7368421	300.375	1835.571
std	62.16808709	76.49594072	3.503712238	64.14206637	179.4061135	62.12112
version 3 mean	390.4285714	500	10.34633323	598	138.125	1839.5
version 3 std	74.27062003	65.09649431	0.57608771	73.11243787	25.14416765	95.24022
version 2 mean	429.5	509.625	8.276469191	576.8571429	462.625	1842.333
version 2 std	37.27887184	39.6157887	2.542079837	63.49128174	65.34188932	19.84607



Best achieved:

Width Variation:

<40 nm RMS (~λ/125)

Layer Thickness:

<65 nm RMS (~λ/75)

Layer Alignment:

<65 nm RMS (~λ/75)

Measurement Technique Granularity: 7nm

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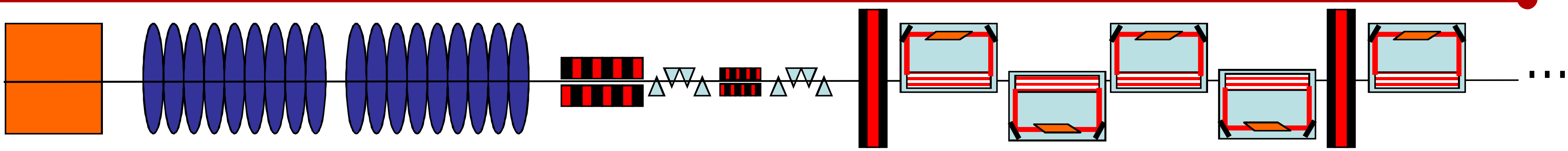
Concept of Laser-Driven Dielectric Linac



CW Injector

Warm rf gun Cold Preaccelerator Optical Buncher

433 MHz x 6E03 e^-/macropulse (145 μpulse/macropulse)

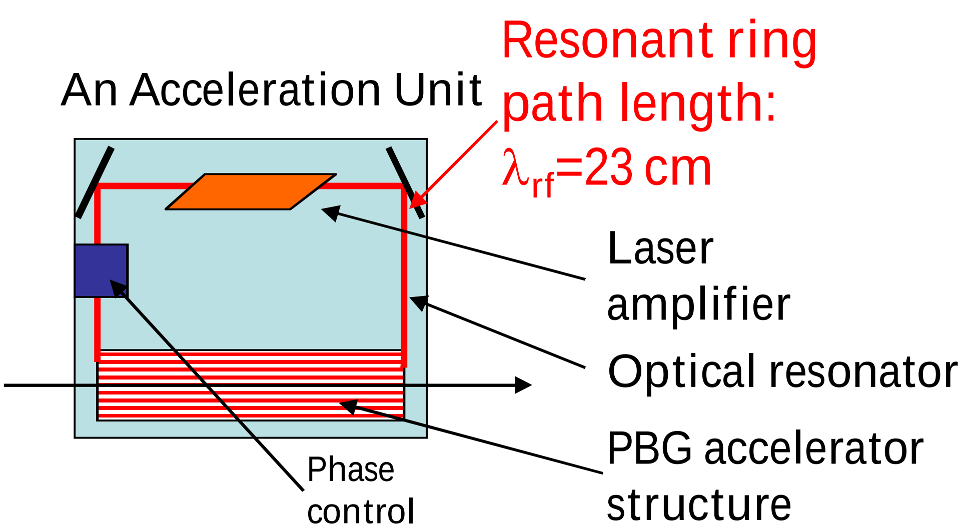
$\varepsilon_N \sim 10^{-10}$ m (but note Q/ε_N << 1 nC/μm)

Laser Accelerator

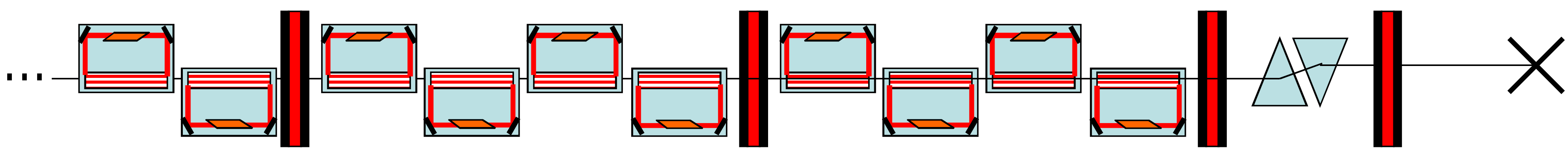
λ=2-4 μ, G~1 GeV/m

Photonic Band Gap Fiber structures embedded in optical resonant rings

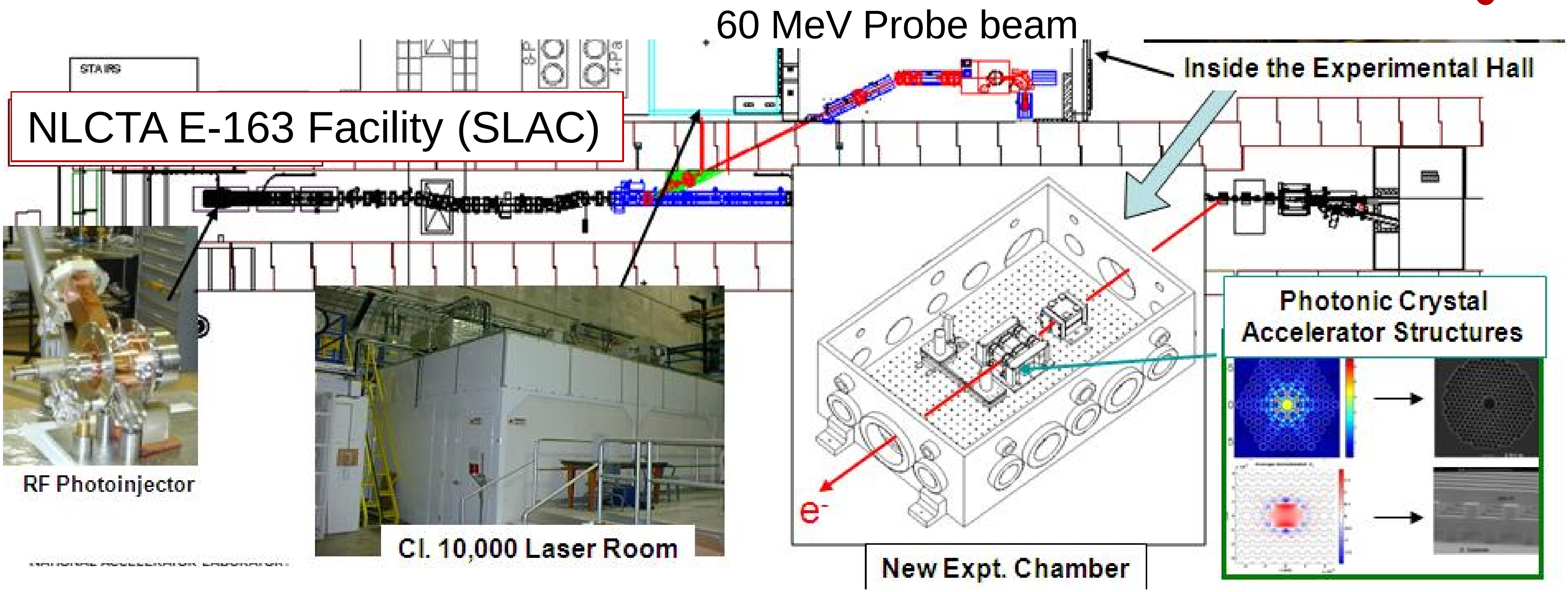
Permanent Magnet Quads (B'~2.5 kT/m)

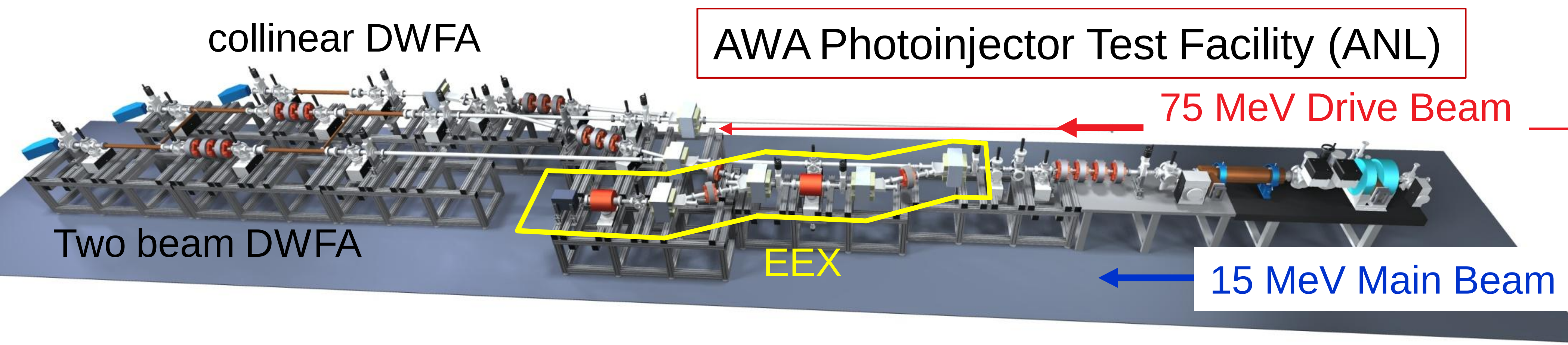


- DLA concept benefits from commercial laser and semiconductor industries
  - 100 MHz lasers with μJ per pulse
  - Potential cost break using lithographic techniques
  - Challenge is nm-level tolerances



Dielectric Accelerator Test Facilities



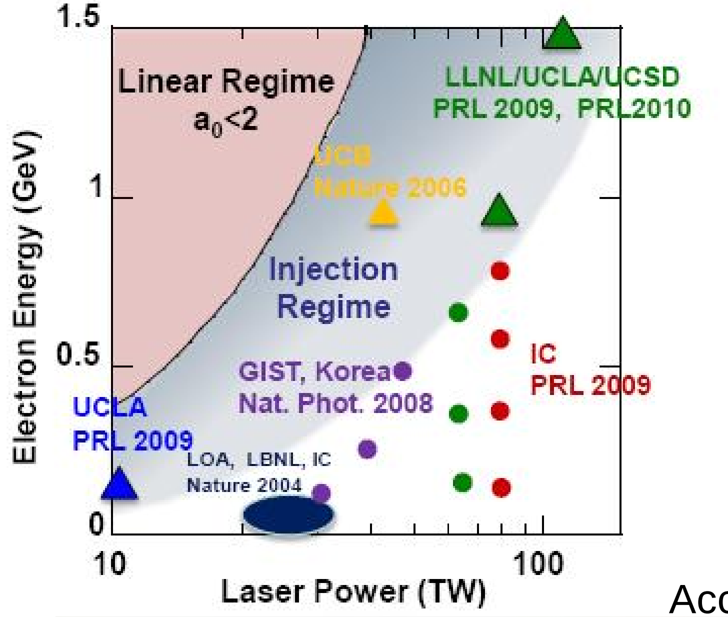


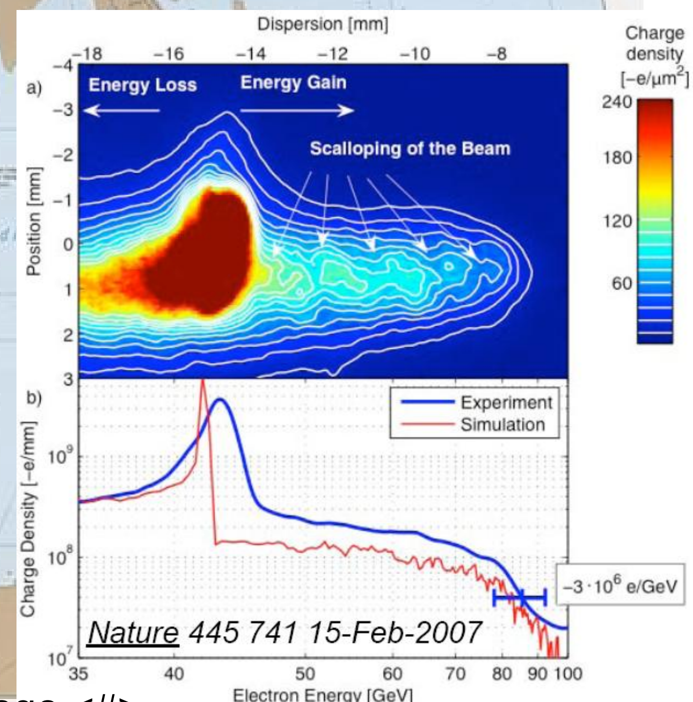
World-Wide Interest in Plasma Acc.

Plasma Acceleration on the Globe, T. Katsuoleas

D. H. Froula

2010 Advanced Accelerator Conference



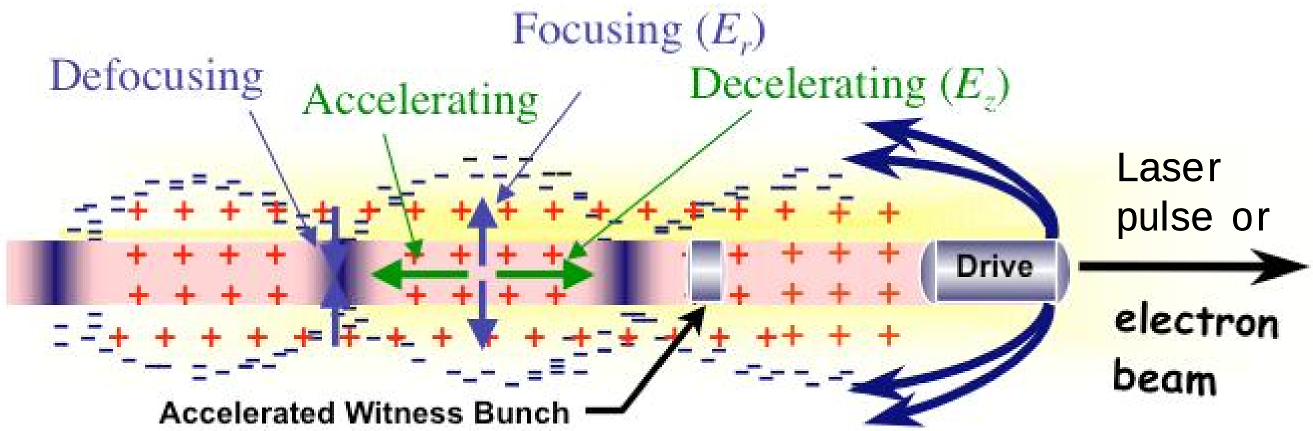


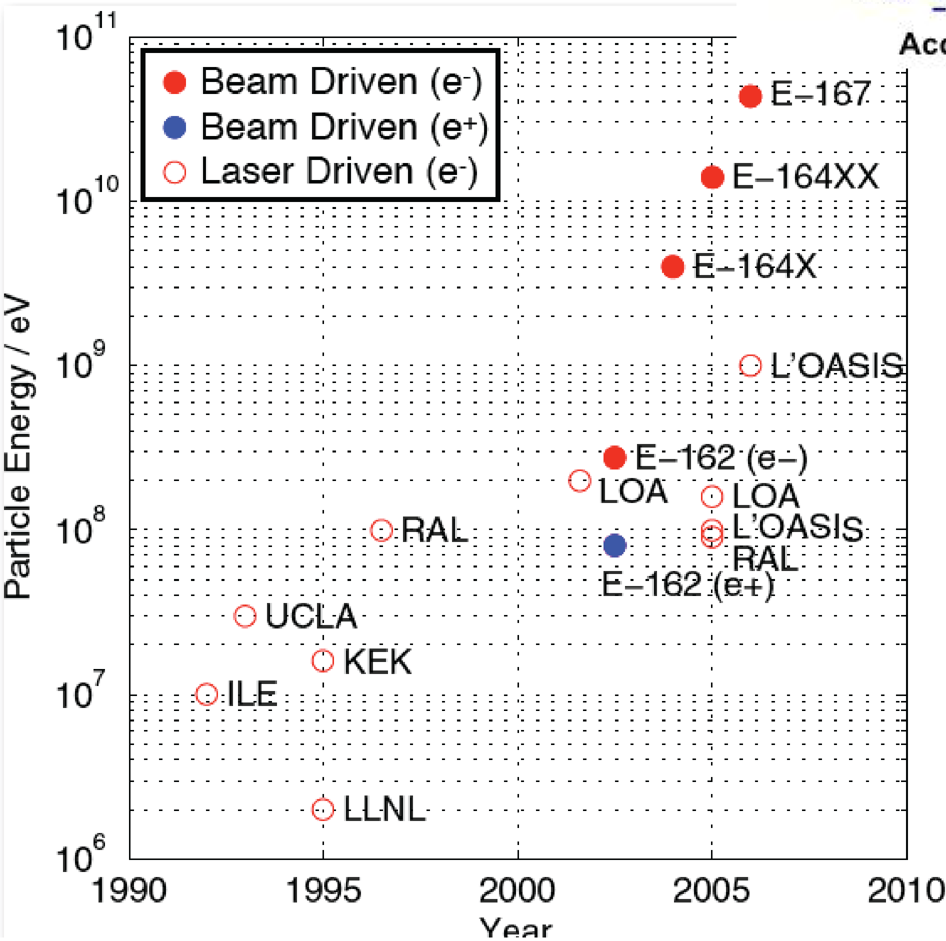
Nature 445 741 15-Feb-2007

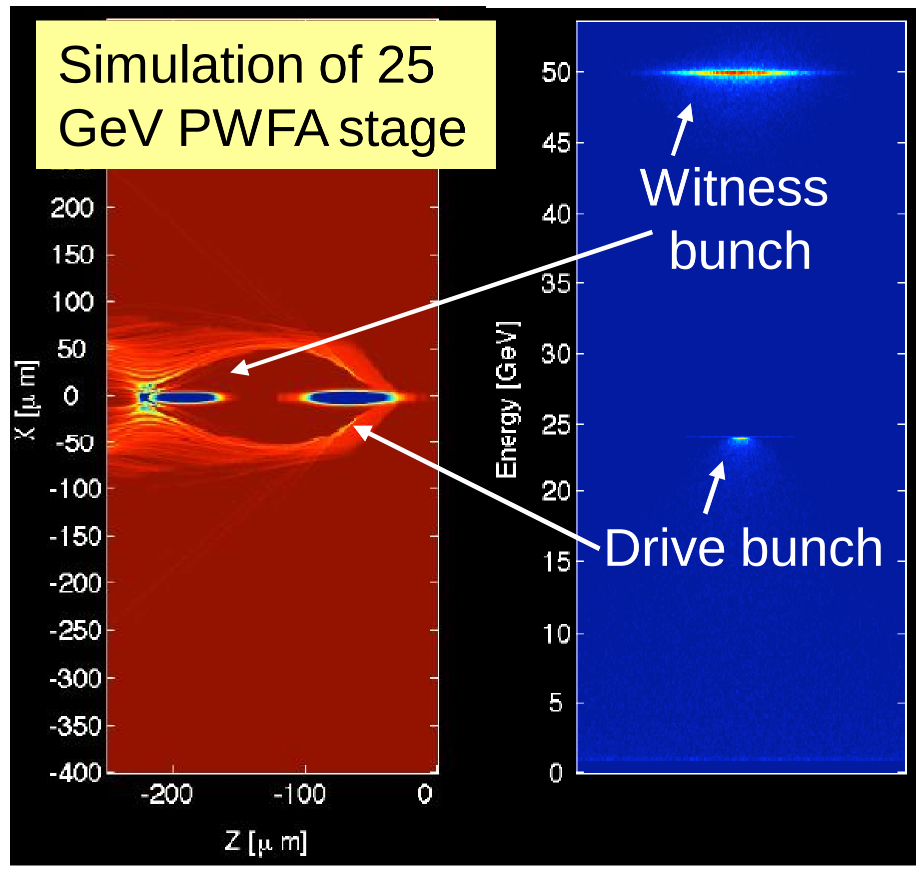
● Laser Wake Expts ● Electron Wake Expts ● e-/e+ Wake Expts

Plasma Acceleration (Beam-driven or Laser-driven)

- 50 GV/m demonstrated
  - Potential use for linear colliders and radiation sources

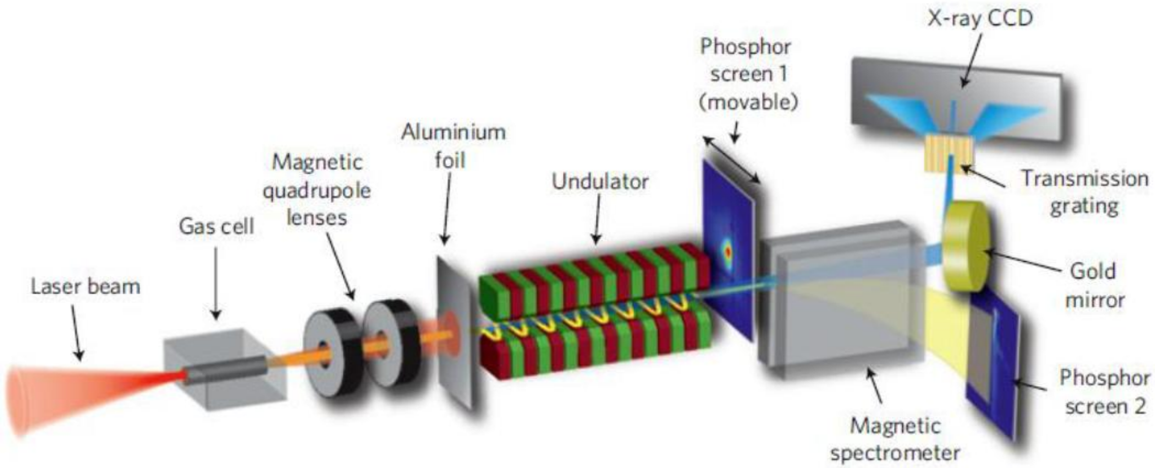


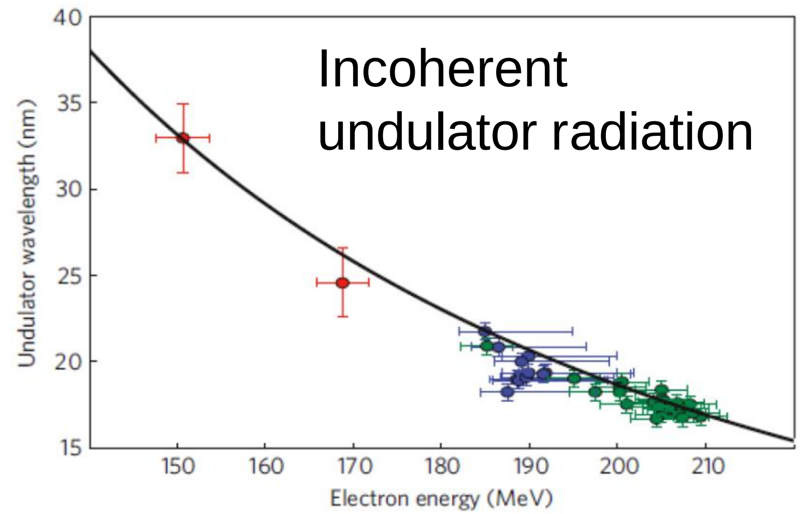




Compact Plasma Accelerators

- Plasma accelerators have many potential applications
  - Experiments at MPQ, Oxford Univ., Univ. of Edinburgh, JAERI aimed at generating a compact laser plasma-based FEL
    - Working on beam quality, stability, etc
  - Many other labs around the world have similar goals

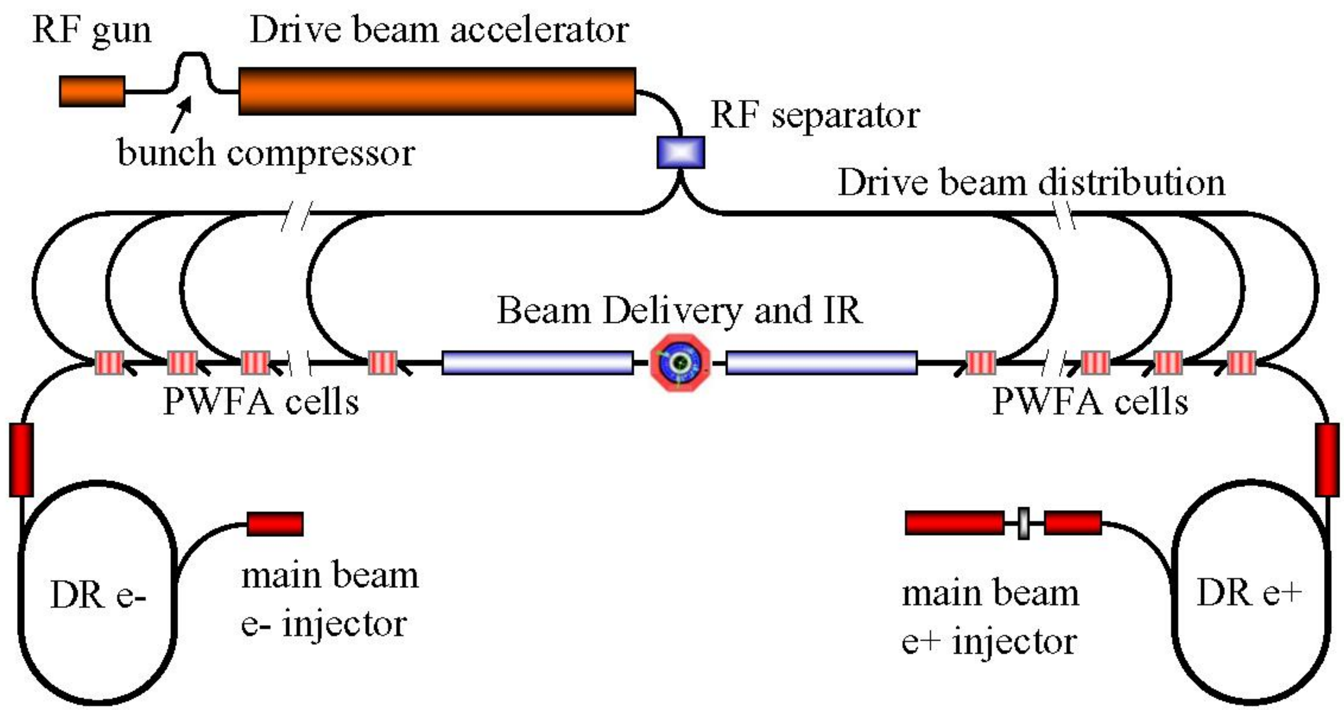




Laser-driven soft-X-ray undulator source
Fuchs et al, Nature Physics (2009)

Concept of Beam-Driven Plasma Linac
Similar Schemes Possible for Laser-Plasma LC's

- Concept for a 1 TeV plasma wakefield-based linear collider
  - Use conventional Linear Collider concepts for main beam and drive beam generation and focusing and PWFA for acceleration
    - Combines PWFA R&D with 30 years of conventional rf linac R&D
  - Concept illustrates focus of PWFA R&D program
    - High efficiency
    - Emittance pres.
    - Positrons
  - Allows study of cost-scales for further optimization of R&D



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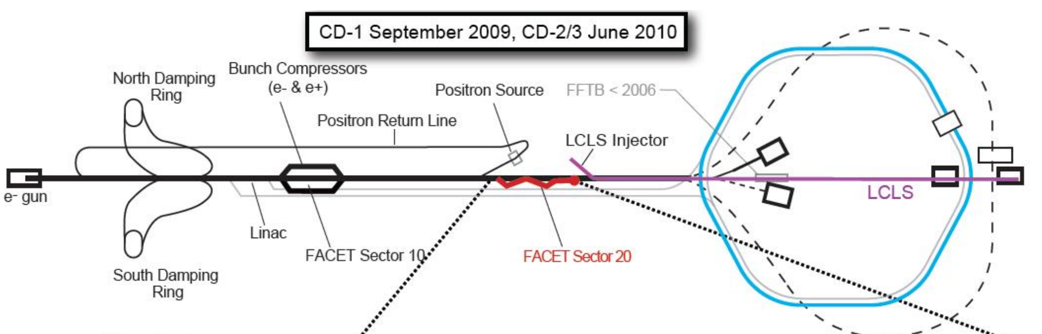
Plasma-based Linear Colliders

- New plasma accelerator test facilities: FACET and BELLA commissioning, FLASH at DESY and KEKB linac in design
  - All are aimed at linear collider relevant parameters:
    - ~1nC per bunch, many GeV energy gain, small emittance beams
  - Will address next generation challenges: emittance preservation, small energy spreads, stability and efficiency

FACET Test Facility



Nominal
FACET Beam Parameters

Energy	23 GeV
Charge	3 nC
Sigma z	14 µm
Sigma r	10 µm
Peak Current	22 kAmps
Species	e^- & e^+

Beam Parameters Driven by Science Needs

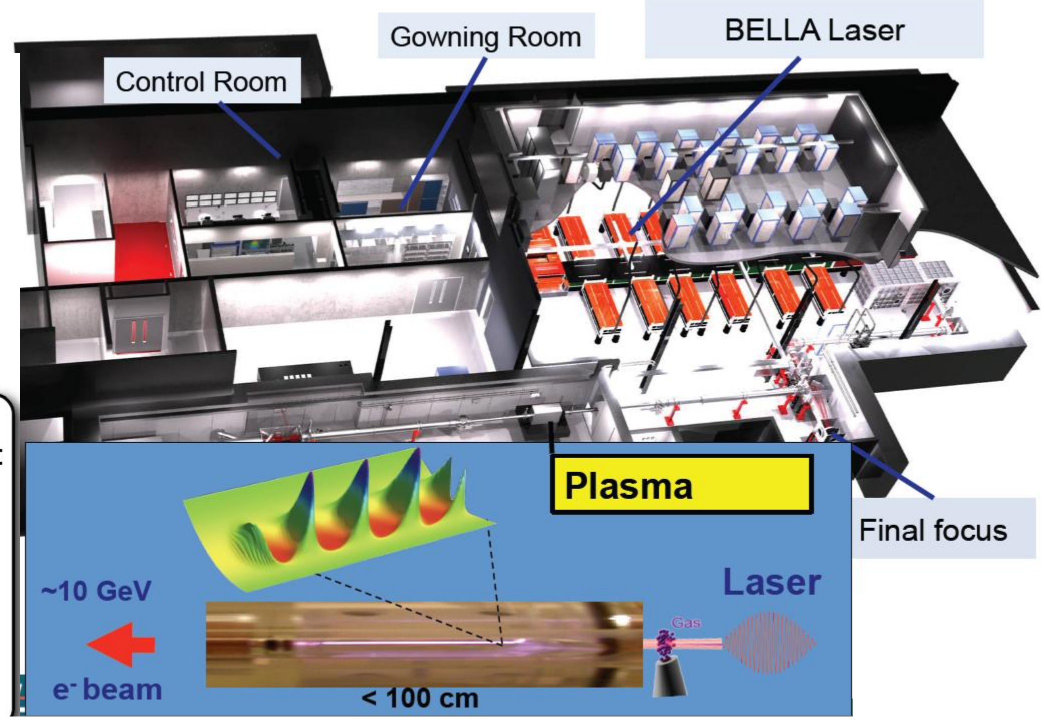
Delivered to 100m area with three distinct functions:

1. Chicane for final stage of bunch compression
2. Final Focus for small spots at the IP
3. Experimental Area(s)

Advantageous location:

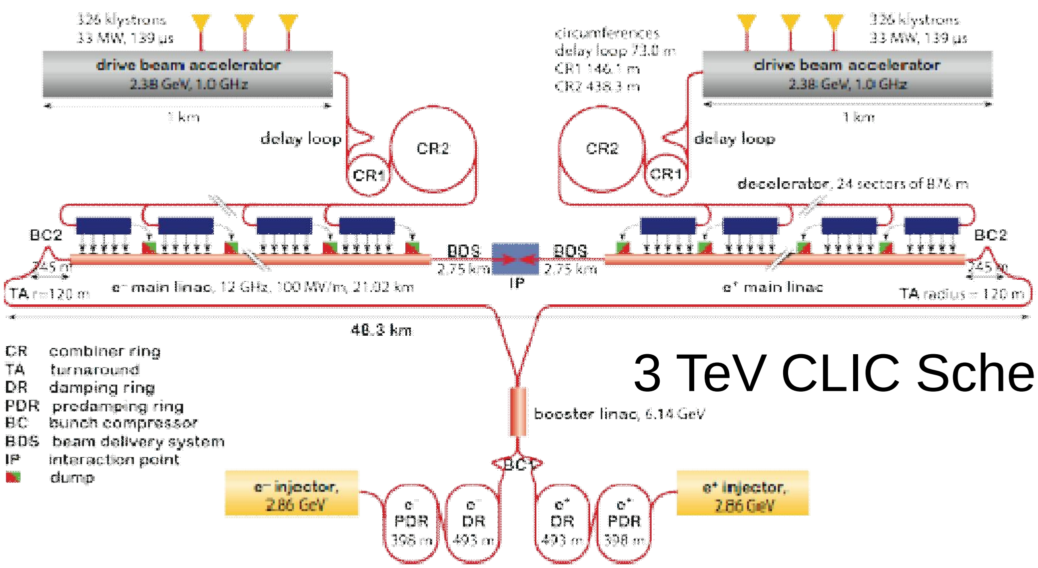
- Preserves e+ capability
- No bypass lines or interference with LCLS
- Linac setup virtually identical to SPPS/FFTB

BELLA Test Facility



Beam-Driven vs Discrete Source

- Beam-driven accelerators could be cost effective for large installations
  - Electron beams couple better to structures than lasers
  - Use highly efficient rf system to generate drive beam
  - Electron beams easier to manipulate than rf
  - Consolidate main power sources



3 TeV CLIC Scheme

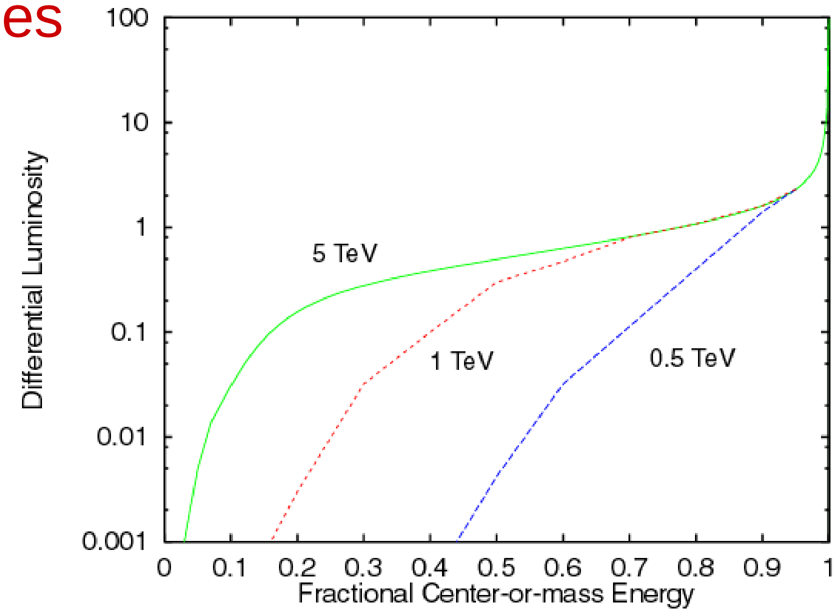
- But:
  - Not appropriate for compact installations
  - Complicated power handling
  - Little experience with large systems and *difficult to demonstrate in test facility*

Challenges for e+/e- Colliders
Energy and Luminosity

- Energy reach → cost but L → AC power & physics

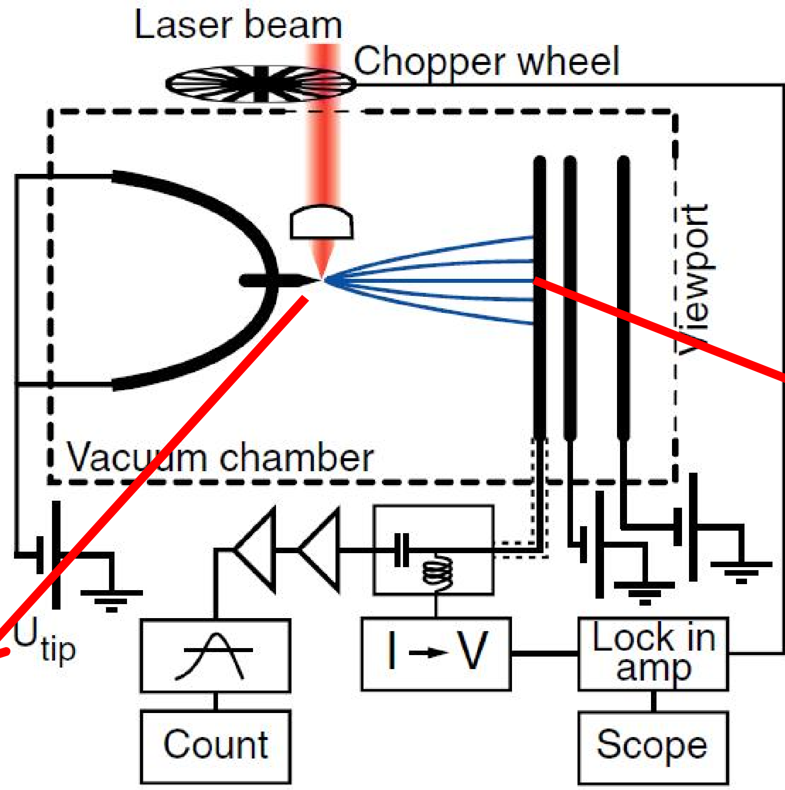
$$L = \frac{f_{rep}}{4\pi}\frac{N^2}{\sigma_x \sigma_y} \quad \Rightarrow \quad L = \frac{P_{beam}}{4\pi E_{beam}}\frac{N}{\sigma_x \sigma_y} H_D \sim \frac{P_{beam}}{E_{beam}}\frac{n_\gamma}{\sigma_y} H_D$$

- Need large beam powers, large bunch charges, and small spot sizes (emittances)
  - Backgrounds and luminosity spectrum ~ N/σ_x (beamstrahlung)
  - Severe challenge for e- at high energies
- All cases have some parameters beyond state-of-the-art
  - Develop/adopt new concepts to allow rebalance of parameters



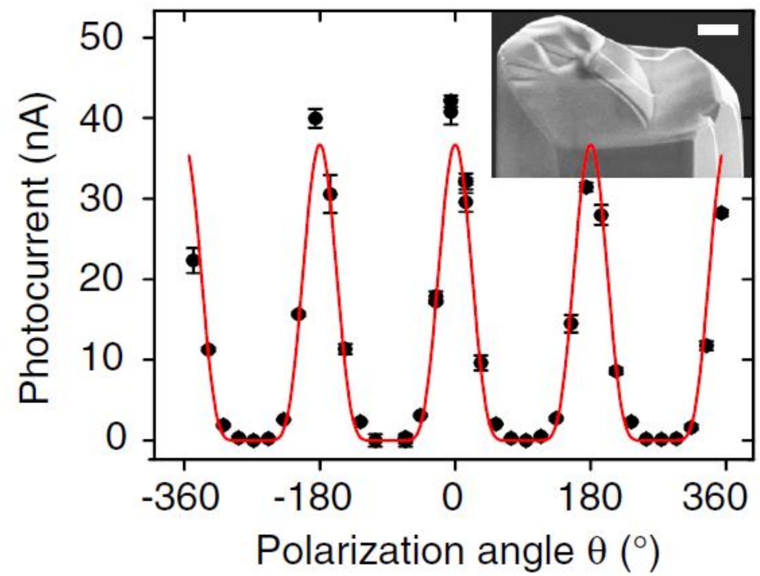
Bunch Charge and Emittance

- At high energy, low charge needed to reduce beamstrahlung
- Small emittances are crucial
  - Damping rings to generate beams with $\gamma\varepsilon_\perp$ ~ few 10^{-7} m-rad
  - RF guns generate beams with $\gamma\varepsilon_\perp$ ~ 10^{-6} m-rad / sqrt(nC)
  - Other sources have potential for even brighter beams but positrons are a problem!



1µm scale bar

PRL **96**, 077401 (2006)



500nm Scale bar

Possible Linear Collider Parameters

0.5 TeV ILC, 3 TeV CLIC, 10 TeV Novel

Case	0.5 TeV ILC	3 TeV CLIC	10 TeV Dielectric Beam Acc.	10 TeV Plasma Accelerator	10 TeV Dielectric Laser Acc.
Energy per beam (TeV)	0.25	1.5	5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	2	6.4	49	71.4	105
Electrons per bunch ($\times 10^9$)	20	3.7	4	4	0.002
Rep. rate (Hz) / number / train	5 / 1312	50 / 312	50 / 416	17,000 / 1	25,000,000 / 1
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	10,000	660	1000	200	0.1
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	30	20	10	200	0.1
β^* x/y (mm)	11 / 0.2	4 / 0.1	10 / 0.1	0.2	4
Horizontal beam size at IP σ^*_x (nm)	474	49	32	2	0.064
Vertical beam size at IP σ^*_y (nm)	3.8	1.0	0.3	2	0.064
Luminosity enhancement factor	1.6	1.9	1.9	1.35	1.0
Bunch length σ_z (μm)	300	50	20	1	300
Beamstrahlung parameter Υ	0.07	6.7	56	8980	0.377
Beamstrahlung photons per electron n_γ	1.7	1.5	1.4	3.67	0.52
Beamstrahlung energy loss δ_E (%)	4.3	33	37	48	4.37
Accelerating gradient (GV/m)	0.031	0.1	0.5	10	0.5
Average beam power (MW)	5.3	13.9	55	54	19
Wall plug power (MW)	200	568	~1200	~1200	~550
One linac length (km)	15.5	23.5	10	1.0	10

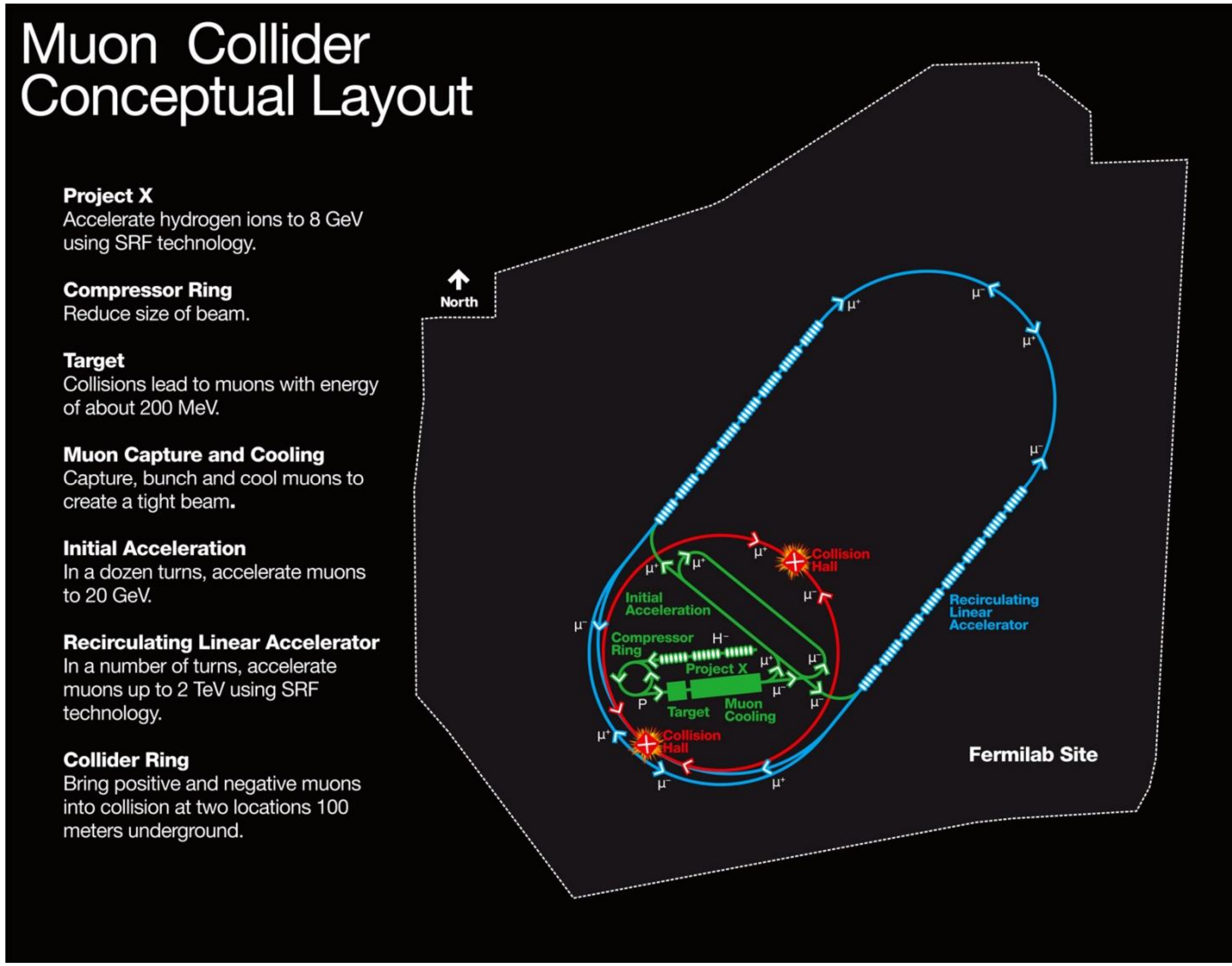
ILC and CLIC parameters from design reports; 10 TeV DBA scaled from Wei Gai communication; 10 TeV DLA and Plasma Accelerator from 2010 ICUIL/ICFA Workshop

3. Muon Collider

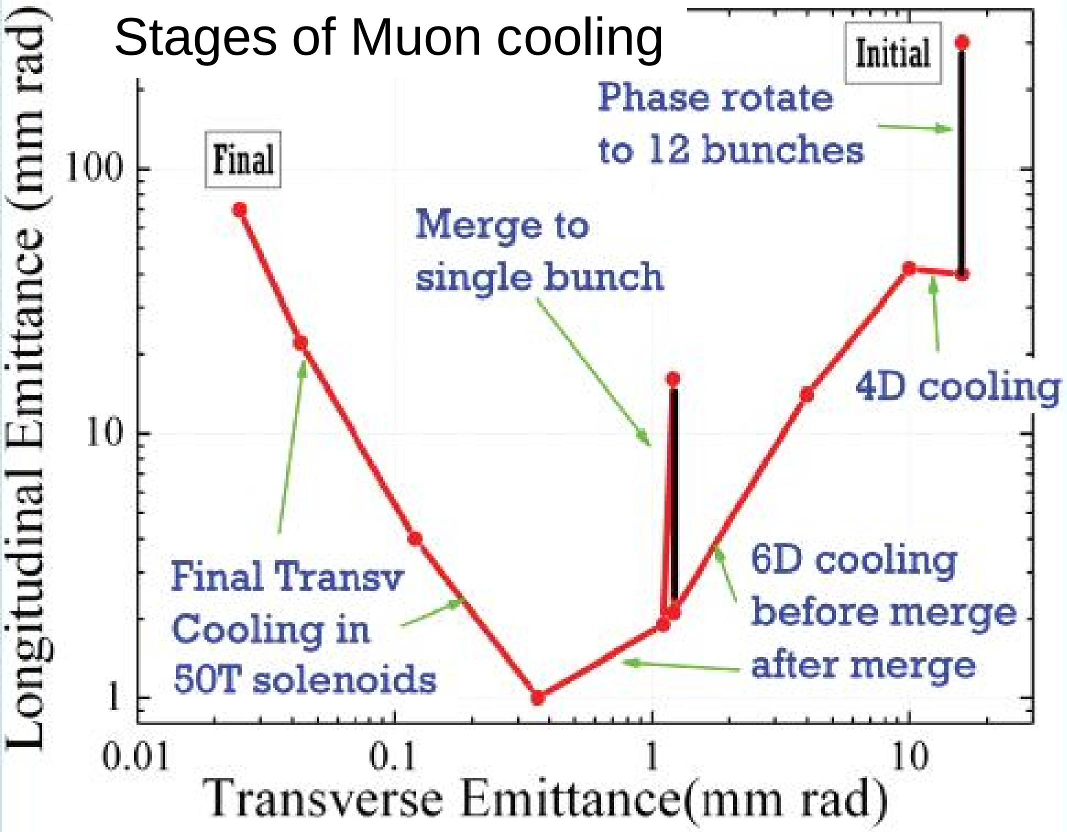
- Compact facility accelerating muons with recirculating linacs

Major Challenges

1. Muon generation
2. Cooling of muons
3. Cost-efficient acceleration
4. Collider ring and backgrounds from decays

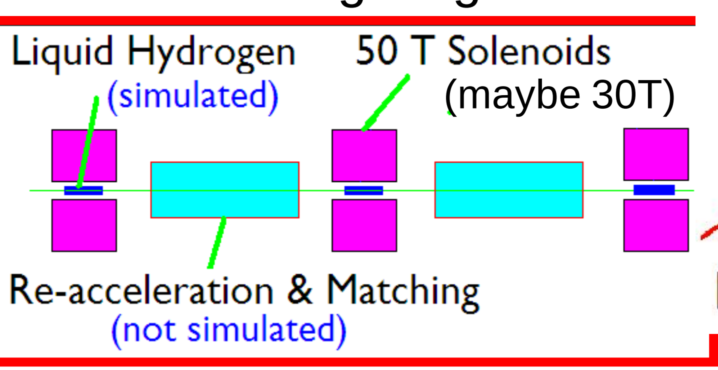


Muon Cooling

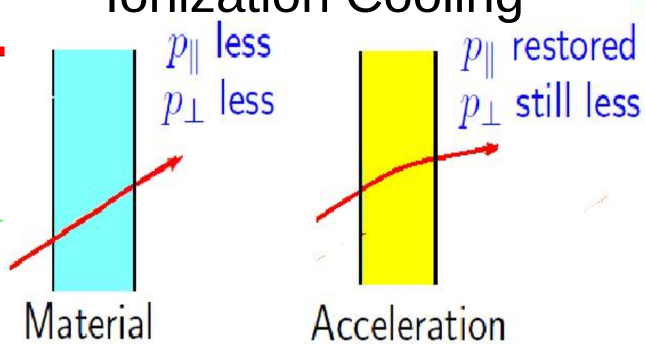


- Ionization cooling is the critical technology for muon collider
  - Requires 10^6 reduction of 6-dimensional emittance
  - Rf breakdown in magnetic field
  - Multiple concepts being studied

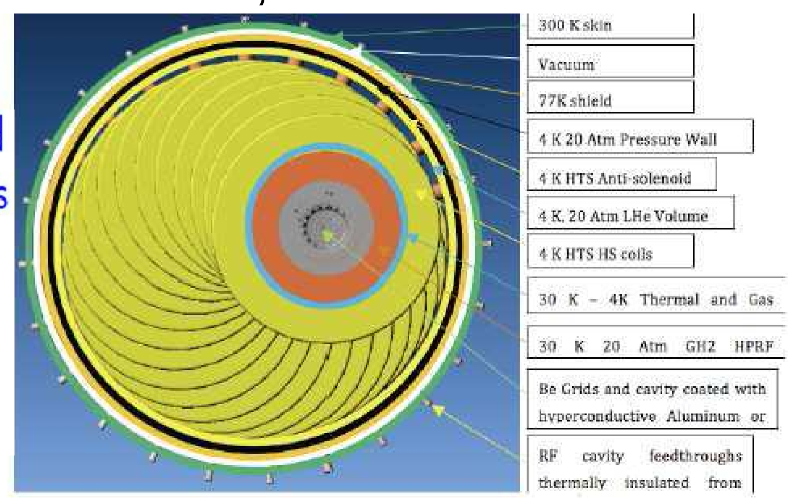
Final cooling stages



Ionization Cooling



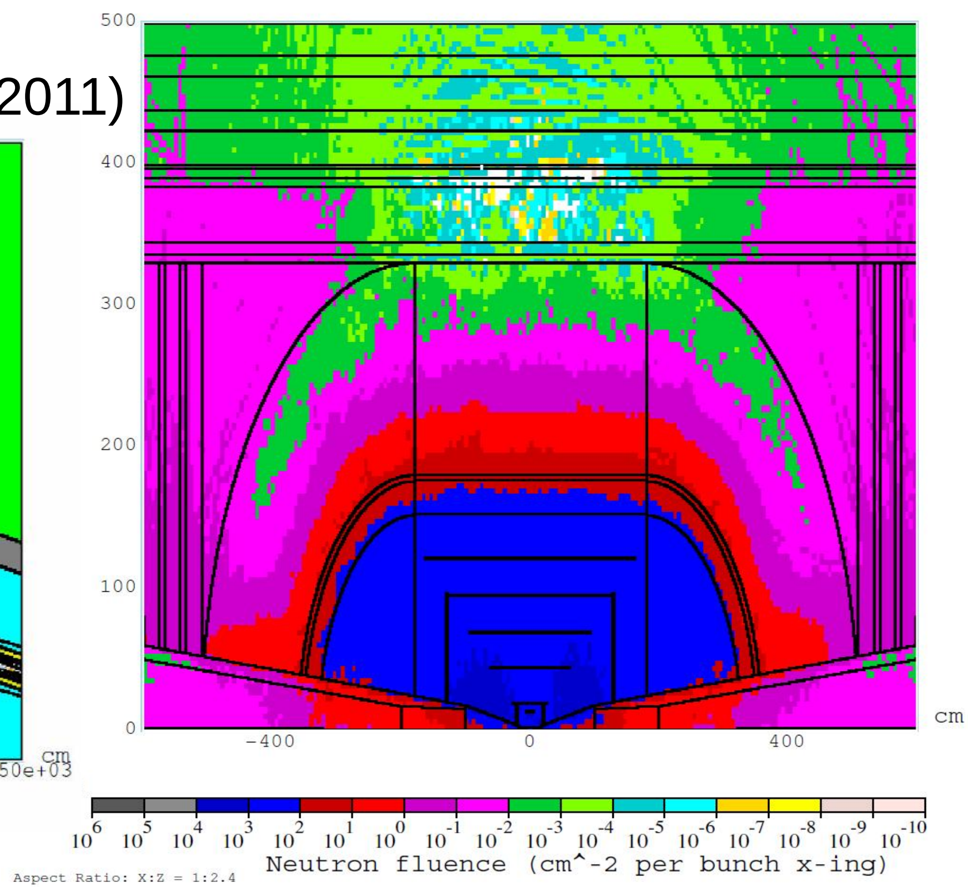
Concept for a Helical Cooling Channel
Palmer, AAC'2010



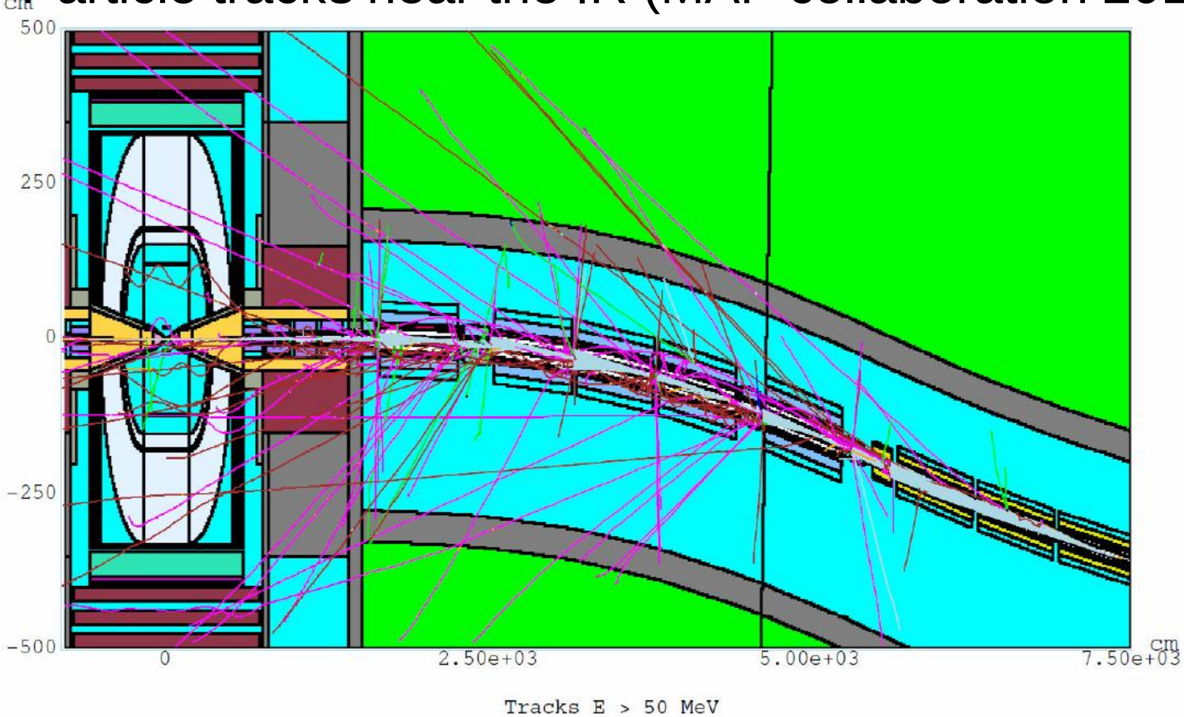
Collider Ring and Backgrounds

- Studies of ring dynamics aperture and machine backgrounds
  - Starting detailed modeling of IR using MARS and ILCroot
  - Focusing on 1.5 TeV cms studies
  - Ready to start reconstructions

Neutron peak/yr = 10% LHC@10^{34}



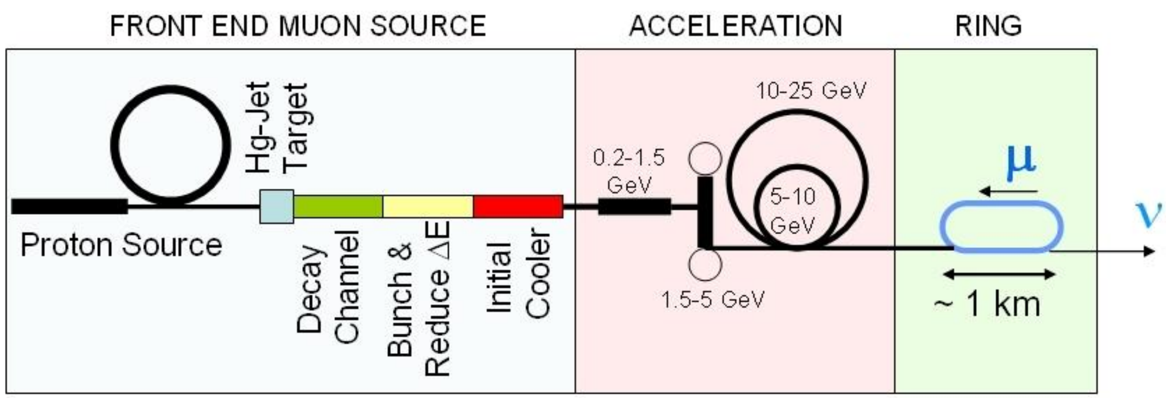
Particle tracks near the IR (MAP collaboration 2011)



Steps Toward a Muon Collider

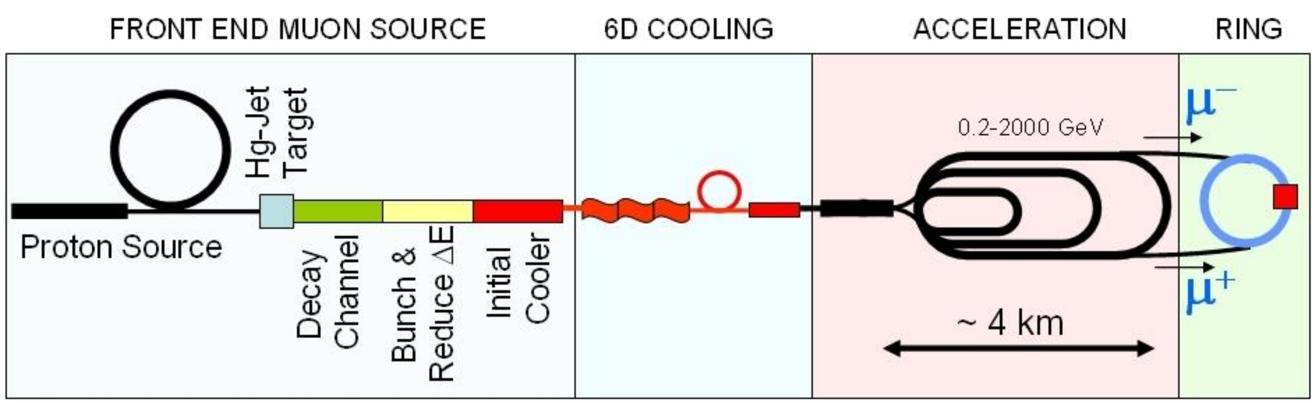
1. Project-X is being designed to deliver 4 MW of 8 GeV
2. Muon test facility would demonstrate capture and 1st cooling

3.



NEUTRINO FACTORY

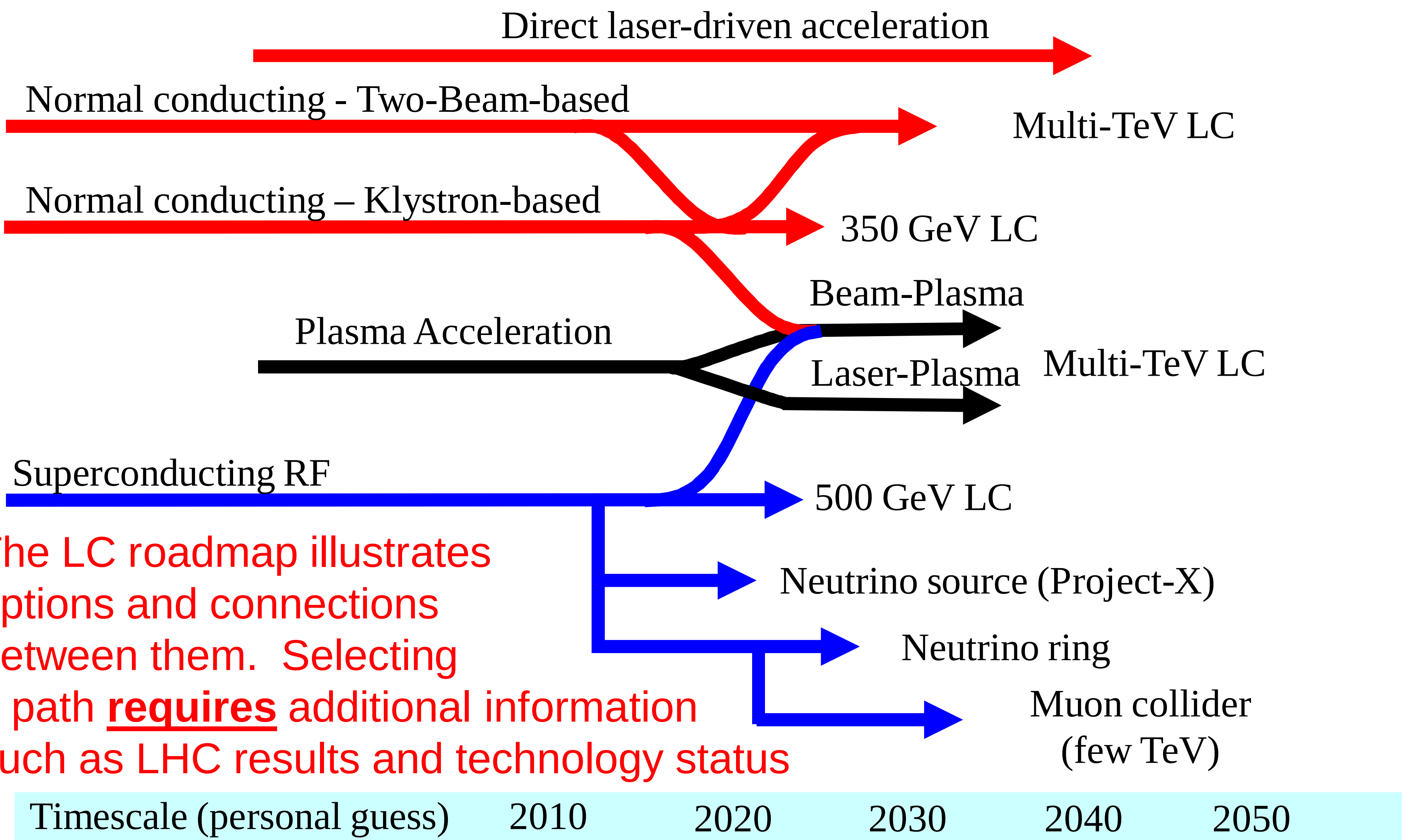
4.



MUON COLLIDER

Each step is a B$-class project

An Example Roadmap for
Multi-TeV Lepton Colliders



The LC roadmap illustrates options and connections between them. Selecting a path **requires** additional information such as LHC results and technology status

Accelerator Research & Development

- Timescales for accelerator development are long
  - Need to maintain pipeline of new ideas
  - Test facilities and infrastructure are critical to enable R&D
  - Important to build on existing ideas and focus on critical advances
- Large-scale projects tend to be conservative
  - Likely will require many systems-level demonstrations
  - Important to understand timescales and costs both for the R&D as well as the demonstrations
- Important to plan for early applications
  - Provides funding while allowing consideration of operational issues and demonstrating technology
  - May be a deciding factor when considering options

Summary

- Next generation HEP accelerators will be limited by cost
- Many advanced concepts with significant potential
  - Laser and beam driven dielectric linacs
  - Laser and beam driven plasma linacs
  - Muon collider based on RCS and recirculating SCRF linacs
  - Small test facilities are being constructed
- Lepton colliders are a very challenging application
  - Need to focus on emittance generation and beam focusing
  - Understand systems-level impacts of technologies
- Early applications are very important to complete development of technologies