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Plasma-Based Colliders:
1) "get practical" – IOTA 70 MeV e- Injector
2) stability challenge (one of many)
3) rough cost estimates
4) on high level roadmap for PWA-LC

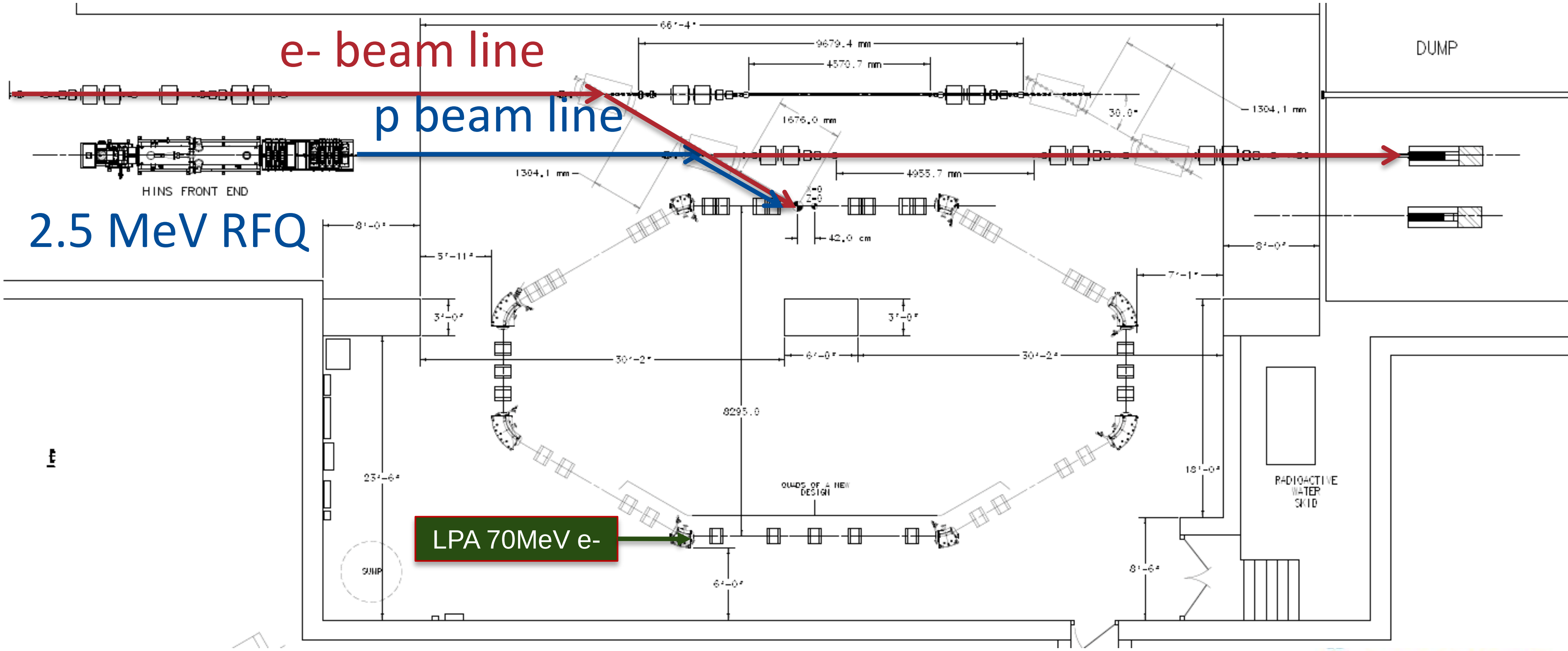
Vladimir Shiltsev, Fermilab

APC Seminar 02/18/2016 - Summary of the

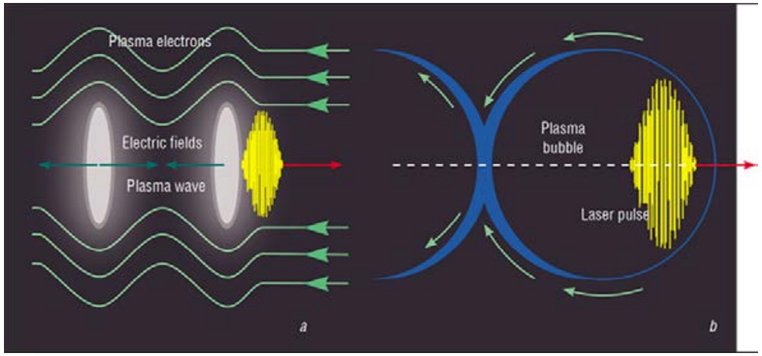
Workshop on "Plasma-based Accelerator Concepts for Colliders"
LBNL, January 6-8, 2016

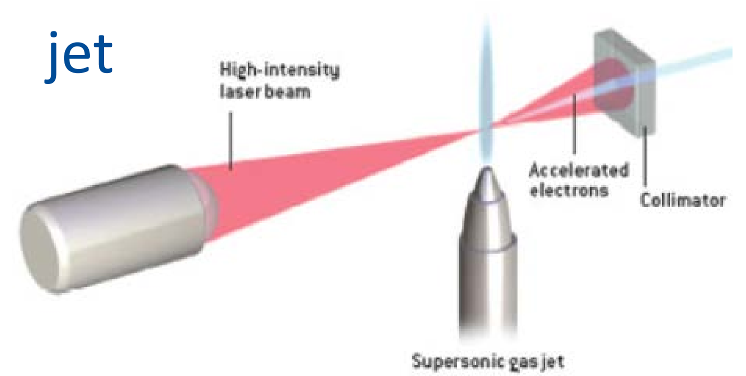
(Dream of) LPWA *e-* Injector for *p+* IOTA Tune Up

- Given expected sensitivity of the Integrable Optics and Space-Charge Compensation to the lattice imperfections, it is very desirable to have an option of reverse *e-* injection to tuneup IOTA optics for record high tune-shift operation with 70 MeV/c protons
- Need compact 70 MeV electron source – e.g., LPWA



Laser Wakefield Acceleration Injector for IOTA ?





Main Specs:

e- Energy	**70 MeV**
Bunch charge	**(¼ - ½) nC**
Rep.rate	**~0.1 Hz**
E* spread d*E*/*E	**< 0.2%**
Emittance, n-rms	**< 100 μm**

Important Considerations:

- Compact (<1 m)
- Injection (matching, on orbit?, kicker?)
- Cost (low)
- Reliability and stability (high)

This would be the first occurrence of the laser wakefield method used as an electron source for injection into an operational accelerator.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 3, 121002 (2000)

Estimates of emittance dilution and stability in high-energy linear accelerators

T. O. Raubenheimer

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 14, 014401 (2011)

Estimation of orbit change and emittance growth due to random misalignment in long linacs

Kiyoshi Kubo
KEK, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
(Received 15 September 2010; published 4 January 2011)

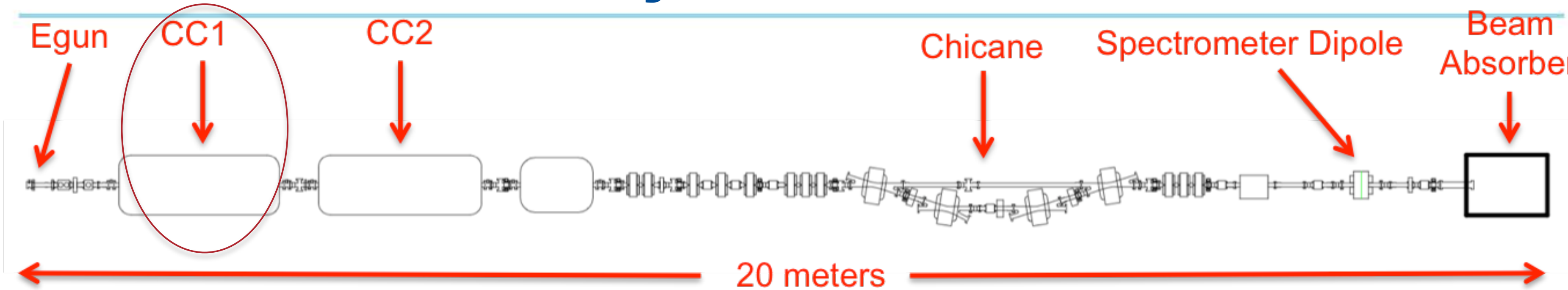
$$\gamma\langle J_f\rangle \approx \frac{eV_c}{8mc^2}\bar{\beta}\log(E_f/E_0)\langle\theta^2\rangle. \qquad (15)$$

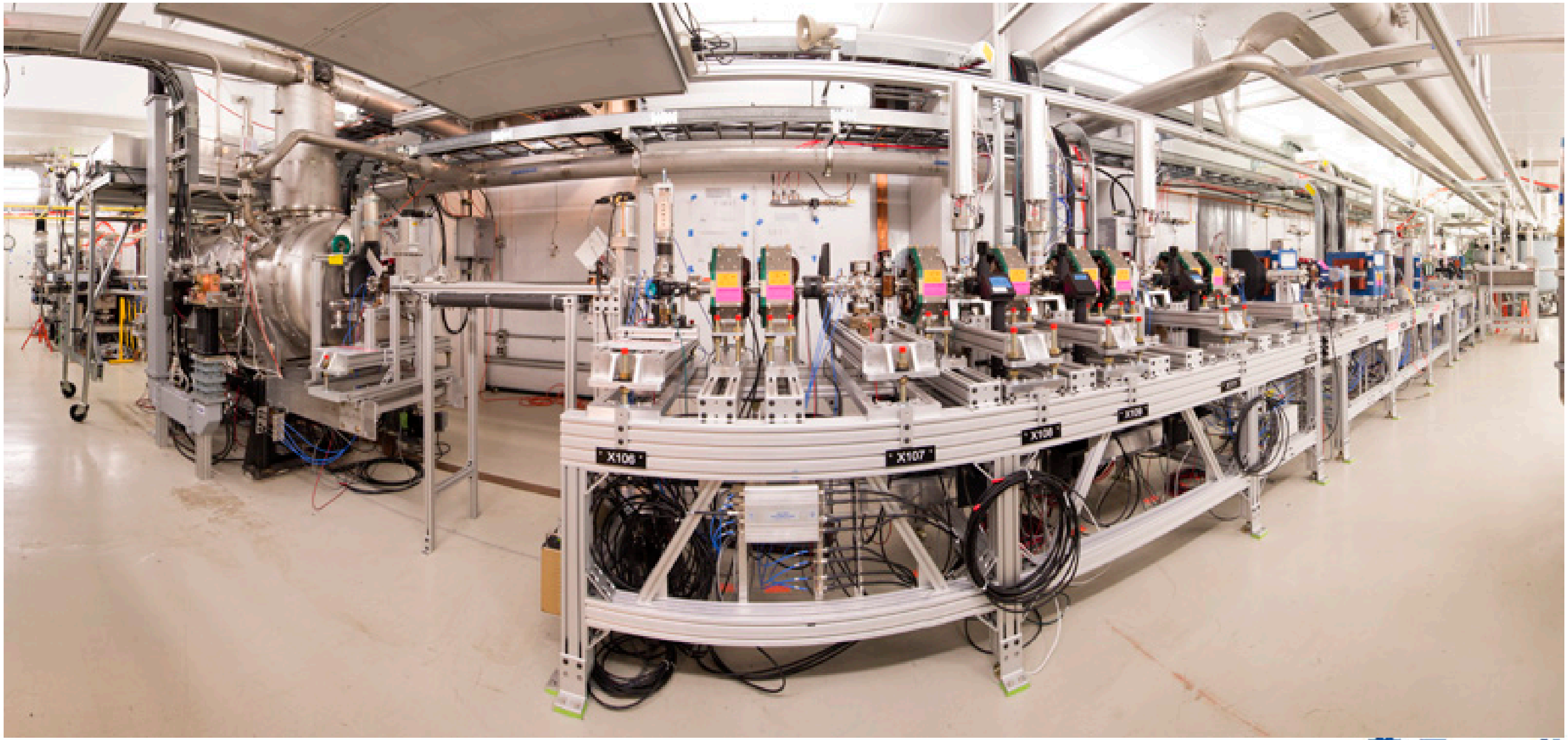
- ILC V_c=31.5 MeV
- CLIC V_c=25 MeV
- LPWA V_c=5-10 GeV
- PWFA V_c=25 GeV →

- CLIC *Y'*_accel structure=1.1 urad
- PWFA *Y'*_accel structure=1.1/30 urad

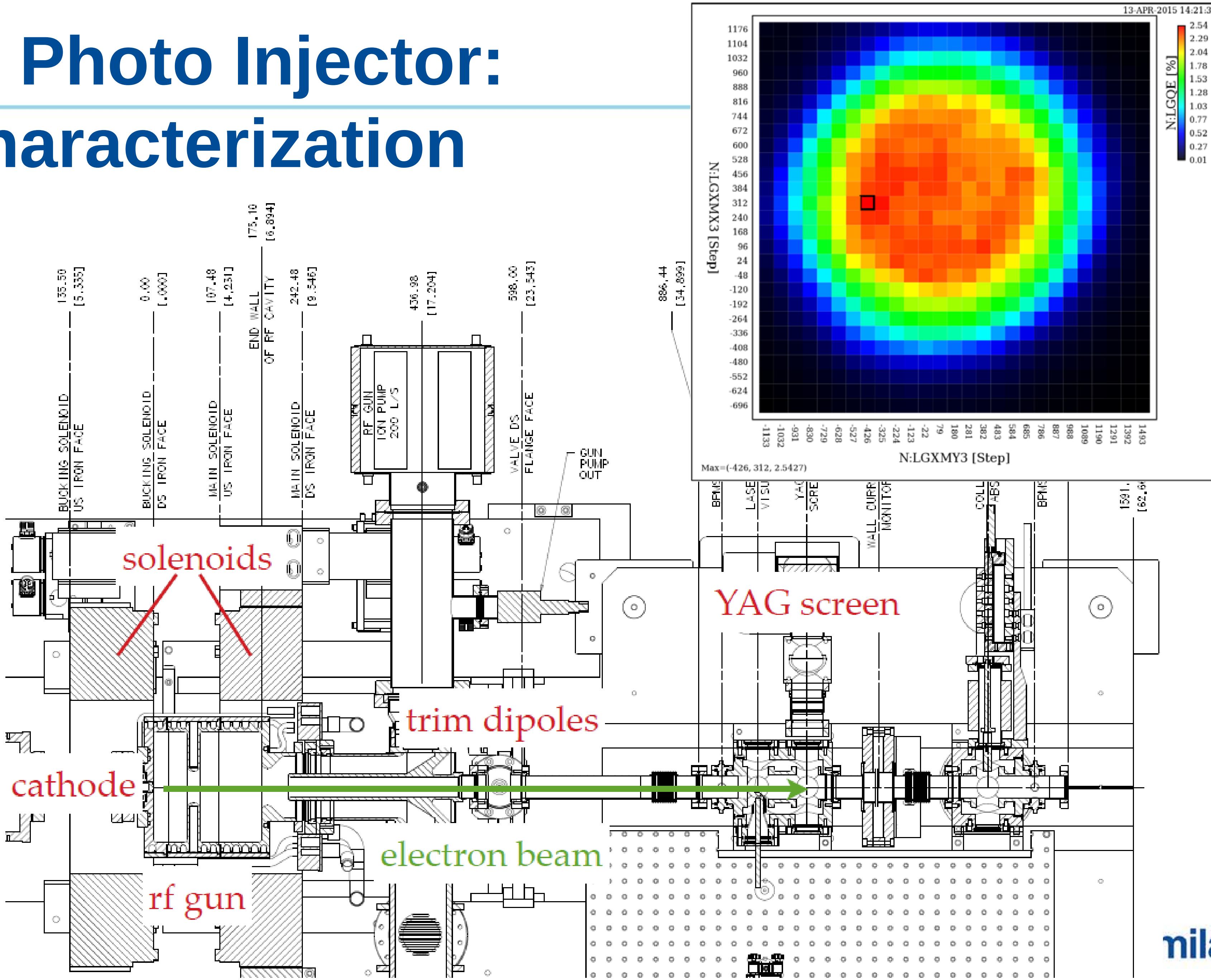
- Tolerance of drive-beam to main-beam angular alignment and angular jitter is ~30 times more stringent than for CLIC

IOTA Electron Injector @ FAST



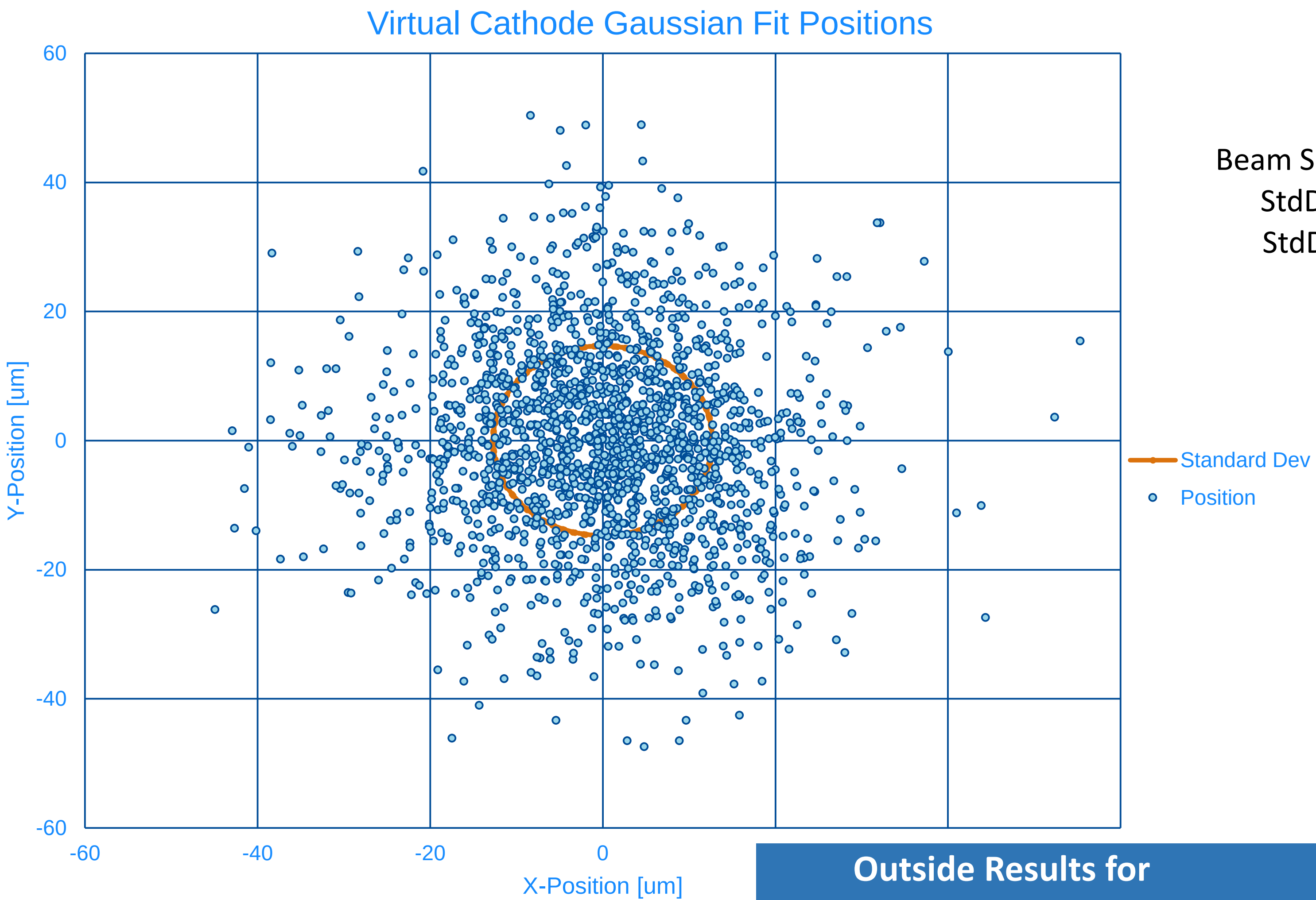


e- Photo Injector: characterization



Cathode QE Scan

Laser Position Stability at Virtual Cathode



Beam Sigma [um]:	518
StdDev X [um]:	12.72
StdDev y [um]:	14.72

Outside Results for Comparison	Reference
Δx = 4.7 μrad, Δy = 5.1 μrad	Optic Express, v. 21, Issue 9, 10727 (2013)

Transverse stability of focusing elements

$$\gamma\langle J_{f,q}\rangle \approx \frac{1}{8mc^2\Delta_{Eq}}(\beta_F k_F^2 + \beta_D k_D^2)(E_f^2 - E_0^2)\langle a^2\rangle. \quad (43)$$

- CLIC Δ_eq=100 MeV
- PWFA Δ_eq=25 GeV →

- CLIC jitter ***a*_q**=1.6 nm

- PWFA jitter ***a* _q** =1.6* sqrt(25) = 8 nm ?
- (for drive beam)

Phenomenological Cost Model

$$\text{Cost(TPC)} = \alpha\, L^{1/2} + \beta\, E^{1/2} + \gamma\, P^{1/2}$$

"Total Project Cost in the US accounting"

"Tunnel Length" Civil Construction

"Energy" – Cost of Accelerator Components

"Site Power" Infrastructure

where **α,β,γ** – technology dependent constants

- **α≈ 2B$/sqrt(L/10 km)**
- **β≈ 10B$/sqrt(E/TeV)** for RF
- **β≈ 3B$/sqrt(E/ TeV)** for SC magnets

  β≈ 1B$ /sqrt(E/TeV) for NC magnets
- **γ≈ 2B$/sqrt(P/100 MW)**

works for 17 large machines within **±30%**

- Shiltsev, *JINST* 9 T07002 (2014)

Phenomenological cost model shows that geometric footprint is the least important factor , the most important is cost of accelerator per TeV

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US accounting TPC in B$ (from WP sent to P5, 2013)

	Known Est.	$\alpha\beta\gamma$ Model	Comments	$L_{[10km]}$	$E_{[1TeV]}$	$P_{[0.1GW]}$
Super B e+e-	1.0 Eur. Acc	1.3	? 2012 ?	0.05	0.01	0.1
Project X p	1.8	2.2	Est. 2012	0.1	0.008	0.23
DAEDALUS p		3	For 3 MWs cyclotrons		0.001	1
Neutrino Factory p→μ	4.7-6.5	4.6	Accounting not clear	0.6	0.012	1
μ+μ- Higgs Factory		7.7	-2 if PD exists	0.7	0.12	1
Higgs e-e+ site filler		9.5		1.6	0.25	5
ILC-0.25 TeV e+e- HF		10.2	~70% of ILC-0.5	~1.5	0.25	~1.2
TLEP Higgs Factory		11.4		8	0.25	5
μ+μ- Collider 3/6 TeV		13/16	-2+ if Prot. Driver exists	2.0	**3**/6	2.3
VLHC-I 40 TeV p-p	11-14	13.1	2001 est (**4.1**)x3.5; - inj	23	40	2
ILC-0.5 TeV e+e-	(16.5)	13.6	2013 est = **7.8 Eur Acct**	3	0.5	2.3
CLIC-0.5 TeV e+e-	7.4-8.3 E.A.	13.0	Coeff β_{CLIC} must be $>\beta_{ILC}$	2	0.5	2.5
Beam-PWA ee LC 3TeV		19-39	60 MW driver alone >8	1	3	2.8
CLIC-3 TeV e+e-		26.9	No public cost range	6	3	5.6
SHE LHC 100 TeV p-p		40.2	Deduct ~15 of injector	8	100	5
Laser-PWA 1/10 TeV e+e-		29/86.6	scaled today's laser cost	1	1/**10**	1.4
VLHC-II 175 TeV p-p		53.8		23	175	5

V.Shiltsev - FNAL - 12/09/2013 12

On "Beam-Driven"-LCs

Approach #1 – estimate with αβγ-model

- 3 TeV machine will be ~10 km long, and mb a factor of 2 more power efficient than CLIC (280 MW vs 560 MW total site power)
- If the cost per TeV will be as in CLIC

BPWA: Cost = $2\cdot1^{1/2} + 10\cdot3^{1/2} + 2\cdot2.8^{1/2}$ =2+17.3+3.3=**22.6±7**

tunnels accelerators infrastructure

- If (as unproven technology) the cost per TeV will be **2xCLIC**

BPWA: Cost = $2\cdot1^{1/2} + 20\cdot3^{1/2} + 2\cdot2.8^{1/2}$ =2+34.6+3.3=**39.9±10**

On “Beam-Driven”-LCs (2)

Approach #2 – guesstimate “pieces” (P1, P2…)

- Leave tunneling and power infrastructure as on previous slide P1=2+3.3=5.3B$

Costs of the main beam production can be taken as in CLIC-0.5 (x2 in US accounting) P2=2.5B$

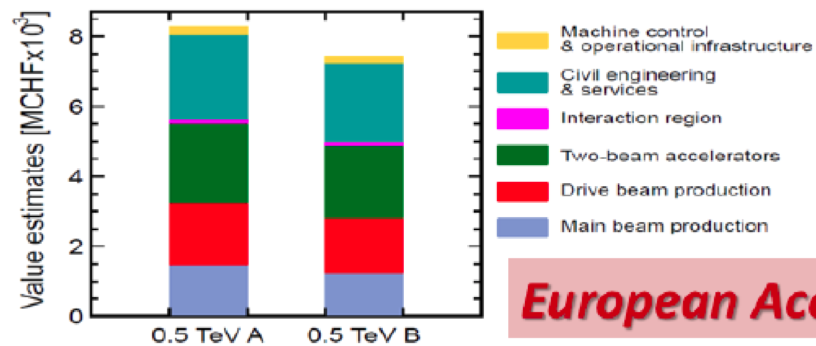
“Accelerator proper” 120 stages 25 GeV each (plasma cells+ matching +drive beam injection lines) is not known well, P3=2-4 B$ (for 3 TeV case)

CLIC-0.5 cost (2012)

- Only for 500 GeV com e+e- (~250 MW)

Table 4: Value and labour estimates of CLIC 500 GeV.

Staging scenario	Value [MCHF]	Labour [FTE years]
A	8300^{+1900}_{-1400}	15700
B	7400^{+1700}_{-1300}	14100



European Accounting

V.Shiltsev - 6: Cost structure of the CLIC accelerator complex at 500 GeV for scenarios A and B. 19

On “Beam-Driven”-LCs (3)

Big Item: Drive beam production P4=10-17 B$

1 TeV LC needs 48MW e- source

3TeV needs either 3x such sources or one for 144MW?

Estimate step 1: Cost of one 48 MW source P4*=6-10B$

- *Reference: Project X (1.7B$) 4MW Power and* 8 GeV *Energy,*
- *LCLS-II (1 B$) 1 MW power and 4 GeV Energy*
- *Use sqrt(P)-scaling with power → P4=6-7B$*
- *Use sqrt(E) scaling with energy/replicate N → P4=9-10 B$*

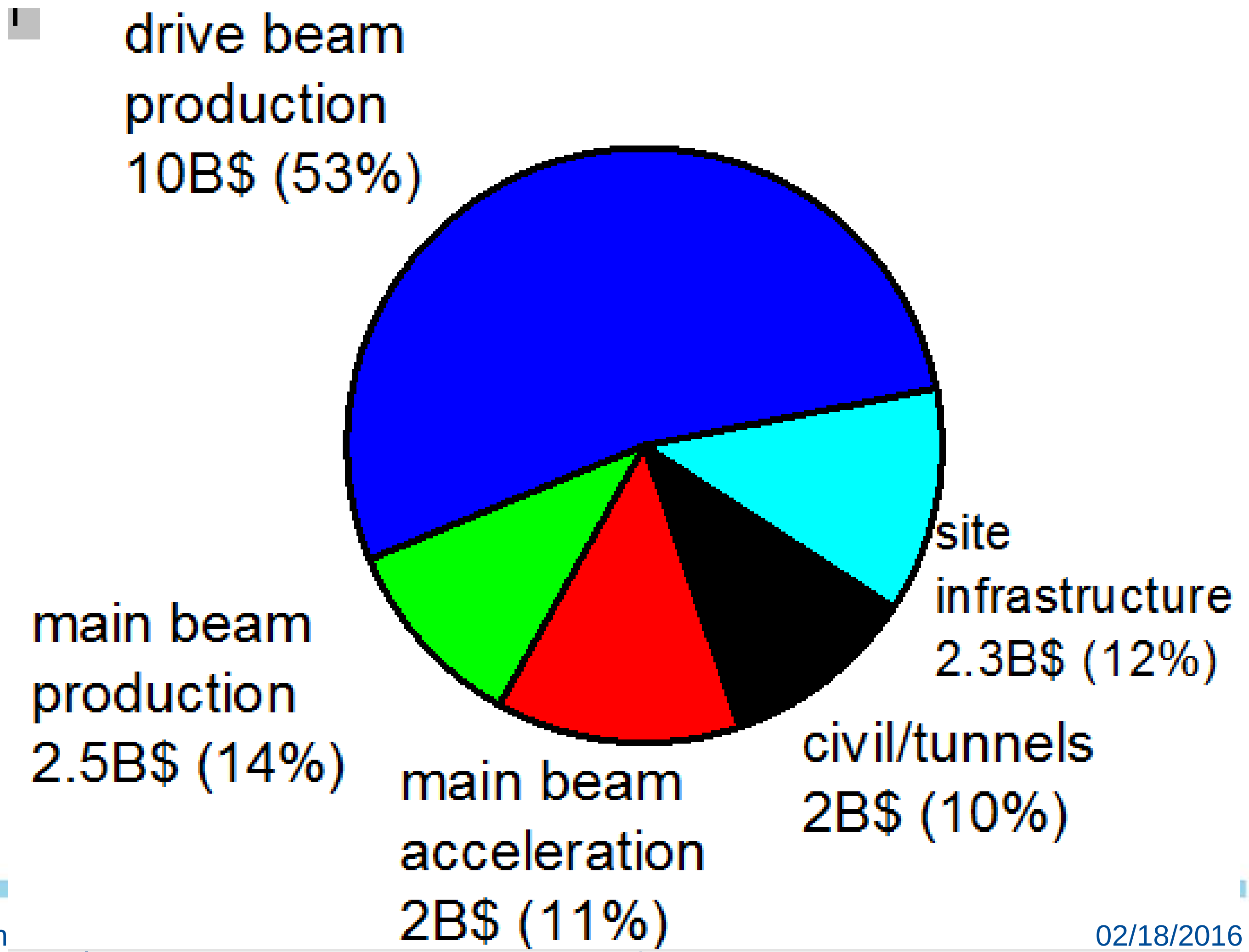
Estimate step 2: Cost of three x 48 MW sources P4=10-17B$

- *Sqrt(3)*

Cost of “Beam-Driven”-PWA LCs (3 TeV cm)

The total cost estimate (FY16$)

P1+P2+P3+P4=5.3+2.5+(2-4)+(10-17)=20-29B$



Advanced LC concepts vs CLIC (now)

	CLIC	DWA-LC	PWA-LC	LWA-LC
Feasibility of Energy	Gradient & staging de-monstrated, e+ OK	Gradient OK, No staging demo, e+ OK	Gradient OK, No staging demo, e+ questionable	Gradient OK, No staging demo, e+ questionable
Feasibility of Luminosity	Risk ~10-100	Risk now ~10-100	Risk >~10^3 ?	Risk >~10^5 ?
Feasibility of Cost	Problems: 560 MW, TPC(US) ~26B$	? 430 MW, TPC(US) ~20B$	? 300 MW, TPC(US) ~20-29B$	? 150 MW, TPC(US) ~30B$
		similar to CLIC	Potential of lower power and lower TPC	Potential of lower power and lower TPC, Promise of many applications

Toward HEP-Relevant Accelerator Facility

- The proposed roadmap may be divided into three stages
  - **2016-2025:** Focus on Energy Feasibility
    - Show High gradient (done for blow-up, not for a hollow channel)
    - Staging to get to energy of interest (1-3-10 TeV – TBD)
    - Acceleration of Positrons
    - Applications (off-ramps): FELs, ring injectors
      - Challenge: quasi-linear is not needed for applications, wall-plug efficiency is not important
  - **2026-2035:** Focus on Performance (Lumi) Feasibility
    - Charge per bunch, emittances, rep. rates ~10 kHz, etc.
    - Final focus system, accelerator-detector interface
    - Integrated Test Facility
  - **After 2035:** Focus on Cost reduction
    - High efficiency
    - Cost (accelerator, drive sources, power infrastructure, etc)